A Distributed Admission Control Model for Class-based IP Networks

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Abstract

Providing Quality of Service (QoS) in the Internet is a complex and multilevel problem involving heterogeneous media, protocols and technologies. Achieving a seamless and ubiquitous QoS solution is even a more intricate issue attending to the plethora of service providers with their own business, management and technological strategies. In this scenario, strong efforts have been made to adapt and improve the TCP/IP stack with enhanced service models and protocols to sustain the integration of applications and services with distinct QoS requirements. From a network level perspective, and following this evolution, the IP service model tends to rely on class-based paradigms such as the Differentiated Services.

Considering that overprovisioning of network resources by itself is not always an attainable and everlasting solution, to allow efficient management of each class resources and fulfill Service Level Specification (SLS) commitments, Admission Control (AC) mechanisms are recommended to keep classes under controlled load and assure the required QoS levels. However, the complexity introduced in the network control plane should be kept as low as possible.

Despite the intense research in the field, handling AC in multiservice class-based networks is still an open issue. This has motivated the challenge of achieving a simple, flexible and efficient AC proposal able to control QoS and SLSs both intra and interdomain. In this way, this thesis proposes a distributed and lightweight AC model based on per-class edge-to-edge monitoring feedback for controlling the quality of multiple services in class-based IP networks. Resorting to QoS and SLSs on-line monitoring performed at egress nodes, relevant service metrics are provided to ingress nodes, which make implicit or explicit AC decisions based on service-dependent rules. These rules, controlling both QoS parameters and SLSs utilization, consider controlled overprovisioning levels to simplify AC while improving service guarantees. The intradomain and end-to-end operation of the AC model, including the main high-level entities involved, are formalized resorting to an expressive and intuitive notation.

A prototype of the AC model has been developed and tested using a simulation platform (NS-2). The devised test scenarios aim at assessing, in a first instance, the effectiveness of the monitoring process in capturing each class QoS behavior and then, at providing a proof-of-concept of the AC criteria in satisfying multiple QoS and SLSs commitments. The results, evincing the relevance and applicability of the defined AC rules, show that the proposed solution provides a good compromise between simplicity, service level guarantees and network resource usage, even for service classes with strict QoS requirements.

Resumo

O suporte de qualidade de serviço (QoS) na Internet é um problema complexo e multifacetado envolvendo um conjunto heterogéneo de *media*, protocolos e tecnologias. Obter uma solução de QoS uniforme e abrangente é ainda mais difícil atendendo ao grande número de fornecedores de serviço com estratégias de negócio, gestão e tecnologias distintas. Neste cenário, tem sido feito um grande esforço em adaptar e melhorar a pilha TCP/IP com modelos de serviço e protocolos mais apropriados para sustentar a integração de aplicações e serviços com requisitos de QoS distintos. Ao nível de rede, e seguindo esta evolução, o modelo de serviço em que o IP assenta tende para um paradigma baseado em classes, de que é exemplo o modelo de Serviços Diferenciados.

Considerando que o sobre-aprovisionamento de recursos de rede, por si só, nem sempre é uma solução sustentável e permanente, para permitir uma gestão eficiente dos recursos e assegurar o cumprimento dos níveis de serviço especificados (SLS), o controlo de admissão (AC) assume um papel relevante na manutenção das classes de serviço sob carga controlada e na garantia da QoS pretendida. No entanto, a complexidade inserida na rede deve ser a menor possível.

Apesar da intensa investigação na área, a abordagem ao AC em redes multi-serviço é ainda uma questão em aberto, o que motivou o desafio da obtenção de um modelo de AC simples, flexível e eficiente, capaz de controlar a QoS e os SLSs intra e inter-domínio. Deste modo, esta tese propõe um modelo de AC distribuído e de sobrecarga reduzida, baseado em monitorização por classe entre nós fronteira, para controlar a qualidade de múltiplos serviços em redes IP baseadas em classes. Recorrendo à monitorização *on-line* de QoS e SLSs realizada em nós de saída do domínio, são disponibilizadas métricas de serviço adequadas aos nós de entrada do mesmo, que tomam decisões de AC implícitas ou explícitas com base em regras específicas por serviço. Estas regras controlam os parâmetros de QoS e a utilização dos SLSs, considerando níveis de sobre-aprovisionamento auto-contidos de modo a simplificar o AC e a aumentar as garantias de cada serviço. A operação do modelo intra-domínio e fim-a-fim, incluindo as principais entidades envolvidas, são formalizadas usando uma notação expressiva e intuitiva.

Um protótipo do modelo de AC foi desenvolvido e testado utilizando o simulador NS-2. Os cenários de teste idealizados visam avaliar a eficácia do processo de monitorização na detecção do comportamento de QoS de cada classe e fornecer uma prova de conceito da capacidade dos critérios de AC em cumprir múltiplos compromissos de QoS e SLSs. Os resultados obtidos, evidenciando a relevância e aplicabilidade das regras de AC definidas, mostram que a solução proposta estabelece um bom compromisso entre simplicidade, níveis de garantia de serviço e utilização dos recursos de rede, mesmo para classes de serviço com requisitos de QoS estritos.

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List of Acronyms

AC	Admission Control
ACK	Acknowledgment
AF	Assured Forwarding
AFx	Assured Forwarding Group
API	Application Programming Interface
AQM	Active Queue Management
AR	Assured Rate
ARM	Active Resource Management
B2Bp	Back-to-back probing
BA	Behavior Aggregate
BB	Bandwidth Broker
BGP	Border Gateway Protocol
BGRP	Border Gateway Reservation Protocol
bps	bits per second
BTC	Bulk Transfer Capacity
CAC	Connection Admission Control
CAIDA	Cooperative Association for Internet Data Analysis
CBQ	Class-Based Queuing
CBR	Constant Bit Rate

CDMA	Code Division Multiple Access
CJVC	Core-Jitter Virtual Clock
CLI	Command Line Interpreter
COPS	Common Open Policy Service
COPS-PR	COPS Usage for Policy Provisioning
CoS	Class of Service
DF	Default Forwarding
DPS	Dynamic Packet State
DS	Differentiated Services
Diffserv	Differentiated Services
DSCP	Diffserv Code Point
ECN	Explicit Congestion Notification
EF	Expedited Forwarding
EMBAC	Endpoint Measurement-based Admission Control
EPFL	Ecole Polytechnique Fédérale de Lausanne
EXPOO	Exponential On-Off Source
FIFO	First In First Out
FTP	File Transfer Protocol
GMPLS	Generalized Multiprotocol Label Switching
GPS	Global Positioning System
GRED	Generalized Random Early Detection
H	Hurst parameter
ICMP	Internet Control Message Protocol
IETF	Internet Engineering Task Force
Intserv	Integrated Services
IP	Internet Protocol

IPDV	IP Packet Delay Variation
IPER	IP Packet Error Ratio
IPLR	IP Packet Loss Ratio
IPOT	IP Packet Octet-based Throughput
IPPM	IP Performance Metrics
IPPT	IP Packet Throughput
IPTD	IP Packet Transfer Delay
IS	Integrated Services
ISP	Internet Service Provider
ITU	International Telecommunications Union
ITU-T	ITU - Telecommunication Standardization Sector
LRD	Long Range Dependence
LSP	Label Switching Path
MA	Moving Average
MBAC	Measurement-based Admission Control
MF	Multi-Field
MIB	Management Information Base
MP	Measurement Point
MPLS	Multiprotocol Label Switching
MTU	Maximum Transfer Unit
NED	Network Description Language
NIMI	National Internet Measurement Infrastructure
NREN	National Research and Education Network
NS	Network Simulator
NSIS	Next Steps in Signaling
NTP	Network Time Protocol

OMNeT	Objective Modular Network Testbed
OSPF	Open Shortest Path First
OWAMP	One-Way Active Measurement Protocol
OWD	One-Way Delay
OWLP	One-Way Loss Pattern
OWPL	One-Way Packet Loss
PAR	Pareto On-Off Source
PDB	Per-Domain Behavior
PDP	Policy Decision Point
PDR	Per-Domain Reservation
PEP	Policy Enforcement Point
PHB	Per-Hop Behavior
PHR	Per-Hop Reservation
pkt	IP packet
PIA	Percent IP Service Availability
PIB	Policy Information Base
PIU	Percent IP Service Unavailability
POI	Poisson Source
pps	packets per second
PPTD	Packet Pair/Train Dispersion
PQ	Priority Queuing
PQ-WRR	Priority Queuing Weighted Round Robin
QoS	Quality of Service
RFC	Request for Comments
RED	Random Early Detection
RIO	Random Early Detection with In and Out

RIO-C	Random Early Detection with In and Out - Coupled
RIO-DC	Random Early Detection with In and Out - Decoupled
RMD	Resource Management for Diffserv
RIPE-NCC	Reseaux IP Europeenne Network Co-ordination Centre
RST	Reset
RSVP	Resource ReSerVation Protocol
RTCP	Real-Time Control Protocol
RTP	Real-Time Transport Protocol
RTT	Round Trip Time
SAA	Service Assurance Agent
SC	Service Class
SIBBS	Simple Interdomain Bandwidth Broker Specification
SICAP	Shared-segment Interdomain Control Aggregation Protocol
SLA	Service Level Agreement
SLoPS	Self Loading of Periodic Streams
SLS	Service Level Specification
SMT	Software Management Tool
SNMP	Simple Network Management Protocol
SPR	Spurious IP Packet Ratio
srTCM	single rate Three Color Marker
TB	Token Bucket
TC	Traffic Conditioning
TCA	Traffic Conditioning Agreement
TCP	Transmission Control Protocol
TCS	Traffic Conditioning Specification
TOPP	Trains of Packet Pairs

ToS	Type of Service
trTCM	two rate Three Color Marker
TSWTCM	Time Sliding Window Three Color Marker
TTM	Test Traffic Measurements
TW	Time Window
UDP	User Datagram Protocol
VC	Virtual Clock
VINT	Virtual InterNetwok Testbed
VoIP	Voice over IP
VPS	Variable Packet Size
VTRS	Virtual Time Reference System
VW	Virtual Wire
WFQ	Weighted Fair Queuing
WG	Working Group
WRED	Weighted Random Early Detection
WRR	Weighted Round Robin
WWW	World Wide Web
XML	Extensible Markup Language

Chapter 1

Introduction

Communication networks have been following a clear trend toward the integration of current and emerging applications and services with distinct Quality of Service (QoS) requirements. This integration process, ranging from personal to local and wide area environments, constitutes a major challenge as it spans protocol stacks orthogonally, imposing new demands from application to physical layers. From the network perspective, the Internet Protocol (IP), due to its well-known characteristics (e.g., simplicity, robustness, maturity), worldwide use and current advances, has been recognized as the level at which network convergence tends to occur. However, it is also well-known that the default best-effort service upon which the Internet is based neither offers QoS guarantees nor consistent solutions to differentiate traffic, becoming insufficient to accommodate the heterogeneity of Internet traffic. Service providers also face an increasing concern and pressure regarding the provision of QoS in their infrastructures, motivated not only by user demands but also by improving services' quality and diversity in a competitive and cost-effective manner. The ability to differentiate traffic will allow introducing QoS-oriented business relationships and pricing models, supported by the establishment of Service Level Agreements (SLAs) and corresponding Service Level Specifications (SLSs). In addition, defining standard SLA/SLSs is a key aspect for interdomain and end-to-end QoS delivery [1, 2].

Supporting the coexistence of heterogeneous applications and services in the Internet has been fostering the evolution of the underlying protocol stack. The research community has been making strong efforts to endow the TCP/IP stack with new service models, enhanced protocols and mechanisms to allow such integration. The QoS quest will not certainly be based on a single and general-purpose solution due to the diversity of technologies, administrative policies and strategies in the field [3]. Each solution requires the assessment of aspects such as its cost of integration into (or migration of) the existing network infrastructure, the QoS guarantees provided or the scalability of the solution. Class of Service (CoS) networks, where flows with similar characteristics and service requirements are aggregated in the same class, are a step forward in pursuing scalable QoS solutions. In this context, the Differentiated Services (Diffserv) model [4, 5] has deserved special attention both from the scientific community and industry due to the acceptable trade-off between complexity and QoS guarantee levels, and to the ability to coexist with traditional best-effort IP networks.

Introducing specific QoS control mechanisms into IP networks is, however, a controversial issue. Actually, overprovisioning of communication resources is a common way to provide QoS in network backbones, avoiding or reducing network control complexity. Although for some service providers overprovisioning might be an attainable solution, it should not be assumed as a generic and permanent answer [6, 7]. In fact, apart from not being widely available, the huge growth of users and applications' demands requires additional service and traffic control mechanisms in order to guarantee that QoS commitments are honored. Despite this need, a major objective to keep in mind, and likely a key aspect for their deployment in real networks, is to maintain the network control plane complexity as low as possible.

1.1 Motivation and objectives

As mentioned above, the support of multiconstrained applications in the Internet launches new demands and challenges on the provision and management of network services and underlying resources. Service-oriented traffic control mechanisms, operating with minimum impact on network performance, assume a crucial role as regards controlling services quality and network resources transparent and efficiently. Within traffic control mechanisms, Admission Control (AC) is recommended for keeping service classes under controlled load and assuring the required QoS levels [3, 8, 9]. In fact, controlling the admission of flows entering the network and sharing a service class aims at avoiding overutilization of existing resources, satisfying the requirements of new incoming traffic flows without compromising the QoS of already active flows and, generically, preventing instability and congestion assuring QoS and SLSs fulfillment.

In general, the QoS guarantees and predictability required by a service class determines the control complexity inherent to an AC strategy. To obtain a good compromise between service guarantees, complexity and efficient resource utilization is, in fact, a major challenge. This challenge is increased when considering the end-to-end QoS delivery as multiple heterogeneous domains may be involved and the negotiated SLSs' between them need to be fulfilled.

Although AC has been extensively studied in the literature, few studies deal with the simultaneous management of domain QoS levels and interdomain SLSs, falling short in establishing and formalizing concrete and flexible AC equations to be applied to multiservice networks. As detailed later in Chapter 3, common AC approaches do not contemplate or balance as a whole aspects such as: (i) the trade-off between service assurance level and network control complexity; (ii) the flexible support of distinct service types; (iii) the simultaneous control of QoS levels and existing SLSs; (iv) the AC operation both intradomain and end-to-end. Attending to these aspects, handling AC in multiservice class-based networks is still an open research topic and it is within this context that the motivation for the present work lays on. Hence,

the main objective of this work is to devise an encompassing, flexible and lightweight AC model able to control QoS and SLSs in multiclass and multidomain environments.

In this way, the AC model should contemplate: (i) the control of distinct network services and assurance levels, supporting applications with different QoS requirements and traffic profiles; (ii) the intradomain and end-to-end operation, controlling both the QoS levels in a domain and the share of existing SLS between domains, to fulfill the applications' end-to-end QoS requirements. Apart from covering multiservice and multidomain operation, the simplicity, flexibility, easy deployment and integration in the Internet are considered relevant goals in the model design. The aim is to accomplish AC without adding significant complexity to the network control plane, requiring reduced state information and minor changes to the network. This will also contribute for the efficiency and scalability of the solution. The flexibility of the proposal regards its ability to accommodate the evolution of services, applications and technologies easily. All these goals are relevant when deploying the model in large scale across multiple administrative domains relying, eventually, on distinct QoS solutions.

Considering the above reasoning, a new AC model is proposed for controlling services quality in multiclass IP networks. An important underlying idea driving the model operation is to take advantage of the consensual need for on-line service monitoring and for traffic control at network domain boundaries, using the resulting monitoring information to perform distributed AC. In more detail, the proposed AC model follows a distributed architecture where AC decisions are driven by feedback from systematic edge-to-edge measurements of relevant QoS parameters for each service type and SLSs utilization. While ingress nodes perform implicit or explicit

AC[1] resorting to service-dependent rules for QoS and SLS control, egress nodes collect service metrics providing them as inputs for AC. To improve the trade-off between complexity and QoS assurance, the AC criteria comprise service-dependent degrees of overprovisioning in order to simplify AC while improving QoS guarantees. The end-to-end operation is viewed as a repetitive process of AC at each domain ingress nodes and cumulative computation of the service metrics available at each domain.

The proposed AC model being distributed, service-oriented, based on per-class on-line monitoring and involving only edge nodes should be able to abstract network core complexity and heterogeneity, to sense each service classes' dynamics and to perform AC with reduced state information, latency and overhead. These characteristics are expected to contribute to pursue the goals outlined above. However, a fundamental question raising from the model properties is the following:

> *Will service-dependent AC rules driven by edge-to-edge on-line monitoring be able to control distinct QoS guarantees and SLSs commitments properly?*

Thus, after defining the AC model conceptually, to provide a proof-of-concept of the proposed solution, illustrating its self-adaptive ability in controlling QoS and SLSs in a multiclass domain, is another major objective to fulfill. In this way,

> *this work also intends to explore the challenges of implementing the proposed AC model, assessing its effectiveness and efficiency in satisfying each service class QoS levels and existing SLSs commitments.*

Attending to the properties of the AC model outlined above, four main areas have been identified as relevant to devise a realistic and consistent AC solution. These interrelated areas, according to Figure 1.1 [10], are as follows: (i) *service definition*, which involves the definition of parameters and semantics of SLSs and of basic services adapted to different application types; (ii) *on-line monitoring*, which keeps track of QoS and SLS status in the domain; (iii) *AC decision criteria*, which involves the establishment of service-dependent AC equations; (iv) *CoS traffic characterization*, which provides the knowledge of the statistical properties of the traffic classes in the domain as a result of aggregation. The present study covers recent research on these areas,

[1]Within AC context, the term explicit is commonly used to express the existence of signaling between the application and the network. When this signaling is not present, AC is based on an implicit detection of flows.

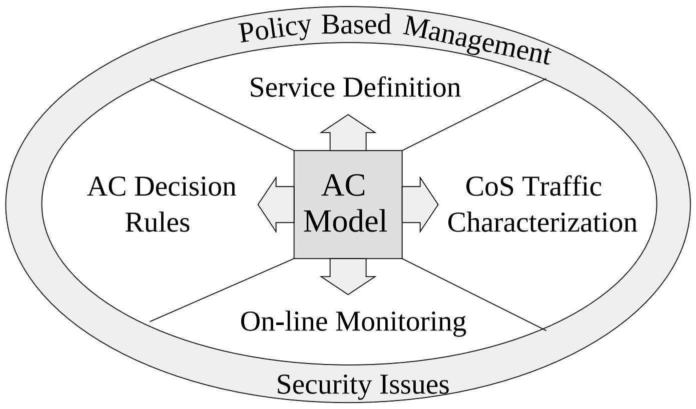


Figure 1.1: Model areas

contributing with new insights for managing intra and interdomain services quality and AC operation. The use of policy-based network management and security considerations were left for further study.

In order to pursue the main objectives stated above, and considering the interrelated areas identified, a more detailed view over the problem to solve has led to the following objectives:

(i) *contextualize and clarify the underlying concepts of class-based IP networks* - within CoS paradigm, the Diffserv model is considered a reference model, justifying the review of the main principles and components behind this model;

(ii) *identify and structure the main issues and tasks subjacent to the definition and building of network services both intra and interdomain* - in this context, the important role of establishing and standardizing SLA/SLS for domain QoS provisioning, interdomain negotiation and end-to-end QoS delivery is an important topic to consider;

(iii) *survey existing AC proposals, covering their main characteristics, advantages and limitations* - this analysis is of paramount importance as it grounds the motivation for the present research study, pointing out the main strategic directions to achieve a new AC model with the defined properties;

(iv) *identify and study the main issues and recent developments related to the problematic of QoS monitoring* - this includes the identification of relevant metrics of network performance, adequate measurement methodologies and timing issues. Special attention will be given to QoS monitoring solutions to be deployed in multiservice CoS networks. This objective also involves evaluating the adequacy and effectiveness of multiclass measurement methodologies in capturing each class QoS behavior;

(v) *understand and characterize statistically the properties of Internet traffic under the CoS paradigm* - this characterization, both at individual and aggregated level, intends to provide important inputs for service provisioning and for establishing and parameterizing service-dependent AC equations;

(vi) *conceive and specify a new AC model for the control of QoS and SLSs in multiservice CoS networks* - this includes defining the model's architecture, specifying its entities, formalizing service-dependent AC criteria and describing the model's operation both intradomain and end-to-end;

(vii) *implement a simulation prototype of the proposed AC model covering a single multiclass domain* - the configuration of this prototype should take as inputs the research outcome deriving from the fulfillment of the objectives defined above;

(viii) *provide a proof-of-concept of the proposed AC model* - this involves testing and evaluating the performance of the AC model, assessing its ability to self-adapt to network dynamics and to assure QoS and SLS commitments in a multiclass domain efficiently;

(ix) *perform an analysis of the proposed AC model* - this analysis should point out the main strengths and limitations of the present work, prompting future research steps and opportunities.

1.2 Research methodology

The research methodology to pursue the main objective of this work comprises several steps somehow evinced by the list of objectives defined above. Firstly, considering the main research areas subjacent to the proposed AC model, relevant literature covering the major developments in each of these areas is surveyed. This bibliographic search and review allows a comprehensive analysis of the current state-of-the-art in those areas, grounding the conceptual and practical decisions made. This review is organized to provide the readers with the necessary theoretical concepts and background for a self-contained understanding of this work. Secondly, a new AC model is devised and its main entities and rules specified. In order to provide a proof-of-concept of the new proposal, the AC model is implemented and evaluated resorting to a simulation environment. In the context of computer communications research, when an experimental validation using real networks is premature or unfeasible, simulation modeling is commonly used. In fact, the flexibility of a simulation environment in setting up a wide range of distinct test scenarios and accommodating model improvements easily, makes it very appealing as a validation methodology that should precede the deployment and ultimate validation in real environments. The simulation model has itself to undergo a validation process for verifying its consistency and correct behavior.

1.3 Summary of main contributions

Although a full discussion on this thesis is included in the concluding chapter, this section provides a brief overview of its main contributions. Taking into account the initial objectives defined above, these contributions are summarized as follows:

- definition of a new encompassing and lightweight AC model for controlling QoS and SLSs in multiservice IP networks based on the CoS paradigm [11, 12, 13, 10, 14]. In this context, other contributions include:
  - definition of service-dependent AC criteria based on complementary rules - QoS control rule, SLS rate control rule and end-to-end control rule - parameterized according to each service type characteristics;
  - introduction of an intuitive and expressive notation based on set theory in order to specify the main network domain entities, the service-dependent AC criteria and the model operation both intra and interdomain [11];
  - development of a simulation prototype comprising a multiclass domain controlled by the proposed AC model, configured considering and interrelating realistic inputs and guidelines from the related research areas;
  - a proof-of-concept regarding the model's ability to perform an effective and efficient distributed control of QoS and SLSs using edge-to-edge on-line monitoring feedback;
  - several proposals for handling concurrent AC in order to tackle eventual over or false acceptance deriving from distributed and concurrent AC decisions [15];

- introduction of the concept of multipurpose active monitoring and development of a new multipurpose colored probing scheme [16, 17];
- proposal of an integrated SLA/SLS template and additional insights on scalable SLS monitoring and auditing tasks [11, 14]. Ongoing work on SLSs topic respects to SLS processing and validation [18];
- definition of a traffic classification criterion and first results on CoS traffic characterization [19], following the work initially carried out in [20];
- comprehensive survey of conceptual and practical issues on major areas supporting the proposed AC model, covering (i) multiservice CoS networks and service definition; (ii) AC in multiservice networks*;* (iii) QoS and SLS monitoring*;* (iv) CoS traffic characterization.

1.4 Dissertation layout

This dissertation is structured in eight chapters reflecting the research work carried out facing the objectives outlined in Section 1.1.

In the present Chapter 1 - *Introduction* - a first positioning of the reader in the area of research is provided, highlighting current trends and evolution. Then, the motivation for this thesis is justified and the main objectives of the work are defined. The main contributions to the research field are also summarized. The dissertation layout is included here in order to provide a global view of the full document, regarding its contents and organization.

In Chapter 2- *Multiservice Class-based IP Networks* - the motivation for adopting multiservice networks based on CoS paradigm is introduced, centering the discussion on IP networks. In this context, the Diffserv model is taken as reference being its architecture, principles and main components summarized. Then, the debate is focused on how to define and build distinct service classes, highlighting the relevance of specifying service level agreements both from an intra and interdomain perspective. A template for SLA/SLSs is proposed and additional deployment issues regarding SLSs control are discussed. The motivation for studying traffic characteristics within CoS networks is presented.

In Chapter 3 - *Admission Control in CoS IP Networks* - after exploring the need for AC in multiservice networks, a detailed study covering current AC approaches is carried out, giving special emphasis to proposals for class-based IP networks. For the most prominent proposals, their AC architectural principles, characteristics and operation mode are surveyed, and their main virtues and limitations identified. This analysis, involving a careful assessment of the trade-off between QoS guarantees and complexity, has grounded the motivation for devising a new AC model for multiservice class-based IP networks.

In Chapter 4 - *Monitoring QoS and SLSs* - the problematic of QoS and SLSs monitoring in multiservice networks is covered. This study is entirely justified by the inherent on-line monitoring approach upon which the proposed AC model is based. The main characteristics of monitoring systems are identified and the definition of concrete metrics and measurement methodologies for QoS and SLS monitoring are presented. Particular relevance is given to active measurement methodologies, debating their ability to fulfill edge-to-edge on-line QoS monitoring efficiently. In this context, the concept of multipurpose probing is introduced and a new probing scheme is presented.

In Chapter 5 - *Proposed Admission Control Model* - a novel service-oriented distributed AC model for controlling QoS and SLSs in multiclass and multidomain environments is proposed. After highlighting its major goals and assumptions, the model architecture is presented focusing on the main conceptual areas and components this model comprises and interrelates. An intuitive and expressive notation is also introduced to sustain a clear definition of relevant multiservice domain entities and to specify the AC decision equations and model operation. An introspective analysis of the AC model is performed, identifying its conceptual merits and hurdles, pointing out possible ways to overcome the latter. In particular, the problematic of concurrent AC is debated.

In Chapter 6 - *AC Model Implementation Issues* - the main aspects concerning the implementation of the proposed AC model are identified and discussed. Aspects such as defining the characteristics of the service classes and corresponding control policies, the AC criteria configuration, the QoS and SLS parameters to monitor and the measurement methodologies to apply are covered, taking into account an analysis of current work and guidelines on these topics. Issues regarding the implementation and validation of a simulation prototype comprising the proposed AC model, using the Network Simulator (NS-2), are also discussed in this chapter.

In Chapter 7 - *Test Scenarios and Results* - several test scenarios are introduced in order to evaluate the monitoring strategy and the proposed AC model. In more detail, the suitability and effectiveness of multiclass and multipurpose QoS monitoring are assessed and the performance of the implicit and explicit AC criteria in granting QoS and SLSs commitments is evaluated. The obtained results include, whenever appropriate, an analysis of the AC model performance at class and packet level.

In Chapter *8* - *Conclusions* - an overview of the present research work is presented, concluding on to what extent the objectives defined initially have been accomplished. This chapter also presents the main contributions of this thesis, providing future research directions based on a critical analysis of the work carried out.

Chapter 2

Multiservice Class-based IP Networks

The support of multiple applications and services with distinct QoS requirements constitutes a challenge spanning different communication levels, ranging from low-level technologies to application level protocols. Facing this challenge, the research community and, in particular, the IETF have put forward several proposals to enhance the TCP/IP stack to provide adequate QoS levels in the Internet[1]. Important examples of these proposals include Integrated Services (Intserv) [23], Differentiated Services (Diffserv) [4, 5, 24], QoS-based Routing [25, 26], Multiprotocol Label Switching (MPLS) [27], Traffic Engineering (TE) [21] and specific protocols such as Resource ReSerVation Protocol (RSVP) [28] and Real-time Transport Protocol (RTP) [29]. These solutions are not mutually exclusive, i.e., they can be adopted complementary to enhance networks' QoS functionality [30, 31, 32, 33]. At lower level, QoS-oriented technologies such as IEEE 802.1Q/D/p [34, 35] and Asynchronous Transfer Mode (ATM) [36, 37] can also be adopted complementary.

As mentioned in Chapter 1, the end-to-end QoS panacea will not be based on a one-size-fits-all solution attending to the diversity of business goals and technologies available. When assessing each solution's feasibility, the network integration or migration costs, the provided

[1]The designation "Quality of Service" (QoS) can be contextualized at multiple protocol layers. From a network-oriented perspective, QoS expresses the performance and guarantee levels to be provided by the network to satisfy the requirements of applications and services. In this way, these requirements, expressing user-oriented QoS parameters (objective or subjective), need to be mapped into quantifiable network performance parameters (objective) such as delay, jitter, loss and bandwidth. To measure and quantify these parameters both ITU-T and IETF have defined a set of concrete metrics (see Chapter 4), which specify the parameters in terms of standard units of measurement [21, 22].

In the present work, following common relaxed terminology, "QoS parameters", "QoS metrics" and "SLS metrics" are generically adopted in the context of network services' performance.

QoS levels and scalability, i.e., the ability of being deployed and used in a large scale, need to be considered. Due to the good compromise established among these aspects, multiservice networks following a CoS paradigm have gained increased support from the scientific community, service providers and industry, in disregard of networks following a flow-based paradigm. In fact, aggregating traffic flows into a limited number of service classes according to their QoS requirements is simpler to manage and more scalable than handling a large number of individual flows. For the reasons pointed out, the AC model proposed in this work is essentially oriented to multiservice class-based IP networks, where the Diffserv architecture is taken as a reference model. Nevertheless, the proposed AC model can be applied to other CoS architectures than Diffserv.

In this chapter, the essential principles and components of Diffserv model are briefly presented. Then, the problematic of defining service classes and corresponding QoS characteristics is debated, with particular emphasis on specifying SLAs/SLSs. Handling SLSs is a key aspect for establishing the services to be supported at each network domain, for facilitating interdomain negotiation and for deploying of end-to-end services. This chapter ends with a discussion on the relevance of knowing the statistical properties of network traffic from a service class perspective.

2.1 The Differentiated Services model

The Diffserv model aims at providing the support for scalable service differentiation in the Internet, overcoming the large-scale implementation and deployment difficulties inherent to flow-based QoS models such as Intserv [38, 30]. The main principles behind the Diffserv model are handling network traffic aggregates, establishing traffic priority schemes in network nodes and bringing the traffic control complexity to network edges, keeping the network core simple for fast packet forwarding. In this model, traffic belonging to different flows is grouped or aggregated into a small number of classes of service according to their QoS requirements. To each class will correspond a set of rules and mechanisms that will determine the network service quality to be provided. Network traffic is classified and then marked accordingly using a specific field of the IP header - the DS-field [24], which corresponds to the fields Type of Service (ToS) in IPv4 and Traffic Class in IPv6. This identifier determines the treatment, called Per-Hop Behavior (PHB) [4], a packet will receive in each network node. Extending this concept, a Per-Domain Behavior (PDB) [39] is the treatment given to a set of packets with the same mark (traffic aggregate) along a Diffserv domain.

The establishment of a Service Level Agreement (SLA) between the customer and the service provider allows to specify the required service level and the traffic conditioning rules to apply at network boundaries, i.e., the Service Level Specification (SLS) and its corresponding Traffic Conditioning Specification (TCS) [4, 5][2]. The support of services spanning multiple domains involves the existence of SLAs between peering domains.

Although the definition of a traffic differentiation scheme based on IP header marking is not a new concept [40], the Diffserv model has gone further in defining a set of network key components such as traffic classification and conditioning functions and PHBs [4], to build a coherent service differentiation architecture, bringing a new stamina for using IP type of service marks. Intentionally, in many aspects, Diffserv provides recommendations to support service differentiation disregarding implementation details. More recently, concrete and practical configuration guidelines for Diffserv service classes have been proposed in [41, 9]. The definition of standard SLSs, discussed later in Section 2.2, are also considered an important step for consistent QoS delivery intradomain and end-to-end.

2.1.1 Model components and operation

To support a scalable service differentiation in a domain, the Diffserv model resorts to traffic classification and traffic conditioning functions strategically located and to adequate queuing mechanisms so that the expected PHBs are obtained. In order to impose a specific and distinct treatment on each service class traffic aggregate, a multiple queuing system comprising, for instance, a QoS-aware scheduling mechanism and active queue management techniques is usually adopted.

The *traffic classification* process consists of identifying and selecting packets according to a given set of rules. These rules can be established either based on IP packet header and payload information - Multi-Field (MF) classification, such as the source and destination IP addresses, source and destination ports, protocol, etc., or based on the DS-field - Behavior Aggregate (BA) classification. While the former is likely to occur at network entrance (end-systems, leaf routers or first ingress router) and is usually needed to perform the initial DS-field marking, i.e., to set the Diffserv Codepoint (DSCP), the latter is applied at domain core nodes and other edge/boundary nodes to packets already marked. In summary, while MF classification is usually applied to individual flows, BA classification is applied to individual or traffic aggregates already marked. In

[2]In [5], the designations SLS and TCS were proposed instead of SLA and TCA (Traffic Conditioning Agreement), as these last ones include several aspects not covered in Diffserv such as pricing.

multidomain operation, the DSCP may need to change along the packet's route, for instance, due to service mapping required at domains' boundaries. This may involve a simple BA classification and DSCP update or a new MF classification according to internal policies in the new domain. Traffic classification criteria issues are further detailed in Section 2.1.1.

The *traffic conditioning* (TC) process involves several functions to ensure that traffic entering or leaving a Diffserv domain is in compliance with the traffic profile defined or negotiated within the SLS. In particular, TC entities such as markers, meters, droppers or shapers are used to enforce TC rules so that the traffic profile is in conformity. The classifying rules and TC rules are defined in the TCS section included in the SLS. According to [4], (i) a marker sets or updates the DS-field to a particular DSCP; (ii) a meter measures the temporal properties of a classified traffic stream, verifying traffic conformance, identifying packets in-profile or out-of-profile and triggering marker, shaper or dropper actions accordingly; (iii) a shaper regulates a traffic stream and may delay packets in order to adjust its temporal characteristics to a defined profile; (iv) a dropper performs the discarding of packets to prevent out-of-profile traffic from entering a network. The action on non-conforming traffic is strongly dependent on the service type, for instance, out-of-profile packets can be either instantaneously dropped or remarked with a high drop precedence to increment their dropping probability inside the class or remarked to suffer a service class downgrade. In practice, although these basic TC functions are conceptually distinct, from an implementation perspective, they are usually grouped to perform, for instance, policing at domain network entrance and shaping at network exit. Examples of commonly used policers/markers are the single rate Three Color Marker (srTCM), two rate Three Color Marker (trTCM) and Time Sliding Window Three Color Marker (TSWTCM) [42, 43, 44], while common shapers are the Token Bucket (TB) and the Leaky Bucket [45]. The description and enforcement of the SLS traffic profile resorting to a TB policer is also common.

In order to be a scalable architecture, Diffserv demanding functions such as MF classification and traffic conditioning are performed at the network edge, leaving the network core simple. Core routers have essentially to deal with BA classification, queuing and forwarding packets according to the corresponding PHB. As described above, BA classification is substantially simpler than MF classification as it works on traffic aggregates using a single header field. Generically, *queuing* consists of packet buffering, discarding and scheduling. Thus, resorting to appropriate buffer allocation, buffer management and scheduling mechanisms, PHBs can be implemented as required. In order to implement distinct CoS, traffic is usually divided into separate queues and handled by a service discipline which dispatches traffic according to its QoS constraints. In opposition to First In First Out (FIFO), which in itself is not oriented to traffic differentiation, examples of CoS-oriented queuing systems are Priority Queuing (PQ), Class-based Queuing (CBQ), Weighted Fair Queuing (WFQ) , Weighted Round Robin (WRR) or hybrid systems such as Priority Queuing Weighted Round Robin (PQ-WRR)[3]. Multiconstrained QoS scheduling approaches dealing with bandwidth, delay and loss differentiation may also be in place [47, 48, 49]. In addition, Active Queue Management (AQM) mechanisms are used to prevent queue congestion by discarding packets according to a particular criterion, combining usually queue thresholds with packet drop probabilities. They aim to avoid congestion and the undesirable effects of dropping packets of the queue tail in case of queue congestion [50]. Initially proposed by Floyd and Jacobson [51], Random Early Detection (RED) algorithm is a reference in this context. Several RED variants have been proposed and adopted by the research community and, in particular, RED extensions to a multilevel RED are suitable to deal with multiple drop precedences in a single service class. A comparative study of RED variants including Weighted RED (WRED), Generalized RED (GRED), Random Early Detection In and Out - Coupled (RIO-C) and RIO -Decoupled (RIO-DC) is presented in [52].

In summary, the functionality of edge nodes and core node is illustrated in Figures 2.1 and 2.2, respectively.

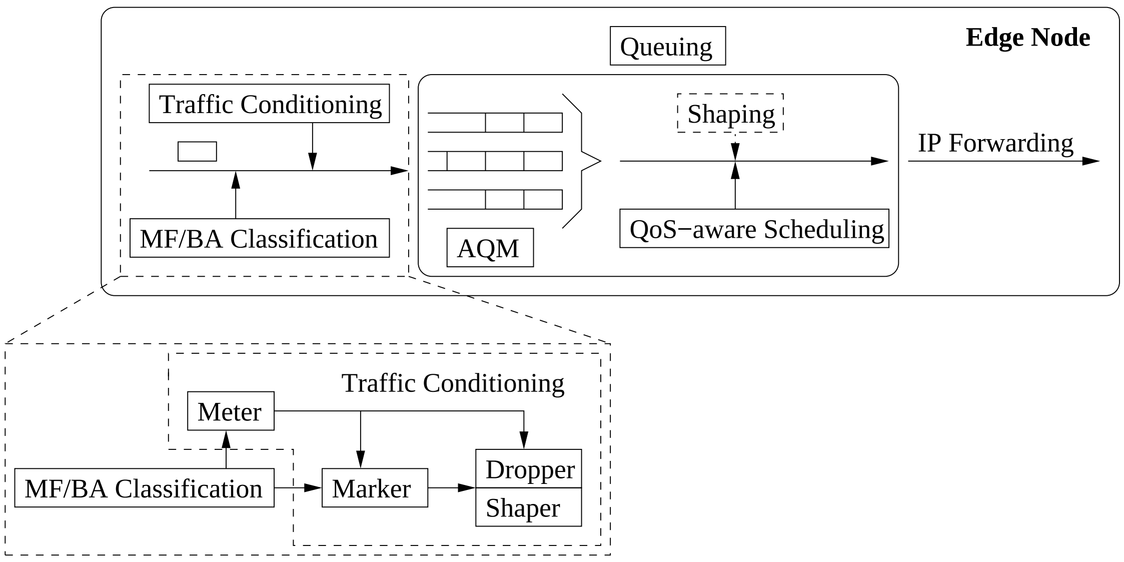


Figure 2.1: Edge node components

[3]PQ implements a strict priority among existing queues. This means that while high priority queues have traffic to be scheduled, low priority traffic will not be served. Although PQ may be particularly convenient to implement EF PHB, it may lead to traffic starvation and/or to a burstiness increase along the path [46]. To solve PQ limitations other queuing schemes that control the bandwidth assigned to each class following a probabilistic or proportional criterion have been proposed.

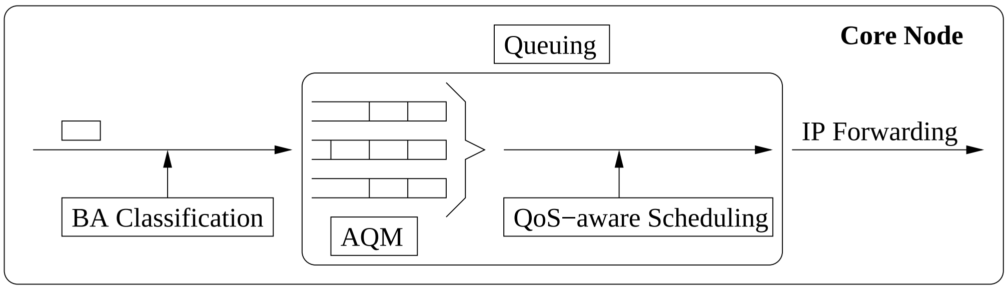


Figure 2.2: Core node components

The traffic classification criterion

Apart from a wide range of mechanisms allowing to handle traffic aggregates according to a specific behavior, a Diffserv architecture needs to be supported by an adequate strategy of traffic classification. Due to economical, administrative and technical reasons the definition of a traffic classification criterion is a subjective task. For instance, for identical traffic types, a client may be willing to pay more than other to obtain a better service quality. Moreover, when a criterion is based on TCP, UDP and IP packet headers, packet fragmentation, packet encryption and the use of negotiated or unregistered application ports make the classification difficult[4]. Therefore, a unified and encompassing classification criterion for Internet traffic is unlikely to be achieved and widely accepted. Thus, in a first instance, such criterion should be simple and generic enough to be easily adopted and implemented. Most of the criteria suggest distinct classes for UDP and TCP traffic so that non-reactive and reactive applications do not compete for the same resources. Some go further suggesting that the duration of flows, the transmission rate and packet size characteristics should also be considered [54]. Classification methods based on QoS application requirements such as delay or loss sensitivity are also common [55, 56]. Considering the above aspects and the ToS proposed for classical applications [55], a possible classification criterion is proposed in [19].

[4]According to [53], while fragmentation of UDP traffic is increasing, TCP traffic (around 85% of Internet traffic) is virtually not fragmented due to the widespread use of MTU path discovery techniques and relatively small default packet sizes. The difficulties associated with encryption can be simplified if a modified IP Encapsulating Security Payload, which leaves protocol ports unchanged, is used. The use of transient ports may imply the analysis of traffic at the associated control channel, which uses well-known ports. Furthermore, when applications use unregistered ports (e.g., distributed on-line games), their usual range of ports or addresses can be considered.

2.1.2 Building services in Diffserv

In Diffserv networks, services are provided using traffic classification and traffic conditioning functions at network boundaries coupled with the concatenation of PHBs along the transit path [4]. While the term *per-hop behavior* is used to describe a behavior in a single node, the concept describing the behavior experienced by a particular set of packets, i.e., a traffic aggregate, across a Diffserv domain has been defined by the IETF as a *per-domain behavior* [39]. These concepts are introduced and detailed next.

Per-Hop Behaviors

According to [4], a PHB is a description of the externally observable forwarding behavior (e.g., loss, delay, jitter) of a Diffserv node applied to a particular traffic aggregate. A PHB determines how node resources are allocated to traffic aggregates, being the basis to construct differentiated services. The IETF has proposed the Expedited Forwarding PHB (EF PHB) and the Assured Forwarding PHB Group (AF PHB), besides the Default Forwarding (DF) PHB, in which the best-effort service behavior is mapped.

The EF PHB [57, 58] can be used to build services requiring low loss, low delay, low jitter and assured bandwidth. To obtain this behavior, the queues encountered by EF packets are expected to be short or almost empty. Hence, the service rate of EF packets on a given output interface needs to exceed their arrival rate at that interface over long and short time intervals, independently of the remaining non-EF traffic load. Giving the high priority treatment EF traffic receives and the high QoS guarantees provided, the access to service classes based on EF PHB has to be tightly controlled with severe treatment on out-of-profile traffic, e.g., dropping it. The EF PHB has been initially defined in [59], where an high-level description of EF PHB was provided. More recently, [57] goes further on EF behavior formalization, defining two types of equations, the “aggregate behavior” equations describing the properties of the service delivered to the EF aggregate by the node, and the “packet-identity-aware” equations that bound individual packet delay knowing the operating conditions of the node. Due to its service characteristics, EF PHB is oriented to support applications and services highly QoS demanding, e.g., requiring a dedicated point-to-point connection or virtual leased line. The viability of deploying these services in the Internet is, however, a controversial topic [60, 61].

The AF PHB [62] group consists of four classes (AF1x to AF4x) representing four assurance levels of packet forwarding. There are three drop precedence levels per AF class which will help to determine the candidate packets to be dropped in case of queue congestion. In each AF class, packets may be marked as having low, medium and high drop precedence as a result of a three color marker policing action[5]. Thus, for instance, AF11 packets are more likely to be forwarded than AF12 packets, which in turn are more likely to be forwarded than AF13 packets. For this reason, these packets are usually referred as green, yellow and red packets reflecting a decreasing likelihood of reaching the network boundary. A possible treatment on AF out-of-profile traffic can be marking these packets with high drop precedence. Regarding the four independent AF classes, although no delay and jitter bounds are provided, a minimum bandwidth is assured to each class. The assurance of AF traffic forwarding depends directly on the amount of resources (buffer space and bandwidth) allocated to the AF class the packet belongs to, the node or class congestion level and the packet drop probability. This PHB group can be used to build services oriented to applications with different tolerance levels to delay and loss, requiring a better service than BE.

As mentioned above, PHBs are achieved by means of appropriate buffer allocation, management and packet scheduling mechanisms. However, PHBs have been defined regarding an expected behavior relevant to define service provisioning policies, without imposing intentionally a particular mechanisms' implementation. As stated in [4], a variety of implementation mechanisms may be suitable for implementing a particular PHB group. In [63], the implementation of EF and AF PHB is analyzed in two different Diffserv platforms: one developed at ICA/EPFL for Linux OS and the other based on Cisco Systems routers. For each platform, the several Diffserv components are tested and evaluated, and the computational efforts Diffserv puts on routers is measured in terms of CPU utilization. Examples of other works implementing and evaluating standard PHBs are [52, 46].

Per-Domain Behaviors

The former IETF Diffserv Working Group (WG) has been sometimes criticized as being good on defining per-node QoS behaviors, but poor on defining how to deploy services in a broad sense. According to [8], while Diffserv mechanisms have been standardized as PHBs, there is still much to be learned about the deployment of that or other QoS mechanisms for end-to-end QoS. In fact, while standard PHBs help fostering service building consistency at a node level,

[5]Although three drop precedences are foreseen, an AF policing/marking scheme may consider less drop precedences. This depends on the type of policer in use and on its configuration. However, within each AF class, a Diffserv node must accept all three drop precedence codepoints and they must yield at least two different levels of loss probability.

the efforts to standardize concrete behaviors and services at a domain level were less successful. In this context, the IETF only provides informational directions on how to define and specify a forwarding behavior at domain level [39].

According to [39], the term per-domain behavior has been adopted to describe the behavior experienced by a particular set of packets with a given DSCP (or set of DSCPs) as they traverse a Diffserv domain from edge-to-edge. A PDB is defined as a technical building block including classifiers, traffic conditioners, specific PHBs and particular configurations with a resulting set of specific observable attributes. A PDB is characterized by specific metrics that quantify the treatment that a traffic aggregate will receive at domain level, i.e., a PDB has measurable, quantifiable attributes reflecting the packets' behavior as they enter and cross the domain. The measurable parameters of a PDB should be suitable for use within SLSs.

The lower effort (LE) PDB [64] has been defined within the IETF with the objective to accommodate traffic requiring very low forwarding priority treatment. This "non-critical traffic" is due to consume network resources only when no other traffic is present. In opposition to traffic belonging to other classes, LE traffic can stand resource starvation, i.e., all other traffic may have strict priority over it. The PHB used by an LE aggregate inside a DS domain should be configured so that its packets are forwarded into the node output link when the link would otherwise be idle; conceptually, this is the behavior of a weighted round-robin scheduler with a weight of zero [64]. In practice, LE PDB should be used by service providers to isolate or schedule certain types of low priority traffic and users to off-peak time periods, taking advantage of spare resources. This PDB can be viewed as a traffic management facility within a Diffserv domain, instead of a regular customer service to be subscribed. Examples of its use include support for peer-to-peer file sharing, bulk e-mail or traffic resulting from WWW search engines when gathering information.

Apart from LE PDB, Diffserv WG has not concluded the specification of Virtual Wire (VW) PDB and Assured Rate (AR) PDB, providing instead high-level rules to build them [39]. The VW PDB is expected to be build using EF PHB, offering a low delay, low jitter, low loss and guaranteed peak rate edge-to-edge behavior. Such behavior should be indistinguishable from a dedicated circuit. The AR PDB is expected to be build upon AF PHB group, providing a suitable means for carrying traffic aggregates requiring rate assurance but not delay and jitter bounds.

Additional issues to support services

Apart from the Diffserv model components described in [4], building consistent services at a domain or end-to-end level involves several other tasks at distinct network operating planes. Most of the components described so far fall within the data plane, where the basic mechanisms handling data packets allow to enforce both a given PHB and PDB. However, several additional tasks within the control plane and management plane assume a preponderant role in the deployment of services, namely, SLS negotiation, QoS and SLS monitoring, service-oriented AC, routing and, generically, traffic engineering (TE)[6].

In the context of this thesis, and according to the main objectives drawn in Section 1.1, the emphasis will be given on SLS definition, negotiation and control, detailed in the next section, and on AC using QoS and SLS monitoring, detailed in Chapters 3 and 4, respectively. Figure 2.3 illustrates the described tasks within the corresponding network operating planes, taking into account characteristics of the AC model proposed in Chapter 5 and inputs from [61, 65, 54].

2.2 Defining and negotiating SLA/SLSs

A Service Level Agreement (SLA) is defined as a contract between a customer and a service provider or between service providers, specifying administrative and technical service information. The technical part of an SLA, called Service Level Specification (SLS), defines the expected service level, QoS related parameters and traffic control issues. The definition of a standard set of SLS parameters and semantics, apart from being a key aspect for QoS provisioning, is crucial for ensuring end-to-end QoS delivery and for simplifying interdomain negotiations [1, 2]. Moreover, the definition and negotiation of SLSs provide valuable inputs for AC, in special, when admission spans multiple domains.

[6]The concept of TE is defined as the application of technology and scientific principles to the measurement, characterization, modeling and control of Internet traffic [32, 21]. TE, closely related to performance evaluation and optimization of operational IP networks, aims at achieving optimal network resource utilization, facilitating reliable network operations while satisfying users demands. This latter aspect is particularly important as optimizing wrong performance measures may achieve certain local objectives, but may have disastrous consequences on the emergent properties of the network and thereby on the QoS perceived by end-users of network services [21]. Therefore, applying traffic engineering concepts iteratively to operational networks may help understanding network behavior through objective measurement and analysis, contributing to enhance QoS levels provided.

TE encompasses a set of tasks both related to capacity management and traffic management [21]. While capacity management includes tasks such as capacity planning, routing control and resource management (e.g., link bandwidth, buffer space and computational resources), traffic management includes per-node traffic control functions (e.g., traffic conditioning, active queue management, scheduling) and other traffic control functions such as AC.

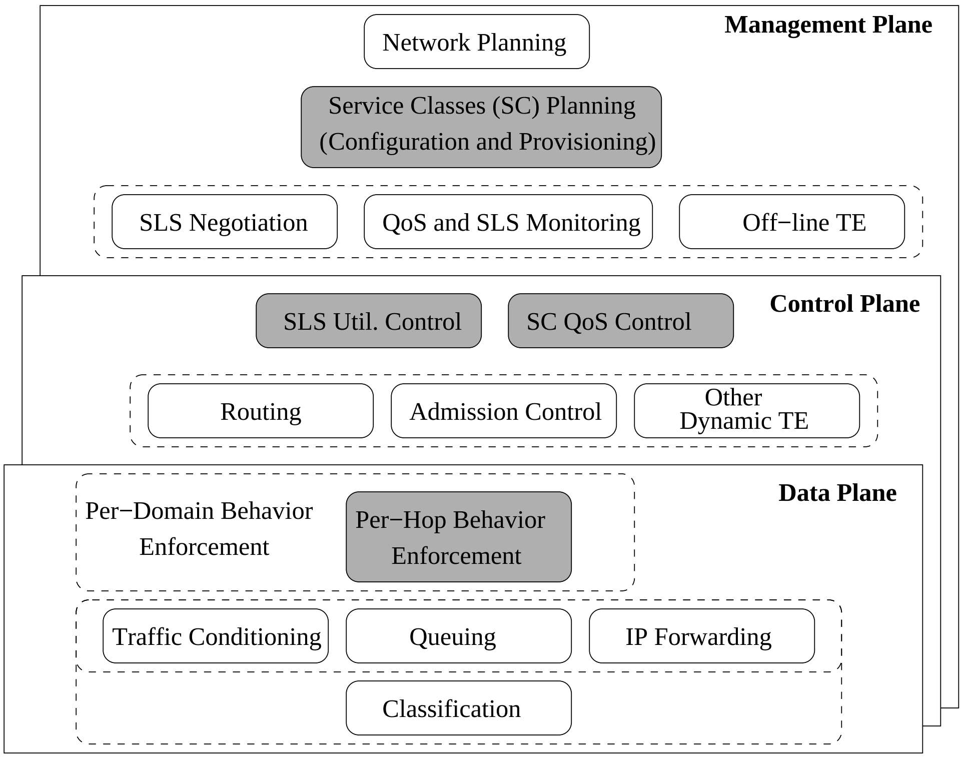


Figure 2.3: Network operating planes

Several working groups are committed to SLS definition [65, 66, 67, 68, 69, 70] and management [65, 66, 71, 72, 73, 74, 2, 75, 76]. Taking these inputs into account, a possible SLA template including relevant parameters and their typical contents is defined in Table 2.1. A more detailed description of the SLS template fields including a XML specification and validation is presented in [18].

Although a large combination of quality, performance and reliability parameters is possible (see Section 4.2.1), service providers are expected to offer a limited number of services. To instantiate the SLS template into quantitative and/or qualitative standard services adapted to different application types is, in fact, a major objective. In more detail, a quantitative description of the expected QoS of an SLS traffic stream expresses performance parameters (at least one of them) in numeric values. Common parameters, as described in Section 4.2.1, are one-way-delay, interpacket delay variation, packet loss ratio and throughput, measured in a defined time interval (measurement period). For delay related parameters, an optional quantile may be used to reflect an empirical gauge for the parameter [67]. A qualitative description does not quantify performance presenting instead the expected performance e.g., delay and loss parameters, in terms

Table 2.1: Service Level Agreement (SLA) template.

Administrative Information		
Administrative entities		Contractual parties involved
Service description		Description of the service behavior
Validity		Contract validity period
Pricing/Tariffs		Pricing and tariffs of the service
Helpdesk info/Trouble tickets		Customer support actions
Monitoring/Accounting reports		Monitoring/accounting rules
Response time to changes		Time for enforcement of changes
Other		Other rules: e.g., provisioning
Service Level Specification	**(SLS)**	
Scope of the service	- Ingress interfaces - Egress interfaces	Boundaries of the region over which the service will be enforced
Traffic classifying rules[7]	- MultiField criterion - DSCP or ToS Precedence	Packet fields used to identify the traffic flow or aggregate
Traffic conditioning rules	- Conformance algorithm - Conformance parameters - Treatment on excess	Information used to identify in-profile and out-of-profile traffic and corresponding treatment
Expected QoS	- Delay, jitter, loss,... - Qualitative objectives - Quantitative objectives	Expected QoS parameters of the conforming traffic stream in the Scope region
Service reliability	- Mean downtime - Time to repair,...	Expected service reliability
Service scheduling	- Start/End time	Service time availability
Others	- Route, security, ...	Left for future study

of values such as high, medium, low. In a commercial perspective, this may be associated to Bronze, Silver, Gold services [67].

In practice, to allow a consistent control of QoS inside a domain, these qualitative descriptions should be mapped to quantifiable values with more or less relaxed thresholds (or to a range of values) defined according to the qualitative expectations. A service based on the LE PDB can be an exception to this need. In [75], that mapping is performed during the SLS pre-processing phase, with respect to SLS to Diffserv configuration mapping process.

To help defining a coherent qualitative to quantitative mapping, substantial work has been done to identify relevant QoS parameters and the perceived quantitative quality of applications and services [77, 78, 79, 80, 81, 82, 83]. Table 2.2 summarizes upper bounds on QoS parameters for generic service classes defined by the International Telecommunications Union (ITU) [77,

[7]The Traffic classifying rules attribute within the SLS template is sometimes referred as Flow Identifier or Flow Description. Despite the adopted terminology, this attribute aims to provide inputs for performing IP packet classification at domain boundaries.

78, 79]. Examples of SLS templates instantiated to distinct services, such as virtual leased line and minimum rate guaranteed services, can be found in [67, 68, 84, 69].

Table 2.2: ITU upper bounds on QoS parameters

ITU-T classes	Class 0	Class 1	Class 2	Class 3	Class 4	Class 5
	Real-time / Interactive		Transactional / Interactive		Non-Interactive	Unspecified
Transfer Delay (IPTD)	100 ms	400 ms	100ms	400ms	1 s	U
Delay Variation (IPDV)	50 ms	50 ms	U	U	U	U
Loss Ratio (IPLR)	10^{-3}	10^{-3}	10^{-3}	10^{-3}	10^{-3}	U
Error Ratio (IPER)	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	U

These inputs, Diffserv PDB and PHB definitions and guidelines from [41, 9] are used in Chapter 6 to identify the services and corresponding QoS parameters to configure and test the proposed AC model. The hierarchical relation between SLSs and the Diffserv building blocks used to develop services is illustrated in Figure 2.4.

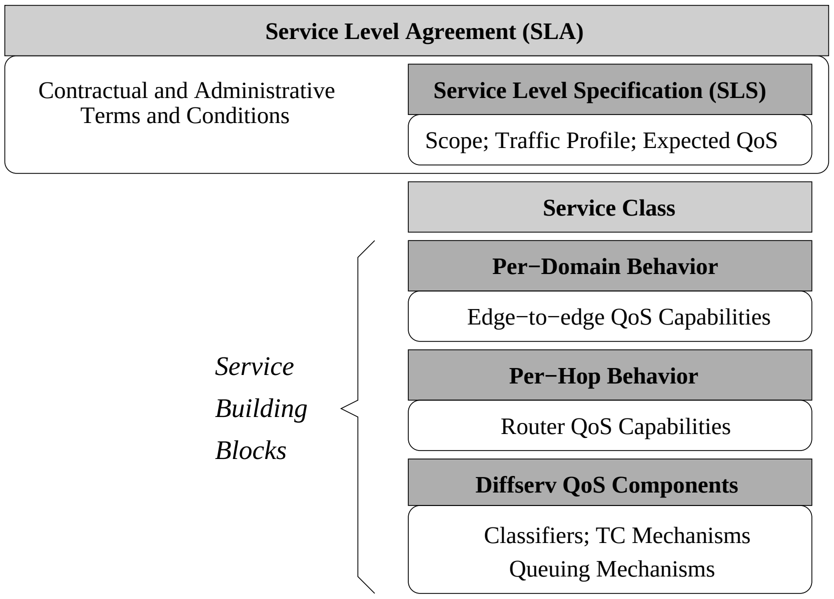

Service Level Agreement (SLA)
Contractual and Administrative Terms and Conditions
Service Level Specification (SLS)
Scope; Traffic Profile; Expected QoS
Service Class
Per−Domain Behavior
Edge−to−edge QoS Capabilities
Per−Hop Behavior
Router QoS Capabilities
Diffserv QoS Components
Classifiers; TC Mechanisms
Queuing Mechanisms
Service Building Blocks

Figure 2.4: Diffserv service hierarchy

Regarding the negotiation of SLSs, although several efforts have been made toward dynamic SLS negotiation and corresponding domain configuration [85, 86, 87, 65, 88, 75, 18], in practice this negotiation and self-configuration process is still immature and is often carried out statically.

2.2.1 Business models

The need for establishing business relationships and agreements (SLA/SLS) between ISPs regarding interdomain and end-to-end QoS delivery is emphasized in [1, 89, 90]. In particular, these works characterize possible business relationships and the financial settlements in the current Internet considering a three-tier Internet model of ISPs (regional, national, international and large national transit ISPs). Two organizational models for the support of interoperator IP-based services [91] - the *Source-based* approach and the *Cascade* approach - have been described and their advantages and disadvantages presented. In the cascade approach, each ISP only establishes SLSs with adjacent ISPs, i.e., ISPs with Border Gateway Protocol (BGP) peering relationships. Thus, the cascade model results in a recursive approach to the end-to-end agreements based on the concatenation of SLSs established between adjacent domains. In the source-based approach, the originating domain/ISP establishes SLSs with adjacent and non-adjacent domains in order to reach a set of destinations with a particular QoS. This involves having an up-to-date view of the Internet topology, i.e., the knowledge of all domains and their interconnections. Although the cascade model has less control of the optimal path, it is more in-line with the coupled Internet structure, being more manageable and scalable. Thus, it is expected to be preferred by most ISPs. In both cases, interdomain routing is SLS constrained, i.e., SLSs between domains must be in place and taken into account.

2.2.2 Additional SLS deployment issues - SLS control and auditing

For a service provider, SLSs incoming traffic aggregates are conditioned, in a first instance, at domain ingress nodes [14]. This consists of SLSs traffic profile conditioning based on the negotiated TC parameters, TC algorithm and out-of-profile traffic treatment (see Figure 2.5). For SLS auditing purposes, SLS monitoring and SLS conformance verification tasks are required (see Figure 2.6).

Service class generic information, including the service parameters to control and the monitoring rules, and eventually specific service information (customer dependent) are used for SLS monitoring and conformance verification. This verification should report whether the negotiated service is being provided or not, allowing to trigger reconfiguration and tuning actions. An important aspect to consider is the space and time granularities in which monitoring is accomplished. Although SLSs off-line monitoring is a common approach, several studies highlight that it should be performed on-line [74, 92]. In some cases, customers may even have on-line access to verify the QoS levels being provided. As an example, this facility is provided by RIPE-NCC Test Traffic Measurements (TTM) infrastructure to the involved parties [92].

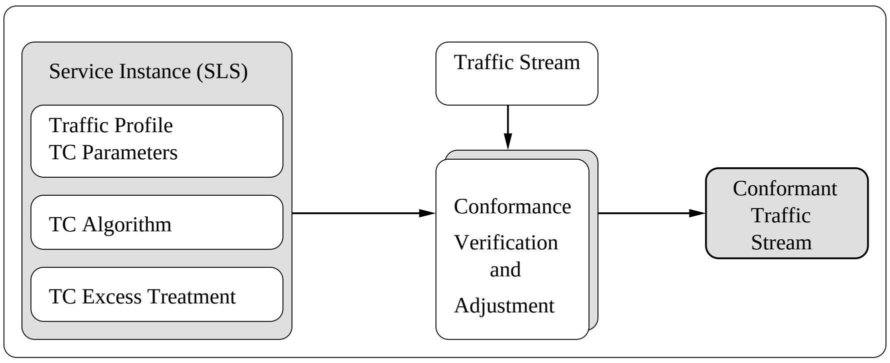


Figure 2.5: SLS traffic conditioning at domain entrance

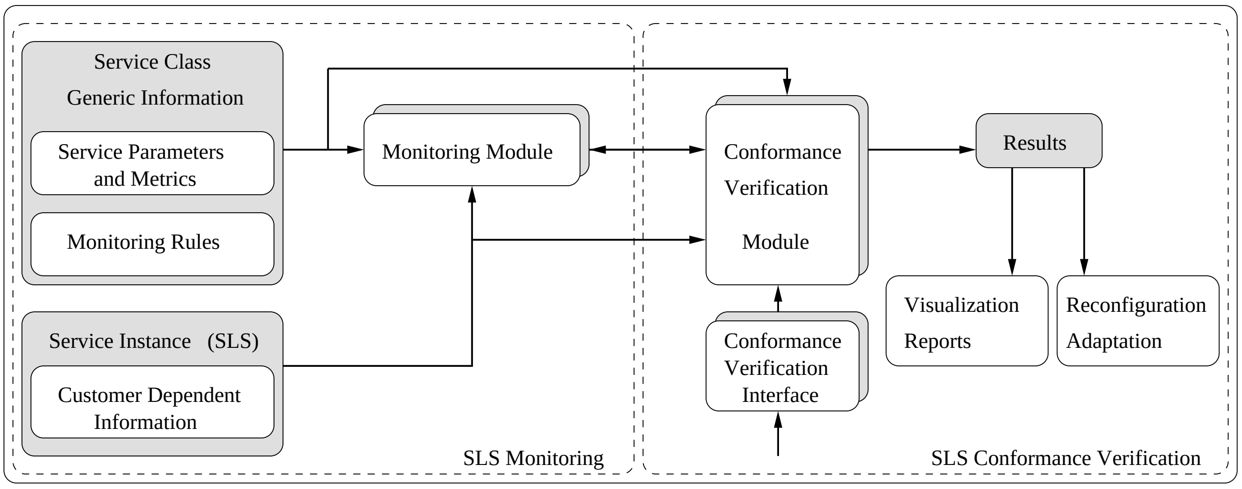

Service Class Generic Information
Service Parameters and Metrics
Monitoring Rules
Service Instance (SLS)
Customer Dependent Information
Monitoring Module
Conformance Verification Module
Conformance Verification Interface
Results
Visualization Reports
Reconfiguration Adaptation
SLS Monitoring
SLS Conformance Verification

Figure 2.6: SLS auditing

In the AC model proposed in this work, SLS monitoring will be carried out resorting to a QoS monitoring module which has an ingress-egress view of the service QoS, therefore, it is particularly suited to SLS auditing. As detailed later in Chapter 5, the QoS control of accepted SLSs for a service class is embedded within the service class QoS control, performed at egress nodes. This means that, to simplify the monitoring process and improve scalability, the specific or customer dependent information should be minimized. Thus, in the proposed model, only the SLS utilization control is customer dependent, being the QoS control performed in a per-class basis and not in a per-SLS basis.

2.3 CoS traffic characterization

The CoS network paradigm poses renewed interest and challenge to network traffic analysis, characterization and modeling. In fact, both the heterogeneity and coexistence of service classes have launched the need for understanding the current traffic behavior at class level and for validating the existing models and principles in which they are based. The knowledge of the statistical properties of network traffic as a whole and of each class traffic aggregate in particular, is essential to: (i) allow adequate dimensioning of network systems; (ii) improve the forecast of network performance; (iii) define realistic SLSs; (iv) help traffic control, congestion control and other TE tasks; (v) allow a better allocation and management of service classes' resources. In addition, modeling traffic sources, either individual or aggregated, properly is the first step to achieve simulation models that express the dynamics and realistic behavior of networks and communication systems.

The study of traffic characterization and modeling was intensified when Leland et al. [93] identified fractal properties in Ethernet traffic, such as self-similarity and Long-Range Dependence (LRD)[8]. This latter property may directly affect the aspects highlighted above, having strong impact on queuing behavior and on the nature of congestion [95]. Although many studies focus on general Internet traffic characterization [94], the effects of aggregating traffic in classes are still unclear. Which are the statistical properties of each traffic class? Will traffic of a particu-

[8]Self-similarity expresses the invariance of a data structure independently of the scale that data is analyzed. From a network traffic perspective, self-similarity expresses a new notion of burstiness. As shown in [93], the bursty structure of traffic may persist over several time scales and bursts do not have a natural length. Furthermore, in opposition to queuing theory principles, the overlap of an increasing number of active bursty traffic sources may intensify the burstiness of the aggregate instead of smoothing it. The presence of self-similarity in network traffic is illustrated by several properties from which LRD is the most popular and the easiest to understand. LRD means that the behavior of a time-dependent process, such as a packet arrival process, shows statistically significant correlations across large time scales [94].

In brief, lets consider $X(t)$ a covariance-stationary stochastic process. Considering $X_t = \{X_1, X_2, ..., \}$ a discrete time series representation of $X(t)$, $X_k^{(m)}$ can be defined as a time series process resulting from the aggregation of X_t, i.e., $X_k^{(m)} = \frac{1}{m}\sum_{i=1}^{m} X_{m(k-1)+i}$ $(k = 1, 2, ...)$, with $m = 1, 2, ...$ representing different aggregation levels. X_t is an exactly self-similar stochastic process if $X_k^{(m)} = X_t$, i.e., the processes are equivalent at least regarding second order statistics. X_t is an asymptotically second order self-similar if $\lim_{m\to\infty} X_k^{(m)} \sim X_t$, i.e., the autocorrelation structure of X_t expressed by $\rho(k)$ is asymptotically preserved, $\lim_{m\to\infty} \rho(k)^{(m)} \sim \rho(k)$. This means that each aggregated process $X_k^{(m)}$ tend to be indistinguishable from the original series X_t. This process is said to exhibit - *long-range dependence* - when the autocorrelation function $\rho(k)$ decays hyperbolically, i.e., $\lim_{k\to\infty} \frac{\rho(k)}{ck^{-\beta}} = 1$ with $c > 0$ constant and $\beta = 2 - 2H$, $(0 < \beta < 1)$, being H the Hurst parameter. When $\frac{1}{2} < H < 1$, $\rho(k)$ is a non-summable function illustrating a infinite persistence over multiple time scale (presence of LRD). When $0 < H < \frac{1}{2}$, no persistent behavior occurs and $\rho(k)$ decays exponentially, i.e., it is summable. In this case, the process X_t is said to exhibit short-range dependence. If $H = \frac{1}{2}$, the variables are independent. Hence, the Hurst parameter is commonly used to measure LRD and a useful indicator of traffic burstiness.

lar service class be responsible for the behavior expressed in [93]? How does aggregation affect burstiness at network nodes and links?

In the context of this thesis, the relevance and major objective of traffic characterization is to understand the statistical properties of Internet traffic under the new perspective of aggregation in classes. As far as AC is concerned, the decision algorithms should consider the QoS to be provided to admitted flows without disregarding the impact a new flow will have, i.e., predicting, whenever possible, the new QoS that would result from accepting additional traffic. In fact, the lack of understanding of the traffic characteristics is an important obstacle to achieve an accurate QoS prediction. When more detailed forecasts of network traffic are available, the QoS prediction can be sharpened and network utilization improved [96]. The work in [96] explores the impact of knowing the traffic characteristics over distinct time scales on AC policies efficiency, measured in terms of network utilization[9]. Although a complete traffic characterization including multiple time scales would allow the use of ideal AC policies, the computational complexity of implementing such policies may be prohibitive. Usually, the traffic characteristics are reasonably known for one well-studied time scale upon which the AC policy is based.

Knowing the characteristics of traffic aggregates is also relevant in order to establish and parameterize the service-dependent AC equations properly. As an example, AC thresholds and safety margins may need to take into account the impact of LRD on the class queuing behavior, to avoid unexpected QoS degradation. Thus, considering the work in [20] as a first step in this research area, in [19] a possible traffic classification criteria is proposed and the statistical properties of each defined class are evaluated using fractal theory.

Apart from studying the behavior of traffic aggregates, other relevant aspects to characterize are: (i) the expected traffic volume per-class, which is relevant to resource usage forecast and provisioning; (ii) the characteristics of individual flows within a class requiring an AC decision. This involves defining the flows' arrival and holding time distributions and the traffic source

[9]The authors discuss the relevance of considering various properties of traffic in the design of AC policies in addition to the peak rate, such as information about the mean rate and the variance in the most relevant time scale. Ideally, characterizing traffic in more than one time scale should be considered in the design of efficient AC policies. The multiple time scales of interest may span several orders of magnitude. In particular, considering 1s as the most relevant time scale, the authors identify the time scale near to 15s also relevant and 360s as the time scale over which knowing traffic properties does not improve efficiency significantly. In the context of measurement-based AC a time scale analysis of several algorithms is provided in [97, 98] and the relevance of how new flows' arrival and departure are treated and the equations sensitivity to traffic fluctuations, controlled by the measurement time interval is discussed in [99] (see Appendix C). In [97], after identifying the critical time scale as $\tilde{T}_h = Avg\_Flow\_Duration/\sqrt{LinkSize\_on\_NumberFlows}$, the authors consider that fast time scale fluctuations (aggregate traffic fluctuations shorter than $\tilde{T}_h$) have to be absorbed by overbooking and that slow time scale fluctuations can be tracked by AC adjusting the number of flows through the flow arrivals and departures.

model regulating the generation of packets within a flow. Regarding this latter aspect, there are well-accepted approaches for modeling applications' behavior [100, 101], and the relation between LRD of a traffic aggregate and the properties of its individual flows is identified in [102]. According to [102], the use of the Hurst parameter (H) to measure the burstiness of the aggregate traffic and LRD is particularly attractive giving that the parameter H ($\frac{1}{2} < H < 1$), denoting LRD, and the parameter α ($1 < \alpha < 2$), characterizing the tail of the distribution of individual flows, are related by $H = (3 - \alpha)/2$. These insights will be considered in the parameterization of the simulation scenario of a multiclass domain, defined in Chapter 6.

2.4 Summary

In this chapter, the motivation for using class-based QoS solutions has been explained and the main principles behind CoS networks introduced. Although supporting the heterogeneity of requirements of present and emerging services may rely on multiple technological solutions, the discussion has focused on IP layer proposals, as IP is pointed out as the layer at which convergence is likely to occur. Taking Diffserv as a reference model within the CoS network paradigm, its architecture, principles and main components have been reviewed. This debate has also focused on how to build service classes, identifying the main tasks within the data, control and management network operating planes. The relevance of specifying standard SLA/SLSs has been discussed as a key step toward the deployment of services both from a domain and end-to-end perspectives. Finally, the importance of considering CoS traffic characterization has been debated. The following chapter will concentrate on AC approaches for multiservice class-based IP networks.

Chapter 3

Admission Control in CoS IP Networks

Either in flow-based or class-based QoS architectures, controlling the admission of traffic entering the network allows to: (i) avoid overutilization of existing network resources; (ii) avoid new flows from impairing flows already accepted; (iii) fulfill service level agreements; (iv) prevent instability, congestion and assure QoS. Despite its need [3, 8, 9], the complexity introduced by AC has to be carefully assessed as Internet traffic is highly dynamic and not every application has strict QoS requirements. Thus, the control complexity inherent to an AC process has to be balanced with the assurance level required. As discussed in Chapter 1, overprovisioning can be useful to improve this trade-off, however, a consistent QoS solution cannot just be based on overprovisioning and further control has to be in place to honor QoS requirements in the network.

In multiservice networks, AC assumes a more challengeable role as service classes have distinct characteristics and require different QoS assurance levels. Therefore, the discussion provided in this chapter surveying current AC research activity will follow, whenever possible, a service-oriented perspective. In particular, studies regarding AC in multiservice networks deserve special attention. Most of the AC proposals tackle the problematic of per-flow admission, connoting it with the admission of a new application, independently of which layers of the TCP/IP protocol stack need to be considered. Some authors classify AC taking into account the semantics involved in the process, for instance, whether it involves connection or session level semantics. In this work, the general case of flow admission is followed as it does not impair that other high-level AC heuristics are in place.

In this chapter, relevant high-level characteristics of current AC approaches are identified in order to allow a comparative study of those approaches. Then, the debate on AC proceeds from a service perspective, drawing considerations on the AC decision criteria. Next, the studied AC approaches are detailed and assessed based on their characteristics. This analysis, identifying the main virtues and limitations of those approaches, grounds the motivation for the new AC proposal presented in this work.

3.1 Identifying relevant characteristics of AC approaches

Classifying AC approaches can be a difficult and subjective task due to the multiple variables involved, not necessarily disjoint. Despite that, identifying relevant aspects that help on characterizing and distinguishing AC approaches will allow a more consistent debate on related work. Important high-level characteristics of existing AC approaches are the following:

- *the underlying network paradigm* - this aspect is related to the network model or architecture in which AC operates. AC approaches span from single service (best-effort) to multiservice architectures, following either a flow or class-based paradigm. Even considering the existence of multiple services, some approaches are targeted for a specific service or set of services. Their scope as regards contemplating an intradomain, interdomain and/or end-to-end solution also varies;

- *the type of service to control* - this aspect is closely related to the guarantee levels to be provided. The terminology to distinguish the services types and underlying guarantees are varied. Common and similar terminology includes deterministic vs. statistical, guaranteed vs. predictive, guaranteed vs. controlled load, quantitative vs. qualitative or hard vs. soft real-time. The type of service is tied up with the applications' characteristics, whether they are rigid or adaptive, have quantitative or qualitative QoS targets;

- *the signaling support involved* - this topic can be viewed in two distinct ways. On the one hand, it is closely related to the type of applications and their ability to explicitly inform the network of their needs, commonly expressed in terms of a traffic profile and/or QoS requirements, using soft or hard state signaling for that purpose. When the AC decision is made without this information, usually using the initial packets of a flow instead, it is called implicit admission and no signaling is involved. On the other hand, signaling may also occur at high-level, for instance between specific nodes in distinct network domains or directly between end-systems. The nodes involved in the signaling process are closely related to the following topic;

- *the location of the AC decision* - this aspect is related to the centralized or distributed nature of the AC approach. This aspect can be further detailed depending on which nodes (e.g., all nodes, specific nodes, edge-nodes, end-systems) are involved and how they participate in the AC process. For instance, a node can make an AC decision or only gather information for some other entity to use. The amount and type (per-flow or per-class) of state information kept in those nodes and the need for coordination among them are also important factors to consider;

- *the characteristics of the admission decision criteria* - these can be determined by (i) the nature of the algorithm, i.e., whether it is parameter-based, measurement-based or hybrid; (ii) the information used for AC, which can be based on keeping track of resources' usage (usually bandwidth) or on congestion indicators (e.g., explicit congestion marks); (iii) the concrete AC equations, which can be based on more or less intricate theoretical concepts involving distinct control parameters, whose tuning will, in turn, influence the conservativeness of AC. Independently of the characteristics highlighted above, as any AC approach is sustained by an AC criterion, this topic is further detailed in the following section before presenting the most relevant AC approaches.

Having discussed these points, the overall performance of an AC approach can be characterized through several related aspects, namely:

- the ability to fulfill the QoS commitments;
- the efficiency of resources' utilization for the service levels provided;
- the intrinsic overhead of the AC approach (e.g., involved state information and computational efforts);
- the overhead introduced in the network data and control planes (e.g., intrusion of probing traffic, signaling, state information, new requirements on nodes), influencing scalability;
- the latency regarding the time it takes to make an AC decision.

The easy of migration and implementation in real environments is another key point as it brings a practical perspective and the real usefulness of the AC approach.

3.1.1 The AC decision criteria

Establishing an admission criterion consists of defining the rules by which flows are accepted or rejected. In any AC approach the admission criterion plays a crucial role as regards service guarantees and network efficiency. Usually AC criteria are parameter-based, measurement-based or follow an hybrid scheme combining both.

Parameter-based AC algorithms take into account the network resources already in use (reserved) by accepted flows and the resources the new flow will consume, according to its explicit traffic descriptor. These descriptors allow establishing upper bounds on the traffic generated by a source. When AC takes uniquely this information, QoS conformance can be easily achieved, leading to acceptable network utilization when the flows are smooth, however, utilization is low for bursty traffic. Thus, parameter-based AC algorithms tend to be conservative and oriented for flows requiring a guaranteed service.

Measurement-based AC algorithms take into account measures reflecting the impact of existing flows on the network load and/or QoS before deciding about a new admission. Essentially, they rely on measurements either at each node or end-to-end, without requiring to maintain state information about reservations in the core. While rate-based AC rules are the most common, estimates of delay, loss or Explicit Congestion Notification (ECN) marks are also used[1]. Measurement-based algorithms are less conservative, taking advantage of statistical multiplexing of traffic to increase network utilization, at an eventual cost in QoS degradation. In this way, they are more suitable for flows requiring a predictive service.

Examples of parameter-based, and measurement-based algorithms are defined and compared in [105, 99, 106, 107, 108, 109, 110, 54]. In Appendix C, a high-level performance discussion of existing algorithms is provided as well as some research directions for their improving.

[1]Most of AC algorithms only control the available bandwidth or capacity, comparing it with the requested flow rate. Although being simple for a single link or node-by-node AC, controlling it along the full path is not straightforward. Methodologies and tools for estimating the available path capacity and available bandwidth are detailed in [81, 103]. The accuracy and on-line utilization of these tools are discussed in [104].

Making AC decisions based on thresholds for the other mentioned QoS parameters is also considered. In this case, a new flow is accepted or rejected after checking the controlled parameter against a pre-defined limit. Tuning these limits, making them useful indicators of the overall QoS status is a fundamental aspect. The major difficulties with the estimation of QoS parameters is that specific fields may need to be included in network packets, such as timestamps, flow ID, sequence numbers. Additional counters and per flow evaluation at edges may also be needed.

3.2 AC approaches: a service-oriented overview

When defining an AC strategy a trade-off between the service assurance level and network control complexity needs to be established. Depending on the QoS guarantees and predictability required, more or less complex AC strategies can be used, with strict or relaxed control of network resources and QoS parameters. The type and number of network nodes (e.g., edge, core, central entities) involved directly or controlled by the AC process can also vary, affecting the solution's complexity.

A lesson learned from the AC model used in Intserv [23, 111] is that keeping resource reservations per-flow in all network nodes, although allowing strict QoS guarantees, is not a scalable solution. Aggregating these reservations [112] reduces the problem but does not solve it. Integrated solutions combining Intserv with Diffserv potentialities have also been proposed [38, 30].

Associated with CoS architectures, such as Diffserv, several AC approaches have been defined with the common aim of avoiding per-flow state information in the core nodes for the sake of scalability. Some proposals suggest the use of central entities for AC and resource management, called bandwidth brokers (BBs) [113, 114, 115, 116, 85, 117, 118]. However, the well-known problems of centralization have led to several decentralized AC approaches. Generically, either using centralized or decentralized AC, the level of guarantee to be provided determines the complexity of the underlying traffic control strategy.

To provide guaranteed or quantitative service guarantees (e.g., for hard real-time traffic) current AC proposals need to control the state and the load of traffic aggregates in the core nodes [113, 119, 116, 120], or even perform AC in these nodes [119, 120]. These solutions tend to require significant network state information and, in many cases, changes in all network nodes. Furthermore, as they are closely tied to network topology and routes, their complexity increases with network dynamics.

Providing predictive or qualitative service guarantees (e.g., for soft real-time traffic) leads to reduced control information and overhead, but eventually to QoS degradation. Obtaining a good compromise between efficient resources' utilization and QoS guarantees is a major challenge. In this context, measurement-based AC (MBAC) solutions have deserved special attention. Initially performed in all network nodes [121, 98, 97, 99], more recent studies suggest that AC decisions should only be made at the edges (end-systems or edge routers), using either passive or active measurement strategies of network load and/or QoS parameters [122, 123, 124, 125, 126, 127, 106]. Despite not requiring changes in the network, active end-to-end MBAC (EMBAC) increases the initial latency and network load as probing traffic is carried out on a per-application basis. The use of routing protocols to propagate QoS measures to edge nodes is also a possible solution [108, 128].

The need to control elastic traffic for more efficient network utilization has also been discussed and implicit AC strategies, i.e., without requiring explicit signaling between the application and the network, have been defined [129, 130, 131, 132]. Conversely, AC approaches for real-time applications commonly assume the use of signaling between the application and the network where, upon a traffic profile and QoS objectives description, an explicit acceptance/rejection message is obtained.

A more complete survey comparing the main features and limitations of current AC strategies is provided in the next section.

3.3 Detailing existing AC approaches

3.3.1 Intserv/RSVP signaling and aggregating reservations

Although being usually associated with the Intserv model, a brief reference to Resource ReSerVation Protocol (RSVP) [28] is provided here as it is commonly suggested as a possible signaling protocol to support explicit AC in class-based networks[2].

RSVP is a soft-state signaling protocol that allows applications to express their resource requirements to the network. Upon receiving a request, the network elements return an explicit accepting or rejecting indication depending on the available resources. Essentially, this signaling process involves exchanging RSVP PATH and RSVP RESV messages to place the request and perform the reservation, respectively, when the AC decision process succeeds. Although independent from the Intserv architecture [23], RSVP is there pointed out as a convenient explicit setup mechanism to signal per-flow resource requirements in order to sustain a node-by-node AC and resource reservation process aiming at a guaranteed end-to-end QoS delivery [111].

The impairments of deploying Intserv/RSVP in large scale [38, 30] have motivated the aggregation of individual flow requests [112]. This aggregation process aims at reducing scalability

[2]Recently, a comparison of existing QoS signaling protocols has been carried out in [133, 134] and the framework Next Steps in Signaling (NSIS) has been proposed [135]. This framework contemplates a wider variety of possible signaling scenarios, being more versatile and flexible than RSVP.

problems, avoiding per-flow signaling and per-flow state information in the core, at cost of reducing the isolation among flows. In this process, interior nodes only maintain a reservation state for aggregates, and their state only changes when the corresponding aggregate reservation needs to be updated (increased or reduced) with a new bandwidth bulk. This is accomplished resorting to RSVP aggregate signaling occurring less frequently than per-flow signaling. Per-flow state information and AC are only handled at aggregating and de-aggregating nodes based on the available bandwidth for the aggregate and, unless an update is needed, RSVP messages are hidden from the aggregation region.

The level of aggregation or bulk size influences the flows' admittance, the utilization and the demand for signaling in the core. While large bulks influence flow's acceptance and utilization negatively, small bulks influence these aspects positively at expense of more signaling. The need for signaling the aggregation region is also dependent on the traffic load variability and, ultimately, under high variability and low aggregation the process tends to the per-flow reservation case. In [136], a performance analysis of the impact of traffic characteristics on the aggregation efficiency is presented.

More specific works combining the aggregation of reservations with topological information provided by routing protocols (e.g., BGP, OSPF) are surveyed in [137].

3.3.2 Intserv/Diffserv integrated solutions

According to the framework for Intserv/Diffserv operation [30], Intserv, RSVP and Diffserv are complementary technologies which can facilitate pursuing the objective of a scalable end-to-end quantitative QoS solution. While Intserv/RSVP allows per-flow request signaling quantifying the resources needed and obtaining a corresponding AC feedback, Diffserv enables scalability in large networks. In this framework, the end-to-end RSVP signaling requires at least that RSVP messages are carried out across the Diffserv region, but depending on the specific realization of the framework, none, some or all routers in the Diffserv region, may process these messages. The coexistence between the two architectures assumes the control of the amount of traffic submitted to the Diffserv region, which must be able to support Intserv-like services through proper PHBs, and Intserv/Diffserv parameters mapping. The option for resource management in Diffserv region may include: (i) static provisioning; (ii) dynamic provisioning using RSVP; (iii) dynamic provisioning resorting to other means, such as Bandwidth Brokers (see Section 3.3.4).

In [38], RSVP signaling is used to gain admission to aggregated traffic architectures such as Diffserv, combining per-flow signaling with aggregate traffic handling, considering AC in strategic places of Diffserv region frontiers. In the example provided, only edge/border routers are configured to participate in the RSVP signaling, which is carried over the Diffserv network transparently (see Figure 3.1). As far as AC is concerned, border routers direct the messages to a companion Policy Decision Point (PDP) which coordinates the authorization and AC process. The admission decisions are made comparing the required bandwidth specified in the RSVP message with the available bandwidth in the corresponding SLA/SLS. QoS management is achieved resorting to policy components and, although the policy information is centralized, the policies are supplied to distributed PDPs and Policy Enforcement Points (PEPs). A single PDP may serve multiple PEPs (e.g., routers, switches), which are enforcement points of the QoS policy.

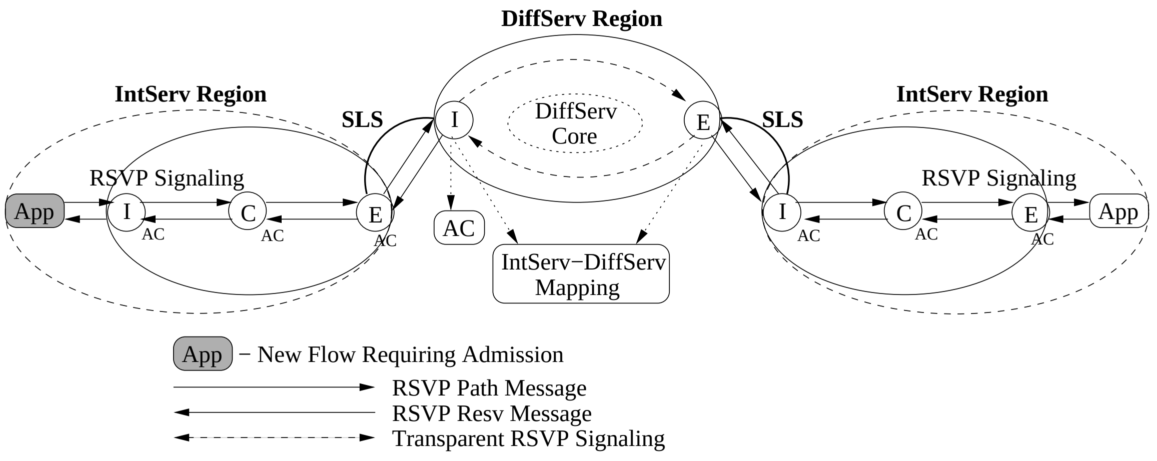


Figure 3.1: Intserv/Diffserv integrated solution

As referred above, this combined architecture intends to take advantage of both Diffserv and Intserv models to improve scalability while maintaining service guarantees. In practice, despite the guarantees provided in the Intserv/RSVP region, with the inherent control overhead, end-to-end services guarantees are dependent on the resource management policies and supported services within Diffserv regions. A consistent mapping of Intserv/Diffserv services and parameters, an effective AC control to Diffserv regions and an effective control of resources inside this region to meet the services levels (PHB/PDB) is essential to achieve end-to-end QoS guarantees.

When accessing a Diffserv region, the degree of centralization of AC tasks in the Intserv/ Diffserv approach can vary according to the elements involved in the AC process. It can be: (i) centralized, when a central entity such as a BB has to be consulted to make decisions; (ii) partially decentralized or partially distributed, when several PDPs are used, each one serving multiple PEPs in the domain or (iii) totally distributed, when the AC decision is made at each Diffserv region edge router resorting to its own companion PDP, or PEP [138]. The advantages and disadvantages of a centralized approach to AC are discussed in Section 3.3.4.

3.3.3 Dynamic Packet State and the SCORE architecture

The service architecture proposed in [120] aims at offering per-flow delay and bandwidth guarantees similar to the Intserv guaranteed service [23], but in a more scalable way. This architecture called Scalable Core (SCORE) is based on: (i) bringing per-flow management to edge nodes; (ii) a stateless core, i.e., a core where no per-flow information is maintained; (iii) a dynamic packet state (DPS) technique, which uses specific fields of the IP packet header to embed per-flow state[3]. Core nodes process each packet based on its state, update it and, eventually, update their own state before forwarding the packet.

DPS technique is the key concept of the SCORE architecture as it allows to coordinate routers' actions and implement distributed algorithms. In fact, the packet state inserted at ingress nodes and removed at egress nodes is used by each core node to perform scheduling, which is based on the concept of packet eligible time and deadline[4], and to support per-hop AC, which is based on an estimate of the upper bound for the aggregate reserved rate, the link capacity and the new flow's reserved rate[5].

Detailing the AC process, it involves essentially two distinct phases. Firstly, there is an per-flow RSVP signaling phase between the sender and the ingress node and between the egress node and the receiver (RSVP PATH and RESV messages), passing transparently through the SCORE domain. Secondly, upon receiving the RSVP RESV message, the ingress node triggers a specific signaling message inside the core along the path toward the egress node which allows to perform local per-hop AC, to account for the number of hops and to compute a label between ingress and egress nodes so that all packets of the flow are sent along the same path. When the egress node is reached, the ingress node is notified to make the final AC decision, informing the

[3]Because of (i) and (ii) aspects, the authors consider the architecture SCORE somehow similar to Diffserv. Moreover they consider that, if PHB and DPS information could be conjugated in packet headers, the flexibility and capabilities of Diffserv will increase significantly.

[4]A variant of Jitter-VC scheduling algorithm called Core-Jitter-VC (CJVC) is proposed to provide the same guarantees of Jitter-VC without requiring per-flow state in the core, using the scheduling parameters encoded in the packet header [120].

[5]Per-hop AC is performed at a setup phase using specific signaling. In particular, DPS supports AC in the sense it allows the estimation of each node aggregate reservation rate using a variable - virtual length - evaluated and inserted by the ingress node in the packet header upon each packet departure.

sender subsequently. In this architecture, per-flow reservation state is only maintained at edges nodes and released according RSVP teardown messages. Figure 3.2 illustrates the behavior of SCORE/DPS approach.

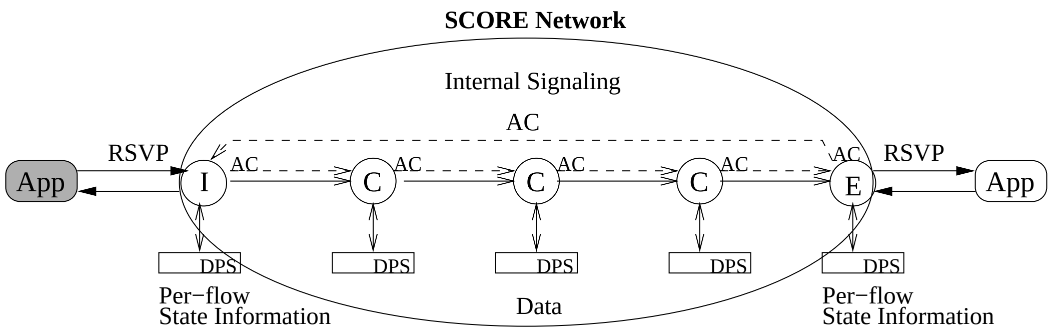


Figure 3.2: SCORE/DPS AC approach

Despite avoiding per-flow state in the core and providing a guaranteed service, this architecture requires that all routers in the flow's path participate in the AC process, implement the same scheduling mechanism and update packet headers. In particular, the proposal for packet state insertion in packet headers may reveal itself incompatible with existing protocols and mechanisms such as Diffserv marking, headers compression and encryption. Although presented as an end-to-end solution, the operation crossing multiple domains is not covered in [120].

Within the Diffserv context, the framework Resource Management for Diffserv (RMD) proposed in [119], although having a broader scope than SCORE, also involves two distinct signaling protocols: one acting on a per-hop basis called Per-Hop Reservation (PHR) and other acting only at edge nodes called Per-Domain Reservation (PDR). At the edge nodes information is maintained per-flow. In addition to its involvement in edge-to-edge AC, PDR is also used to establish a bridge between the application's signaling and PHR. In the PHR context, the information state at each node is PHB-based instead of flow-based, and AC can use either explicit reservations or measurements of traffic aggregates.

3.3.4 Centralized approaches based on Bandwidth Brokers

One of the first approaches to perform resource management and AC in a Diffserv domain suggests the use of a central entity called Bandwidth Broker (BB) [118]. Above all, this entity aims at allocating and controlling the bandwidth shares in the domain. A BB is viewed as a central agent which can be configured with organizational policies, keep track of domain resources and decide upon new flow requests based on the established policies and current resource allocation. According to the decisions, which may involve message exchange between BBs in adjacent domains, the configuration of relevant network nodes may take place.

The principle behind BB architecture is to introduce in a Diffserv domain several service management tasks required to provide a consistent QoS, without complicating the control plane inside the network. This is achieved by centralizing information concerning network resources and their usage, domain topology, service policies, negotiated SLSs, which is required to perform control tasks such as AC, removing these tasks and the corresponding state information from the network core.

As far as AC is concerned, at an intradomain level, when a new flow requires admission, a signaling message is sent to the BB specifying the flow profile and QoS requirements asking for an AC decision[6]. The BB, after authenticating and authorizing the request, makes a decision considering the domain service policies, the corresponding SLS usage and the available resources along the path. If the destination is outside the domain, the AC decision may involve interdomain signaling with downstream BBs, extending the AC process and resource reservation end-to-end[7]. According to the resulting AC decision, each BB updates its state information databases and configures the involved edge nodes consistently (for classification and TC) using, for instance, command line interface (CLI) commands, Simple Network Management Protocol (SNMP) [139, 140] or Common Open Policy Service (COPS) [141, 138]. For scalability reasons, the AC requests to BBs, the reservations and the interdomain communication should consider flow aggregation.

Figure 3.3 illustrates the operation described above. A more detailed description of the BB functionality and operation is available in [118]. In the context of Internet-2 Qbone architecture [85, 114, 117], an in-depth discussion of BB requirements, architecture and signaling is also provided. A protocol for inter bandwidth broker communication called Simple Interdomain Bandwidth Broker Specification (SIBBS) was also proposed [86, 142].

[6]The signaling message sent to the BB, e.g., using RSVP, can be sent either by the application or by the ingress router when a new flow request arrives.

[7]Initial studies advocate an incremental deployment of BB architectures where, in a first stage, the management of SLSs is static and flow admission does not cover interdomain communication. In a second stage, SLSs management is dynamic, concerning their establishment and eventual renegotiation, and the admission control is viewed as an *informed admission* giving that interdomain communication and end-to-end availability verification take place [85]. Apart from the scenario described above other possible end-to-end scenarios include the setting up of core tunnels as a vehicle for aggregating reservations and reducing signaling between BBs of intermediate domains [86]. Flow reservations, SLSs and tunnels are unidirectional.

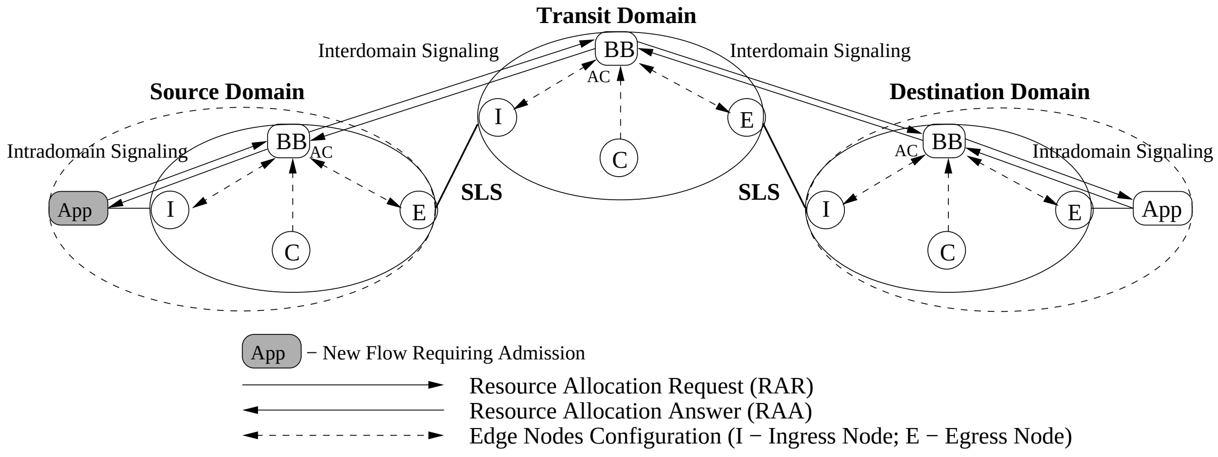


Figure 3.3: Centralized AC using BBs

In [116], a BB's architecture based on a core stateless Virtual Time Reference System (VTRS) [143] is suggested as a way to achieve a scalable solution to provide guaranteed services without requiring per-flow state in core routers. This proposal resorts to AC algorithms based on the entire path state and specific scheduling mechanisms to support end-to-end per-flow delay guarantees. Core nodes perform data plane functions such as scheduling and forwarding using packet state carried in the packets' headers, which has to be updated in every node (see discussion of the DPS technique in Section 3.3.3), leaving to the BB the centralization of all the relevant network control plane tasks and information.

The AC task, carried out at BB level[8], involves the use of specific AC algorithms which consider several state information databases, including details about flows, nodes and paths, as the flow AC decision must consider the characteristics and reservations in the involved nodes along the entire path (e.g., the minimal residual bandwidth along the path). The proposed algorithms intend to provide guarantees both on a per-flow and on a per-class basis, considering dynamic flow aggregation. This means that the proposed architecture can sustain the granularity of either integrated or differentiated services. Despite that, the scalability problems due to the large amount of state information required, the problematic of interdomain QoS reservations and control of involved SLAs, and the support of additional services were issues left for further study. According to the authors, these issues need to be solved satisfactory before the proposed archi-

[8]The BB is informed of a new flow request by the ingress router which in case of acceptance will be configured to perform edge conditioning, initializing and inserting the necessary packet state in packets' header before entering the core. In the core, a rate-based or mixed rate and delay-based scheduler will act on packets consistently with their DPS headers data.

tecture can be deployed. The requirement of implementing the DPS technique in all routers in the flow's path is an additional impairment to its deployment.

For Diffserv environments, a BB approach based on an Active Resource Management (ARM) mechanism that reallocates dynamically bandwidth among clients has been proposed in [144].

The main advantage of centralized AC approaches is that centralizing state information and control tasks allows a global vision of the domain's QoS and operation, relieving the control plane inside the network. This centralization process also facilitates creating and changing service policies and control mechanisms such as AC algorithms. The cost of centralized approaches is however high. BBs need to store and manage large amounts of information, which in large and highly dynamic networks with many signaling messages and information state updates needing to be processed in real-time is even hard or prohibitive. The congestion and functional dependence on a single entity is another well-known problem of centralization.

To improve reliability and scalability in large network domains, several approaches consider the use of a distributed or hierarchical architecture involving multiple BBs in the domain instead of a single centralized BB [113, 145, 116, 118]. A single BB strategy is considered more suitable to small and less dynamic environments involving long lived flows. In the case of large and more dynamic domains, the use of multiple BBs improves reliability, BB congestion avoidance and scalability, at an eventual cost in coordination among BBs and in resources' fragmentation.

3.3.5 Measurement-based AC approaches

AC approaches based on network measurements performed node-by-node, edge-to-edge or end-to-end have erupted within the context of providing predictive service guarantees. They intend to solve or reduce the disadvantages of the described AC approaches, in particular, regarding the state information and control overhead, at an eventual cost of QoS degradation. Measuring network utilization and congestion can be expressed by the estimation and control of parameters such as bandwidth, delay, loss or ECN marks, during a given measurement period.

A generic example of edge-to-edge passive and active measurements performed in a multi-class network domain is provided in Figure 3.4.

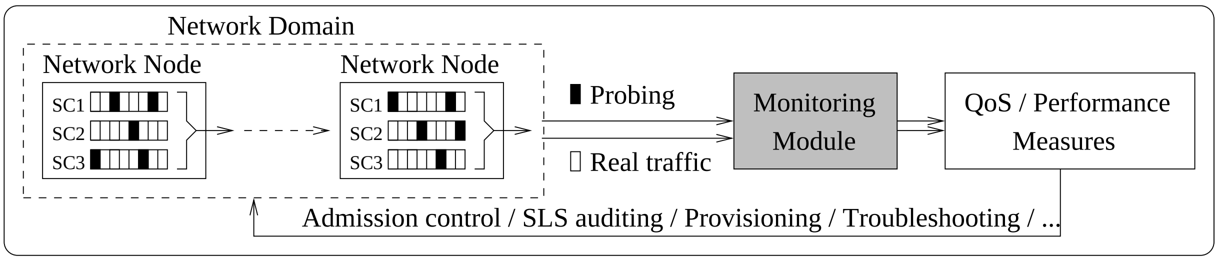

Network Domain
Network Node
Network Node
SC1
SC2
SC3
SC1
SC2
SC3
Probing
Real traffic
Monitoring Module
QoS / Performance Measures
Admission control / SLS auditing / Provisioning / Troubleshooting / ...

Figure 3.4: Passive and active multiclass monitoring

Passive measurement-based AC approaches

The designation *passive* stems from the fact that the measurement process resorts to real traffic within the network for parameters' estimation. While classical passive MBAC is performed node-by-node, approaches involving only edge nodes have also been proposed.

In the context of Intserv, MBAC has been proposed to assist the provision of a predictive service for tolerant applications able to accommodate occasional delay bound violations [121]. As the behavior of existing flows is determined by measurements rather than by their rate reservations (e.g., worst-case parameters), the service provided is less reliable due to traffic fluctuations. However, this allows to improve AC flexibility and to take advantage of statistical multiplexing, which may lead to significant utilization gains. The approach proposed in [121] involves making AC decisions in all network nodes, i.e., AC is distributed node-by-node, using rate and/or delay-based equations. This AC process is applied to flows requiring a predictive service or, considering bandwidth reservations, a guaranteed service. In particular, the admittance of a new flow to a predictive service class considers the new flow requested rate, measurements of the node's current utilization and queuing delay. The flow is rejected if the target link utilization level is exceeded or the admittance of the new flow is expected to cause delay bound violations in the class or in lower priority classes. Other relevant MBAC algorithms are presented in [97, 98, 99].

Taking into account the burden of performing AC in all network nodes regarding the changes and overhead introduced in those nodes, a different type of passive MBAC considers measuring the edge-to-edge network status without requiring additional processing in the network core. AC is then left for network edges such as ingress nodes, egress nodes or both.

In the context of multiclass networks, [122, 123] propose an AC solution based on the theory of traffic envelopes [146, 123]. In this proposal, egress nodes assume a preponderant role as they perform both edge-to-edge aggregate traffic measurements and AC. The measurements assess passive and continuously the available service on a path between ingress-egress pairs, without involving per-flow state in any network node and ignoring core details. More precisely, for each ingress-egress pair, egress nodes evaluate two types of aggregate traffic envelopes: (i) the arrival envelopes, which reflect the maximum rate of arrivals; (ii) the service envelopes, which reflect the minimum available service. The first is based on the number of bytes received during the measurement time interval and the second is based on the packets' delay.

As regards AC, the new flow specifies its needs through RSVP signaling, which passes transparently through the core to be processed only at egress nodes (see Figure 3.5). The underlying AC equation considers the admittance of a new flow based on its peak rate, the admissible delay bound, the measured peak rate arrival envelope and its variance, the class minimum service envelope and its variance[9], and on a parameter setting according to the required violation probability or confidence level (see equation details in [122]). Although in principle, the admittance of a new flow should not interfere with already admitted flows, QoS degradation may occur when the congestion conditions change.

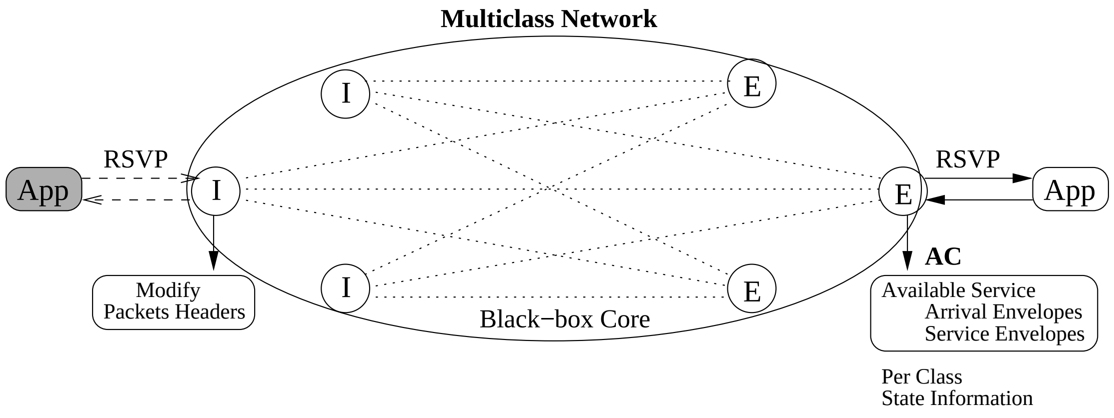


Figure 3.5: Traffic Envelopes AC approach

The implementation design and details of the traffic envelopes approach for a single and a multiclass model are provided in [147]. As referred, in addition to the need to adapt RSVP and improve the traffic capture process, the insertion of specific information such as timestamping, sequencing and ingress identification in all real packets is also required. The solution pointed out for that insertion in IP packet headers poses disadvantages similar to the ones mentioned for DPS. Despite the scalability resulting from not involving the network core, the need for ingress-

[9]The variance of these measures is used to determine the confidence level of the class QoS prediction.

egress continuous measurements makes the solution more oriented to a single domain than to end-to-end. Moreover, the problematic of controlling SLSs is neither covered in this approach nor in the passive and active AC proposals discussed below.

In [148], measurements of the quality experienced by on-going Voice over IP (VoIP) sessions are used to perform AC both at ingress and egress IP telephony gateways of a best-effort IP network. In particular, loss and delay statistics computed at egress are shared between peer gateways and used in the setup phase for AC. The corresponding AC equation resorts to aggregate measures that are compared to pre-defined thresholds to decide if a new VoIP call can be accepted. To support this passive approach, it is also necessary to insert additional fields such as call identifiers, sequence numbers and timestamps in the existing VoIP packets and to be able to identify peer gateways.

For Diffserv networks, a set of dynamic provisioning algorithms for edge nodes based on utility functions and measures of traffic load in the network core is proposed in [88].

Active measurement-based AC approaches

In opposition to passive measurement, the designation *active* measurement is adopted when specific traffic, called probing traffic, is injected into the network for measurement purposes. As regards AC, this technique intends to overcome the overhead associated with signaling and AC processing in network nodes, leaving uniquely to endpoints (end-systems or edge routers) the responsibility of inferring the network congestion status between them and of deciding on flow admission. This inference process resorts to per-flow probing traffic to obtain measures of delay, jitter, loss or ECN marks reflecting the congestion along the corresponding path, assessing simultaneously the path ability to support the new flow. AC approaches based on this technique are commonly called Endpoint Admission Control, Probe-based Admission Control or End-to-end Measurement-based Admission Control (EMBAC) [127, 124, 125, 126, 131, 137].

Generically, in EMBAC, the admission of a new flow is preceded by a *probing phase* where a stream of probing packets with similar characteristics to the flow to be admitted is sent from the sender endpoint to the receiver endpoint. After this phase, the receiver endpoint reports to the sender the measured congestion level suffered by probes so that it can decide on the corresponding flow admission. Alternatively, the receiver endpoint may decide itself based on the specified flow admittance limits, informing the sender accordingly. The sender endpoint upon receiving AC feedback either enters in a *data phase*, where flow packets are sent, or aborts the sending process. In order to increase robustness, the sender implements a timeout mechanism associated with the start of the probing phase to deal with missing feedback. Figure 3.6 illustrates this behavior.

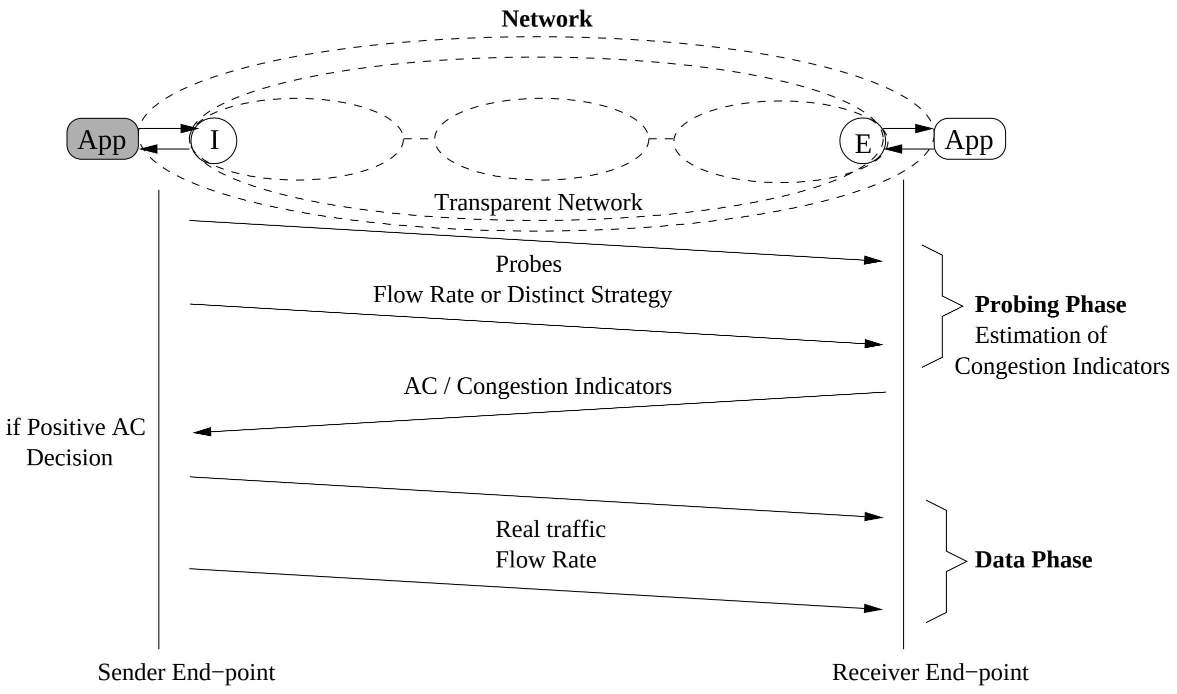


Figure 3.6: EMBAC approach

In more detail, the existing EMBAC approaches differ in several aspects: (i) the measured parameter involved in the AC decision, e.g., packet loss ratio; (ii) the characteristics of the probing phase such as its duration and/or rate; (iii) the underlying network model. Within class-based networks probing may be either in-band or out-of-band. The term in-band probing is used to indicate when probes are embedded within the service class, i.e., share the corresponding resources allocated to the class. Out-of-band probes are usually sent in a less priority class. As regards the type of service to be applied to, EMBAC solutions are intended to have the same applicability of other measurement-based AC solutions, i.e., soft real-time services. A detailed discussion of EMBAC performance for a simplified network model with two priority service levels is available in [106].

Despite, the simplicity and scalability of EMBAC solutions, requiring none or reduced changes from networks[10], several disadvantages are commonly pointed out, namely:

[10]Note that some EMBAC proposals may implicitly require changes in the core such as ECN marking capabilities

- their significant initial latency or setup delay, usually in the order of seconds which may limit its attractiveness for certain applications;
- the overhead of per-flow probing traffic. Although the probing phase allows to assess beforehand the effect the new flow will have on the network performance, it will contribute to the overall network load, which may lead to QoS degradation depending on the weight and overlapping degree of the current probing phases;
- the inherent problems caused by probes stealing bandwidth from established flows and denial of service situations when simultaneous probing attempts congest the network and none is accepted although resources are available [106, 61][11];
- the use of a single probing sampling during a reduced period of time to infer congestion makes the measurements very dependent on the network congestion felt at the moment. This probing time may also impair the estimation of low loss ratios [106];
- this technique is more suitable to be used by trustable sources and, similarly to MBAC, it tends to favor less demanding QoS flows or flows crossing a shorter path [106, 99].

3.3.6 AC proposals to control elastic traffic

Although performing AC for real-time traffic is generically consensual, the need to control the admission of elastic TCP traffic is more arguable, dividing opinions. While some argue that once TCP is adaptive controlling the number of flows sharing the available bandwidth is unnecessary, others are in favor saying that controlling the overload is required in order to preserve an acceptable throughput per active flow, and thus, the QoS offered to users [129, 130, 131, 132].

Actually, network overload leads to packet loss and retransmission, to a bandwidth share decrease among flows, which may result in the interruption of some flows due to users' impatience or triggered by TCP or higher layer protocols. Both the packet retransmission process and the

or the ability to change specific probing fields. When the endpoints are edge routers, the implementation of that AC strategy in these nodes is also needed.

[11] According to [106], when multiple flows enter the probing phase at once and no one succeeds, the system enters into a thrashing regime, i.e., the cumulative level of probe traffic impairs new admissions even when the network could afford to support part of them. To reduce this problem, the authors suggest using a slow start probing and early rejection mechanisms. Stealing is another problem pointed out in [106], which may occur as consequence of the scheduling mechanism behavior. In multiclass networks stealing may also occur when borrowing between classes is allowed, and a probing phase in a low load high priority class leads to flow acceptance which may cause degradation to the existing flows in less priority classes using borrowed bandwidth [137].

reattempts of initiating aborted flows affect negatively network stability and efficiency, leading eventually to congestion collapse [129, 132]. In fact, a minimum TCP bandwidth is required to achieve a minimal session level user utility [130] and the use of AC will assure that, avoiding wasting network resources on retransmissions and incomplete transfers [129].

Due to the large number of TCP flow arrivals and their eventual small duration, controlling individual flows using explicit signaling and reservations is impracticable, therefore, in general, a measurement-based AC approach for elastic traffic is proposed to assure that the solution is able to react and scale properly. Without per-flow signaling, the detection and acceptance/rejection of a new flow is made implicitly. Common implicit AC criteria [130, 131, 132] use the estimation of current load, available bandwidth or packet loss probability, comparing the obtained estimation with a pre-defined threshold, which may depend on an upper limit of admitted flows. These estimates can relate to a link or path, however, path estimations are preferable when considering AC only performed at ingress nodes. In this context, several proposals for path estimations are summarized in [132].

Within implicit AC the simple discard of initial flow packets is usually enough to inform the source of a rejection decision, otherwise those packets will proceed. In more detail, possible solutions to support detection and corresponding AC decision are:

- to detect packets initializing the TCP connection (TCP SYN and/or SYN ACK); drop these packets or send an RST to the sender or to the involved parties, in case of rejection [130];
- to maintain a list of accepted and active flows based on the corresponding flow identifiers. Each incoming packet is forwarded if its identifier is in the list of flows, otherwise, being a packet of a new flow, it is forwarded (and its flow identifier inserted in the list) or dropped depending on the acceptance decision [132].

While the former solution is easy to implement, the latter may be more flexible but critical for high-speed interfaces due to its potential overhead.

As a final remark, the implicit AC concept can be applied to other traffic than TCP, for instance, to UDP traffic from real-time applications that do not send explicit signaling to the network (see further discussion in Section 5.3.1).

3.3.7 QoS related projects: the AC perspective

The problematic of supporting QoS in multiservice IP networks has been topic of research within several projects [149, 150, 151, 152, 153, 154]. In general terms, these projects propose encompassing QoS architectures covering multiple aspects related to traffic control, resource management and other relevant issues for QoS deployment. Part of these projects' deliverables are mainly focused on defining the architecture components and their interaction from a high abstraction level, leaving open the adoption of multiple solutions to deal with concrete tasks such as AC. For instance, AC directives range from centralized to distributed models based on either parameter-based or measurement-based AC criteria.

In brief, the AC proposal for intradomain and end-to-end operation within Internet2 project [154] falls within the BB centralized approach presented in Section 3.3.4. Both Tequila [61, 2] and Aquila [155, 54] projects consider centralized and distributed entities. While AC decision entities are distributed, a central entity controls their operation in a larger temporal scale than per-flow AC.

Tequila architecture covers the most relevant aspects of QoS management, including SLSs management and AC, however, the AC approach is described at very high level, not detailing and formalizing concrete AC equations to be applied in order to obtain an integrated and end-to-end QoS solution [2, 84, 61].

More recently, in the Mescal project, a follow up of Tequila outcome, the AC approach is further detailed [156, 157]. AC is performed at ingress nodes based on algorithms that consider the available bandwidth on those nodes, as reflecting the minimum available bandwidth in any of the possible paths. The control of SLSs is not covered and the multidomain approach is based on the control of the peak rate at the ingress nodes. Thus, concerning AC, simple assumptions are made and a single node/link evaluation is provided. Conversely, in Mescal deliverables, especially in [65] an in-depth analysis and proposals for the problematic of SLS management both intra and interdomain is provided.

As regards AC, Aquila goes further on detailing distinct AC equations to be applied for each of the supported traffic classes [54]. Aquila's QoS architecture considers AC at ingress nodes, and eventually at egress nodes, and includes five classes. Apart from best-effort, in the remaining classes AC is explicit and supported by parameter-based equations that consider existing reservations and the link capacity allocated for each class. In Aquila testbed, the AC evaluation considers the access link capacity, without covering SLS control [54]. Although Aquila approach is oriented to per-flow treatment, per-flow reservations are aggregated. The interdomain operation is sustained by the Border Gateway Reservation Protocol (BGRP)[12] [160].

The AC proposal presented in this thesis falls within the QoS-II project [153].

3.4 Comparing the main characteristics of AC approaches

Considering the high-level characteristics of AC approaches identified in Section 3.1 and the detailed discussion provided in Section 3.3, Table 3.7 summarizes the most relevant aspects of the studied approaches in order to allow an easier comparison between them.

3.5 Motivation for a new AC proposal

Conceptually, the present discussion surveying the characteristics of current AC approaches clearly illustrates the compromise between the level of QoS guarantees and the complexity introduced in the network control plane. In fact, the stricter the QoS guarantees are, the tighter the control of network resources usage needs to be. A broad view over the AC approaches evolution exhibits a tendency in adopting solutions based on measurements of network usage and performance rather than solutions bringing too much state information about reserved resources into the network. Therefore, the move is toward simpler and more implementable solutions at cost of eventually relaxing the service levels guarantees.

In multiservice environments, where different QoS levels need to be provided, all the highlighted aspects make difficult to achieve an encompassing AC approach that is simultaneously simple and easy to deploy. When considering its operation across multiple domains, where distinct QoS solutions are likely to be in place and existing SLSs' need to be fulfilled, the challenge is even higher.

Despite the wide range of AC approaches proposed in the literature, from which the most representative have been discussed above, few studies deal with the management of multiple in-

[12]In [158], the BGRP aggregation process efficiency is compared to an alternative approach called Shared-segment Interdomain Control Aggregation Protocol (SICAP) [159]. In this approach, over-reservation is considered in the process of releasing aggregated resources. This means that resources are not completely released when a flow resource release message occurs. Instead, considering the initial reservation, fewer resources are released and the created over-reservation allows decreasing signaling overhead.

AC Approach	Architecture	State Information	Signaling	AC criteria	Net. Paradigm / Service Type	Main Advantages	Main Disadvantages
Intserv RSVP/AggRSVP	Distributed AC in all nodes AC in AggRSVP nodes	At all nodes Per flow or aggregate	Explicit	Flow profile Available resources (bw) Reserved or Measured (MBAC)	Inserv Guaranteed or Predictive	Service guarantees Tight resources control AggRSVP−Aggregated state information	Scalability problems Control overhead State information Signaling Difficult to deploy widely
Intserv/Diffserv (IS/DS)	Distributed IS − AC all nodes/Agg. DS − AC at boundaries with dist. or cent. control	IS − At all nodes DS − At edges / BB / PDP Per flow or aggregate	Explicit	Flow profile Available resources Reserved or Measured	Intserv/Diffserv Guaranteed or Predictive Best−effort	Tradeoff service guarantees vs. scalability dependent on DS control strategy, IS region dimension and control, RSVP request type Mapping functions needed	
SCORE/DPS	Distributed AC in all nodes	Per flow at edges Per aggregate in core Embedded in packets	Explicit − two distinct phases End−systems − Edges Internal signaling	Flow profile Estimated upper−bound of aggreg. reserved bw	Proprietary (IS−like) Adjustable to Diffserv Guaranteed Service	Service guarantees Low state information at core Scalable core	Proprietary Difficult to deploy widely Changes in all nodes Packets updating Route enforcement
BB	Centralized Distributed BBs	At BBs Net. resources usage Topology, SLSs, policies Per flow or aggregate Per flow at edges for TC	Explicit End−systems/ingress and BB	Flow profile Available resources SLS status Reserved or Measured	CoS −Diffserv or proprietary Guaranteed or Predictive Best−effort	Edge and core simplified Service guarantees Global network vision Flexibility to improve control rules SLSs management	Dependence on a single entity Single point of failure and congestion Large amount of info. to manage Signaling overhead (intra and interdomain) Latency and Scalability Distributed BBs: resources fragmentation BBs coordenation
Passive Mon. MBAC	Distributed AC in all nodes	At all nodes Usually per aggregate	Explicit	Flow profile Available resources (bw) Rate and/or delay Measured	Intserv−like Predictive	Less conservative Better resources usage Take advantage of stat. multiplexing Flexibility to adjust to traffic fluctuations	Difficult to deploy widely Eventual QoS degradation Fairness
Passive Mon. Envelopes	Distributed AC at egress	At egress nodes Per class and Ingress−Egress pair	Explicit End−systems − Egress	Flow profile Measured service Service envelopes Arrival envelopes	CoS − Proprietary Adjustable to Diffserv Predictive	Involves only edge nodes Black−box core Low state information Service guarantees	Difficult to deploy end−to−end number of I− E combinations Changes in all packets Measurement overhead
Active Mon. EMBAC	Distributed AC at endpoints	At endpoints Per flow in probing phase No state in the network	Between endpoints Transparent to network	Congestion indicators Measured Thresholds	CoS − Proprietary or Diffserv Predictive Best−effort	Easy deployment Scalability End−to−end operation Low state information	Initial latency Per flow probing intrusion Stealing and thrashing regimes QoS estimation based on one sample QoS instability and Fairness
Elastic traffic	Distributed AC at boundaries	At ingress nodes Measures for AC Eventual per−flow tables No state in the network	Implicit Flow detection	Current load Available bandwidth Congestion indicators Measured	CoS or Best−effort Best−effort	Easy deployment Low complexity	Difficulties in high−speed interfaces Heavy flow tables (if used)

Figure 3.7: Comparison of AC approaches

tradomain QoS levels and interdomain SLSs simultaneously [38, 85], lacking in formalizing a generic model with concrete and flexible AC equations to be deployed in CoS networks. However, studying the characteristics, virtues and weaknesses of current AC approaches provides valuable knowledge to ground and devise enhanced AC proposals.

In this context, the new AC model described in detail in Chapter 5 brings new insights to perform an encompassing and lightweight AC in multiservice class-based environments. The proposed AC model aims to: (i) support multiple services with distinct assurance levels; (ii) control the QoS levels inside each domain and the existing SLSs between domains; (iii) operate intra and interdomain providing an unified end-to-end solution; (iv) be simple, flexible, efficient, scalable and easy to deploy in real environments.

Facing the debate on related work, several aspects were identified as relevant for pursuing these objectives namely, distributing control between edge nodes, relieving network core from control tasks, reducing state information and control overhead, sensing and adapting to network dynamics through measurements, supporting AC irrespectively of applications' ability to explicit requirements and signaling the network. In addition, although not covered in the studied AC approaches, a certain degree of overprovisioning should be considered to achieve a simple and manageable multiservice AC solution. This degree, which should be service-dependent, aims at simplifying the AC process while providing the required service level guarantees.

Following these characteristics, the AC model is fully defined and specified in Chapter 5, where concrete per-class AC equations are proposed to cover the model operation both intra and interdomain. The comparison of the proposed monitoring-based approach with other MBAC and EMBAC solutions is left for Section 5.7.

3.6 Summary

In this chapter, the need to perform AC in multiservice IP networks has been justified and the main AC approaches surveyed. This survey starts with an identification of the multiple high-level aspects that distinguish existing AC approaches. Then, after a brief service-oriented overview, a detailed description of the main proposals in the field has been presented. Although this discussion has covered the AC perspective in IP networks following distinct QoS paradigms, the emphasis has been given to approaches proposed for class-based IP networks. Identifying their main virtues and limitations, and assessing the existing trade-off between complexity and assurance has sustained the motivation for proposing a new encompassing and lightweight AC approach for multiservice class-based IP networks. The defined AC criteria comprise complementary rules for QoS and SLS control, which are driven by feedback resulting from systematic on-line monitoring. Thus, the problematic of QoS and SLS monitoring will be discussed in the next chapter before detailing the proposed AC model, which will occur in Chapter 5.

Chapter 4

Monitoring QoS and SLSs

Monitoring today's IP networks assumes a crescent and crucial role both for service providers and customers as it provides valuable inputs for service provisioning, management and auditing tasks. This role is further stressed in multiservice network environments where distinct QoS profiles and service specifications need to be fulfilled. Currently, it is commonly accepted that systematic network monitoring has to be carried out as it allows to: (i) keep track of the ongoing QoS and network performance levels; (ii) verify SLSs compliance; (iii) provide feedback to traffic control mechanisms; (iv) trigger network recovery procedures and, generically, (v) support traffic engineering decisions. Network operators, service providers and customers want to have a well-defined and objective view of network services' performance. While network operators and service providers aim at efficient resource utilization, high performance and competitiveness, customers want to get the level of service they expect and pay for. In this way, the research community and industry has made strong efforts to define relevant network performance metrics and in developing measurement methodologies, measurement tools and monitoring systems for their estimation and control.

The monitoring process should provide measures reflecting the real status of the network without introducing significant overhead or interfering with operational network traffic. To achieve this, measurements have to be accurate, fast and carried out on a regular basis, while minimizing intrusion. In multiclass networks, where each traffic aggregate receives a distinct treatment, QoS evaluation needs to be carried out in a per-class basis so that each class measuring requirements and behavior are met and sensed properly. In the context of the present work, this evaluation has to be performed on-line so that AC decisions are made in useful time based on the current view of the network.

This chapter discusses the problematic of QoS monitoring, emphasizing the use of on-line monitoring in multiclass networks. Starting with a debate on different monitoring approaches, the focus is given on identifying relevant QoS metrics and efficient monitoring strategies for their estimation, mainly from an edge-to-edge perspective. This analysis constitutes a fundamental background to define the characteristics of the monitoring process that will provide the feedback to support the AC model operation. The remaining of the chapter focuses on scalability considerations about monitoring systems.

4.1 Identifying relevant monitoring systems characteristics

Monitoring systems play a key role in the support of traffic engineering and service management of IP networks [161, 162, 22]. These systems may provide monitoring information to assist service and network operational tasks and decisions in different time scales. The temporal resolution of network events may vary from coarse time periods, for instance, when planning the advisable network capacity, to fine time intervals when events occur at packet level. Depending on the time granularity involved in these events, monitoring can be carried out off-line or on-line, i.e., based on a pos-processing or real-time data analysis. *Off-line monitoring* is more oriented to guide long-term decisions and provide a broad view of the network operation, accounting and diagnostic. *On-line monitoring* is specially oriented to provide feedback to short or medium term network management and traffic control mechanisms, i.e., the monitoring outcome is required to drive reactive mechanisms so that traffic control decisions can be made without being decoupled from the current network status. Currently, with the need of QoS and SLS control, on-line monitoring is also required to provide up-to-date information of network services' performance. Furthermore, SLS auditing, formerly taken as an off-line task, assumes a crescent relevance as an on-line task [74, 92], as customers are increasingly demanding in assessing the provided service levels on a near real-time basis.

As regards the metrics' computation overhead, off-line monitoring may require huge amounts of storage resources but it is a fairly straightforward process. Computing metrics on-line can be a difficult task, specially in high-speed networks due to high traffic volumes and very low packet processing time. Ideally, the measurement process should not interfere or should have marginal impact on the normal network behavior.

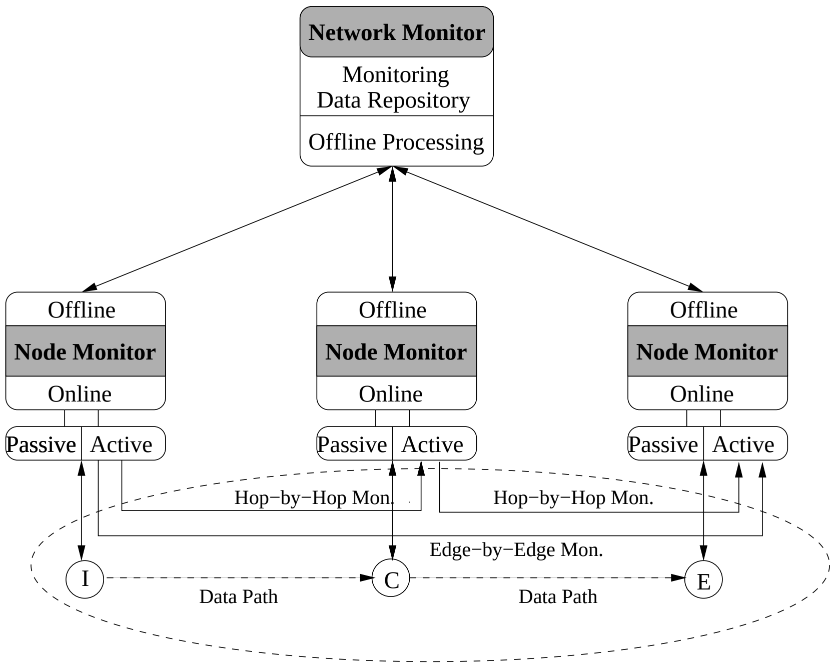


Figure 4.1: Example of a monitoring system

A monitoring system can follow either a centralized or distributed architecture. In centralized systems the data collected is forward to a special purpose central server for analysis and storage. This centralized approach facilitates an integrated and consistent view of the network performance, but problems with scalability may occur in infrastructures involving large number of monitoring nodes and significant amount of monitoring data. In distributed monitoring systems, the data collected is processed (stored and analyzed) locally at each measurement point (MP) or, more commonly, at the receiver side of each pair of MPs, following a sender-receiver model. This latter approach is followed by most of the available freeware Software Management Tools (SMTs) and has been widely used for on-line measurement purposes, particularly to obtain QoS measures on an edge-to-edge or path basis.

The classic methodologies for obtaining those measures resort to passive or active measurements, i.e., based on existing or intrusive traffic, respectively (see Section 4.2.2). Even in distributed monitoring environments, a central entity is usually present for a network-wide pos-processing of the measurement data collected individually and for maintaining a measurement data repository [162, 163]. This entity may also use collected hop-by-hop measures for calculating edge-to-edge measures [162]. Figure 4.1 illustrates these concepts. Current monitoring applications and tools are briefly surveyed in Appendix D.

Besides the temporal and architectural aspects discussed above, other relevant characteristics of today's monitoring system have also been identified in [81]. For instance, a measurement infrastructure should be: (i) flexible in order to accommodate an evolving environment, such as new service demands; (ii) secure, contemplating authentication and authorization issues; (iii) capable of providing trustable and exchangeable measurement results, in special, to support measurements across multidomain environments[1]; (iv) independent of the operating system; (v) able to support active and passive measurements with low overhead; (vi) capable of supporting test facilities for end-users and network managers.

4.2 The problematic of QoS monitoring

Despite the generic characteristics of a monitoring system discussed above, there is a clear need to obtain an unified and accurate view of the Internet quality, performance and reliability through a set of concrete and well-defined metrics. Thus, in practice, the problematic of monitoring involves the definition of adequate metrics, measurement methodologies and timing decisions. The following sections will focus on the main concerns and recent developments regarding these aspects.

4.2.1 Definition of metrics

The definition of metrics requires identifying relevant parameters and statistics for different aspects of network behavior. Both International Telecommunications Union - Telecommunication Standardization Sector (ITU-T) work on QoS in IP networks and the IP Performance Metrics (IPPM) WG within IETF have devoted substantial efforts to this topic [165, 22, 166]. IPPM aims at developing a set of standard metrics providing unbiased quantitative measures of quality, performance and reliability of operational Internet services, proposing also measurement methodologies for the defined metrics [22, 167, 168, 169, 170, 171, 172, 173]. Examples of operational environments and projects using IPPM outcome are RIPE-NCC TTM [92] and Surveyor [174, 175]. Although adopting different terminology, ITU-T work is fairly consistent in

[1]The requirements of a One-Way Active Measurement Protocol (OWAMP) to support interoperability between measurements of one-way performance metrics are identified in [164]. Such protocol should provide the ability to measure, record and distribute results of measurements of one-way singleton metrics (see Section 4.2.1) allowing to create an interoperable measurement environment independent of devices' vendors and OWAMP implementations.

Table 4.1: Quality, performance and reliability metrics

Type of metric	IPPM	ITU	Other
Delay	One-way delay (OWD) IP packet delay variation (ipdv) Round-trip delay (two-way)	IP packet transfer delay (IPTD) IP packet delay variation (IPDV)	
Bandwidth	Empirical Bulk transfer capacity (framework)	IP packet throughput (IPPT) IP packet octet throughput (IPOT)	Available bandwidth Available capacity Throughput
Loss	One-way packet loss (OWPL) One-way loss pattern (OWLP)	IP packet loss ratio (IPLR)	
Other		IP packet error ratio (IPER) Spurious IP packet ratio (SPR)	ECN marks MTU size
Availability and Reliability	Connectivity (one or two-way)	Perc. IP serv. unavailability (PIU) Perc. IP serv. availability (PIA)	Mean downtime Mean time to repair Mean time btw failures

defining the relevant metrics to be considered[2], identifying also some worst-case QoS upper bounds for common services and applications (see Section 2.2).

Taking these works into account, in Table 4.1 quality, performance and reliability metrics are classified in major groups depending on what they intend to measure. It is noticeable that one-way metrics have deserved special attention and preference over two-way metrics. In fact, due to possible asymmetric paths and/or different network resource allocation and queuing behavior in both directions, one-way measurements give more precise information and are, therefore, more useful. The impact of some of these metrics on the perceived quantitative quality of applications is identified in [77, 78, 79, 80, 81, 82, 83] (see Section 2.2). As regards SLS metrics, the available bandwidth, one-way packet loss, one-way loss pattern, IP packet delay variation and one-way delay are identified as the most relevant SLS metrics [81]. Note that, this order and relevance are rather subjective as they are service-dependent (see Section 6.3). Several tools useful for measuring the SLS metrics have also been developed and tested [81, 176].

Defining a metric, identifying its type (analytical or empirical), its composition (in spatial and temporal terms) and its corresponding instances (singleton or sample metric) are topics to be addressed concerning the defined parameters [22].

[2]Despite the consistency regarding the most relevant metrics, they differ in the way some of these metrics are defined. For instance, while IPPM prefers deterministic definitions, ITU adopts statistical or probabilistic definitions. IPPM work is more objective in the measurement methodologies, despite being more limited on the type of suggested test streams (usually Poisson) [83].

Formal definition of metrics

The formal definition of the QoS metrics related to the current work is briefly presented in this section, debating the different perspective ITU-T and IETF IPPM may have on them. The definition of other less commonly used metrics is available in [165, 166, 177, 69].

According to [22], the metrics are usually defined as:

- *singleton metrics* - atomic or single instance metrics;
- *sample metrics* - derived from singleton metrics by taking a given number of distinct instances, e.g., to verify metrics variations and consistencies;
- *statistical metrics* - derived from a given sample metric by computing statistics of the obtained values. For instance, mean, median, maximum, minimum, percentile and inverse percentile are possible statistics to be applied to a particular sample.

For many Internet metrics, the value of the metric depends on the type of IP packets used to make the measurement[3]. Due to this property, IPPM has introduced the notation *packet of type P* [22], which is used to define generic *Type-P-** metrics and the corresponding measurement methodologies. In some contexts, P is explicitly or partially defined and, when performing real measurements, these Type-P definitions need to be clearly specified. Without introducing a generic notation, the need to include information about the packet type(s) within the populations of interest when defining and evaluating performance parameters is also pointed out in [165].

A) *Delay related metrics*

- One-way Delay (OWD) - According to [167], the Type-P-One-way-Delay from a source to a destination is defined as the time elapsed since the first bit of a Type-P packet leaves the source until the last bit of that packet is received by the destination. Thus, intuitively, it is the time required by a packet to be transmitted and fully received by the destination. This definition considers the time needed by the first bit of the packet to go from source to destination and the time needed to transmit all the bits of the packet. The first part includes the propagation time of a link [22], which depends mainly on the physical distance, the number and type of active/passive equipment crossed along the path and the instantaneous

[3]Examples of information identifying the type of packets can be the protocol number, UDP/TCP port numbers, size and precedence/ToS.

network load, and the second part depends on the line transmission speed and packet size [82]. Among other purposes, this metric is a useful indicator of congestion in a network path, reflecting the path suitability to support delay sensitive applications. The OWD is either a real value or an undefined number of seconds. An undefined OWD means that the packet failed to arrive within a reasonable period of time[4], defined in the measurement methodology. If a packet is fragmented and, for some reason, reassembly does not occur the packet will also be assumed as lost. Considering a sample of the singleton Type-P-One-way-Delay metric, e.g., the sample metric Type-P-One-way-Delay-Poisson-Stream (when Poisson sampling is used), several statistics can be computed as mentioned above.

- IP Packet Transfer Delay (IPTD) - The definition of IPTD [165] is consistent with OWD. ITU defines the *IP Exit Event* and *IP Entry Event* as the observation time of the first bit of the IP packet and the last bit of the IP packet, respectively, coming from the host or test equipment. For practical measurement purposes, the time of occurrence of these reference events can be approximated by observing the IP packets crossing the associated physical interface, which should be as near as possible of the desired MP, instead of considering the IP protocol stack. If a packet is fragmented, the time considered as a packet receiver event is from the last fragment. The waiting time value suggested by ITU-T to consider a successful IP packet transfer is $T_{max} = 255s$. The mean IPTD is the proposed statistic.

- IP Packet Delay Variation (ipdv / IPDV) - This metric is derived from OWD / IPTD metric, however, being a metric resulting from differential measurements it is less sensitive to synchronization problems between MPs. ITU-T and IETF IPPM definitions for this metric are distinct [178]. For IPPM [169], Type-P-One-way-ipdv for two packets (called pair) is defined as the difference between the value of Type-P-One-way-Delay from a source to a destination at $T2$ and the value of Type-P-One-way-Delay from the same source to the same destination at $T1$. While $T1$ is the time at which the source sends the first bit of first packet, $T2$ is the time at which the source sends the first bit of the second packet. Therefore, ipdv is defined as the difference between the Type-P-One-way-Delay of the pair. The value of ipdv is either a real (positive, zero or negative) or undefined number of seconds, which occurs when one of the two packets sent is not received. As an example, this metric is useful for sizing play-out buffers for isochronous applications, using the maximum ipdv, or to assess the dynamics of queues in a network or router. Considering a stream of packets this singleton definition can be applied to achieve a sequence of ipdv

[4]For instance, the theoretical upper bound on the lifetime of IP packets is 255s and the upper limit of 10s is used in [175].

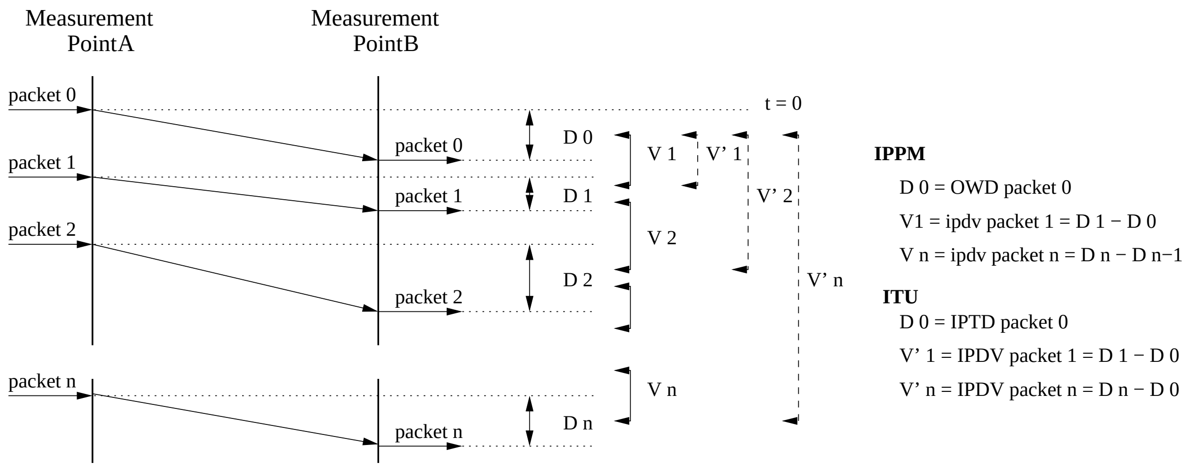


Figure 4.2: Delay related metrics for IPPM and ITU

measurements over which several statistics can be computed. The selection function which specifies each pair can be consecutive, i.e., $ipdv_n = owd_n - owd_{n-1}$, or not. For ITU-T a two-point IPDV for a packet is defined as the difference of the IPTD of the packet and a defined reference IPTD between the same two MPs, i.e., $IPDV_n = IPTD_n - IPTD_0$ [165]. The reference IPTD can be the IPTD experienced by the first IP packet [165] or a more or less randomly chosen IPTD [178]. This definition of IPDV, which characterizes the variability in the pattern of IP packet arrival reference events at a destination with reference to the pattern of source events, is closer to the common definition of jitter usually expressing a variation of packet delay. A more complete comparison between ITU-T and IPPM definitions is presented in [178]. Figure 4.2 exemplifies both concepts.

B) *Loss related metrics*

- One-way Packet Loss (OWPL) - The Type-P-One-way-Packet-Loss from a source to a destination is 0 or 1 depending on whether the Type-P packet sent by the source is received or not by the destination [168]. Thus, the value of this metric is either 0 for a successful transmission, or 1 when loss occurs. Packets that do not arrive in a pre-defined time upper bound, packets that arrive but are corrupted and packets reassembled unsuccessfully are counted as lost; if multiple non-corrupted copies of a packet arrive to the destination, the packet is counted as received. Similarly to OWD, this metric is a useful indicator of congestion in a path, reflecting its suitability to support loss sensitive applications. Considering the sample metric obtained from the singleton Type-P-One-way-Packet-Loss metric, statistics such as the average of packet loss in the stream can be computed.

- IP Packet Loss Ratio (IPLR) - According to [165], IPLR is the ratio of the total lost IP packet outcome to the total transmitted IP packets in a population of interest. Conversely to IPPM definition, packets that arrive corrupted are considered in a distinct metric, the IP Packet Error Ratio. This may be useful for voice applications as they are able to distinguish those packets [83].

- One-way Loss Pattern (OWLP) - Derived from OWPL, two sample metrics aiming at capturing the loss patterns suffered by packet streams are defined in [170] - loss distance and loss period. The loss pattern or loss distribution can be particularly relevant to the performance of some real-time applications, involving voice and video, and non-real-time applications using an adaptive protocol such as TCP. Considering that the sequence number of the test packets increases monotonically by one, the Type-P-One-Way-Loss-Distance-Stream metric is defined as a sample of <*loss distance*, *loss*> pairs, where *loss* follows the Type-P-One-way-Loss-Stream, and *loss distance* is 0 when *loss* is 0; otherwise, it is the difference between the sequence number of the lost packet and the sequence number of the packet that was previously lost. The Type-P-One-way-Loss-Period-Stream metric is defined as a sample of <*loss period*, *loss*> pairs, where *loss period* is 0 when *loss* is 0 or *n* if the *loss* is 1. The value *n*, initially set to 0, is increased by one each time *loss* is 1 except for consecutive occurrences of 1; thus, the value of *n* indicates the loss period to which the packet belongs.

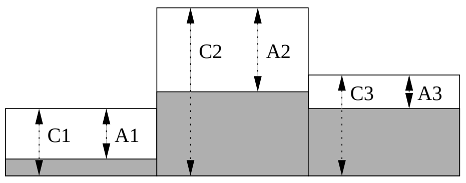
C) *Bandwidth related metrics*

The terms bandwidth or throughput quantify the amount of data that a network link or network path can transfer per unit of time (*data rate*), usually in bits per second [179]. In this context, several bandwidth related metrics were defined, being the Empirical Bulk Transfer Capacity (BTC), the capacity and the available bandwidth the most common. The first one is usually only defined for an end-to-end path, being specific for congestion-aware transport protocols; the last two can be defined for both individual links (per-hop) and data paths (end-to-end), and do not depend on a specific transport protocol. The bandwidth estimation concept is understood as being generic, involving the estimation of BTC, capacity and available bandwidth. A more complete discussion on these metrics, on the most prevalent measurements methodologies for their estimation and on the existing measurement tools is presented in [179].

- Empirical Bulk Transfer Capacity (BTC) - According to [173], BTC is a measure of the network ability to transfer significant quantities of data with a single congestion-aware transport connection such as TCP. Intuitively, it corresponds to the expected long-term average data rate, in bps, of a single TCP connection over the path. The diversity of transport algorithms makes difficult the standardization of BTC metrics, however, the specific definition of BTC that must be reported by a BTC tool is $BTC = data\_sent/elapsed\_time$, where $data\_sent$ only represents data bits and retransmitted data is counted only once [173]. A theoretical model for determining BTC or goodput of one TCP connection is proposed in [180] and an implementation of this model can be found in [81]. In practice, BTC is the maximum throughput obtainable by a single TCP connection [179]. Aggregate TCP throughput is the sum of the throughputs of N parallel TCP connections [177].

- Capacity - According to [179], the capacity of a link depends on the underlying transmission technology and propagation medium whereas the capacity of a hop, which is lower, is defined as the maximum possible IP layer transfer rate at that hop. When considering a path, the capacity is the maximum possible throughput that a path can provide to a flow and, therefore, the upper bound of the available bandwidth in the path. This metric is relevant to debug, calibrate and manage a network path [177].

- Available bandwidth - The available bandwidth of a link is typically a time-varying metric that relates to the unused or spare capacity of the link during a certain time period. The available bandwidth of a path is the maximum possible throughput to saturate a path, considering the current load. This metric is useful for predicting end-to-end performance [177]. Figure 4.3 [177] illustrates the path capacity and path available bandwidth concepts.



Path Capacity (C)

C = min (Ci) = C1
Ci = capacity of link i ; (i=1...N)

Path Available Bandwidth (A)

A = min (Ai) = A3
Ai = available bandwidth of link i; (i=1...N)
Ai = Ci (1−Ui); Ui = utilization of link i in time interval T

Figure 4.3: Path capacity and path available bandwidth

- The work reported in [165] envisages two types of throughput parameters: IP Packet Throughput (IPPT), defined as the total number of successful IP packet transfer outcomes observed at the egress MP during a time interval divided by that time interval, i.e., it gives the rate of successfully transmitted IP packets; Octet-based IP Packet Throughput (IPOT) is a similar metric which measures throughput in number of octets instead of packets.

4.2.2 Measurement methodologies

Measurement methodologies are typically classified as active or passive.

Active measurements resort to intrusive traffic, or probes, specifically injected in the network for measurement purposes. This type of methodology allows to emulate a wide range of measurement scenarios, providing a straightforward approach of assessing edge-to-edge QoS objectives (see Figure 4.4). For instance, as specific packets are injected in the network containing timestamping and sequencing data, delay and loss estimations are simplified. However, as an intrusive process, probing needs to be tightly controlled so that it does not disturb or interfere with the normal network operation. This concern is further stressed when it is carried out per traffic class. Relevant projects and monitoring systems that resort to active measurements include NIMI [181], RIPE-NCC TTM [92], Surveyor [174] and AMP [182]. A summary comparing these and other research projects related to active measurements is available in [183, 184].

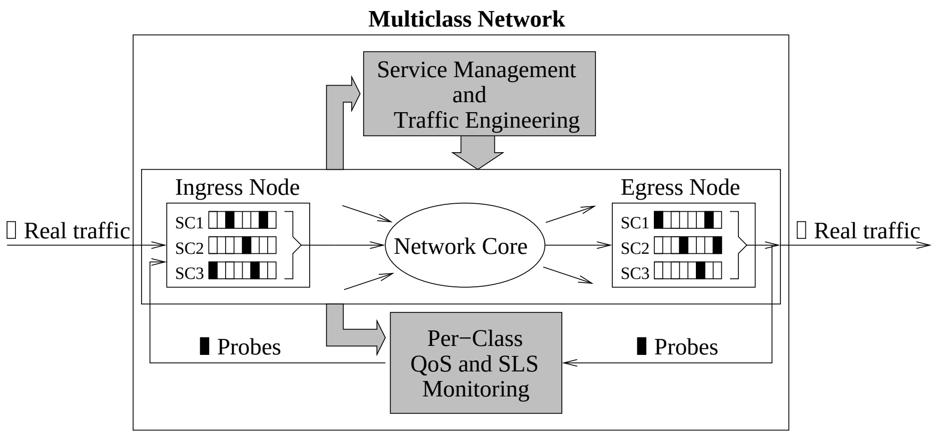


Figure 4.4: Edge-to-edge multiclass active monitoring

Passive measurements use existing network traffic for metric computation. Particularly suitable for troubleshooting, passive measurements commonly resort to special-purpose devices and built-in mechanisms available in network devices. Monitoring solutions based on SNMP are representative of this type of measurement. For instance, the Diffserv MIB [185] was defined including specific objects for the management of differentiated services. Examples of solutions oriented to passive measurements are Cisco's NetFlow [186], tcpdump, Ethereal, NeTraMet, CoralReef [176], and DAG-card based systems [187]. In high-speed networks, passive measurements are a particular challenge, specially when all packets have to be accounted for, as the amount of data gathered tend to be substantial and the packet processing time very small. To deal with this, sampling techniques, more powerful hardware and new packet buffering techniques may be required [188, 189].

Although passive techniques are usually used to monitor the performance of single nodes, they can also be applied to edge-to-edge measurements, for instance, combining hop-by-hop metrics along the network path. This allows reducing the network interference and amount of synthetic traffic[5], at expense of increasing processing and synchronization needs. According to [162], the accuracy tests when measuring one-way delay and loss through active edge-to-edge and hop-by-hop aggregation produced similar results. While this latter approach is claimed to be more scalable (if assessed in terms of intrusive traffic load), the heterogeneity of network nodes and the need for metrics portability may impair deploying large-scale passive monitoring solutions. Moreover, obtaining edge-to-edge estimates combining link-by-link measures is not an efficient and easy solution [190].

An alternative edge-to-edge approach still within the scope of passive measurements relies on the analysis of information of real application flows (e.g., using TCP ACK or RTCP data). This approach is also referred as passive probing [191].

To take advantage of the positive aspects of both methodologies, many authors propose the use of integrated measurement environments, where passive and active measurements are combined to achieve more scalable monitoring systems [162, 192, 163, 193, 188]. Due to their characteristics, both methodologies are important for QoS monitoring and SLS auditing. The metrics propagated by routing protocols can also provide useful QoS information about links and paths to the edges.

Apart from direct measurements using probing traffic and aggregated measurements, other methodologies identified in [22] include the projection of a metric from lower-level measurements and the estimation of a metric at time t_i from related metrics at time t_j. Additionally, [22] identifies important properties for a measurement methodology, such as *repeatability* - the methodology for the metric should be repeatable resulting in consistent measurements; *continuity* - small variations in conditions should result in small variations in measurement results;

[5]Actually, gathering and transport passive measurement data may also interfere with the normal network operation. To reduce this overhead, event notification and statistics summaries may be used.

conservativeness - the act of measuring should not modify the value of the metric and *certainty* - the measurements should be made using as few unconfirmed assumptions as possible. Uncertainty and errors (e.g., from clock synchronization) should also be quantified, minimized and documented.

ITU-T guidelines on measurement documentation include a clear identification of: network sections under measurement; measuring time and samples length; exact measuring traffic characteristics; type of measurement (in-band/out-of-band, active/passive) and measured data summary (means, worst-cases and/or empirical quantiles).

Parameter estimation mechanisms

Apart from the measurement methodology itself, there are several measurement mechanisms that can be used for parameter estimation [105, 107]. In particular, *Time-Window*, *Point Sample* and *Exponential Averaging* mechanisms are commonly an option due to their simplicity. In brief, *Time-window* (TW) computes an average for the parameter under control for every sampling period S. After a window consisting of T samples S, the highest average is taken as the estimation for the next T window. At any time, the estimate is immediately increased when a measured sample is higher than the current estimation or a new flow is admitted. In the latter case, the estimate is increased by the corresponding flow's parameter value according to the parameter's semantics. For instance, when estimating network load, the advertised flow rate is added. At this point, the window T can be restarted so that a full new window is used to capture the new flow impact. This avoids a too optimistic AC view of the network whenever the new flow traffic is not immediately sensed by the measurements. Figure 4.5 illustrates the operation of TW, restarting and without restarting T. *Point Sample* (PS) simply takes a sample of the parameter in each sampling period S as the average [105]. *Exponential Averaging* (EA) takes a sample of the parameter in each sampling period S, however, the average v' is computed as a function of previous measurements v and the current one v_t, i.e., $v' = (1 - \gamma)v + \gamma v_t$. The parameter γ determines the weight the new measurement has on the estimated average. Similarly to the time-window mechanism, when a new flow is admitted, the estimate is artificially increased [121].

Tuning these mechanisms configuration, i.e., finding appropriate values for S and T is obviously a key point as regards the realism of the estimation. While S controls the measurement sensitivity, T controls the mechanism adaptability. A lower value of S leads to a higher sampling frequency. This means that the mechanism is more reactive to bursts, leading to high measures, ending up in a more conservative AC. In opposition, the larger S, the smoother the estimation

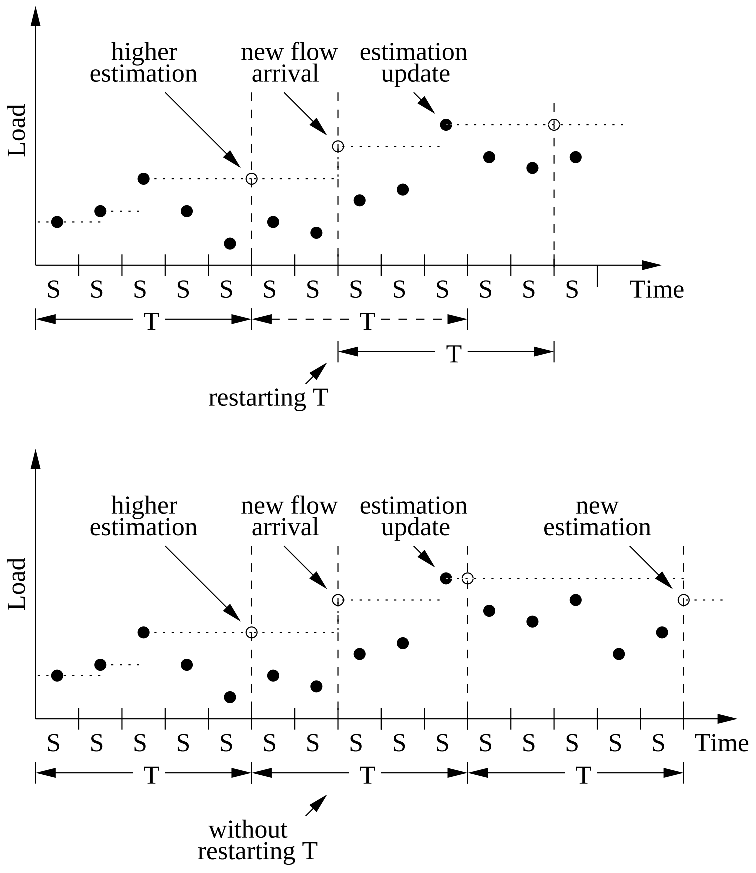


Figure 4.5: Time window mechanism

process reacts to flow traffic variability. In this case, the number of accepted flows tends to increase. The value of T rules the window size. An higher T leads to less frequent estimate updates and more stability due to the memory effect of past estimates. This reduces the capacity of the method to react, leading to a more conservative estimation approach. The window size T also needs to be balanced with the flow arrival rate and flow duration. While the former impacts on how the time window is reinitialized, the latter may lead to overestimates in case of short-lived flows. According to [121], the most visible effect on parameter estimation, and indirectly in AC, results from tuning T. This variable provides the most pronounced effect on the experienced delay and link utilization.

In the context of AC, the measurement mechanisms described above are usually applied to single node measurements. In this work, the same concepts are applied to edge-to-edge measurements as discussed in Section 6.3.

4.2.3 Timing issues

Focusing on an on-line monitoring process, the timing issues involved can be twofold. At a higher level, timing decisions are related to the periodicity of measurements. Depending on the measured parameters' purpose, timing decisions can vary significantly. For instance, while for AC a time scale ranging from seconds to minutes is appropriate [54, 194, 157], for active queue management or packet scheduling mechanisms the operating time scale varies from picoseconds to milliseconds [21]. Apart from being constrained by the temporal resolution of the network control task, choosing a time scale should consider that a small time granularity increases the metric computation and dissemination overhead, leading eventually to excessive reaction to short-time traffic fluctuations, whereas a sparse granularity may lead to measures reflecting out-of-date network state information.

At a lower level, timing decisions may require a solution to minimize or solve the problem of accurate clock synchronization between MPs in different systems. This need is notorious when measuring absolute time differences such as one-way delay [195], or when aggregating hop-by-hop measurements. Usually, the choice of a synchronization solution should be made establishing a trade-off between accuracy, complexity and cost involved. Common solutions resort to Network Time Protocol (NTP) or specific Global Positioning System (GPS) equipment strategically located in the network. More recently, the clock associated with Code Division Multiple Access (CDMA) mobile telephone network has been used as a highly accurate, synchronized distributed clock source [196].

The impact of higher level timing decisions on the AC model evaluation results is discussed in Chapter 7.

4.3 Multiclass and multipurpose active monitoring

For the reasons pointed above, active measurement techniques are particularly suitable for edge-to-edge on-line QoS monitoring purposes, providing that the levels of intrusion are kept tightly controlled.

Multiclass networks pose additional challenges to on-line active monitoring. As each traffic aggregate receives a distinct treatment from either a node [62, 59] or domain perspective [39], probing needs to be carried out in a per-class basis (in-band) so that it can be adjusted to each class measuring requirements and the class behavior is correctly sensed (see Figure 4.4). Being an intrusive process, probing in high priority classes may take over resources required by real traffic not only in those classes but also in low priority ones. Therefore, special concern is needed when defining the probing pattern characteristics [190].

Particularly in multiclass environments, an efficient on-line active monitoring should be an accurate, fast, continuous, low-overhead and low-interfering process. While accurate and fast measurements allow a correct assessment of the current network state providing up-to-date information, systematic measurements allow to auto-correct the measures and capture each traffic class dynamics. As regards the overhead and interference introduced, the probing process should avoid degrading the class's QoS, e.g., decreasing the classes' throughput or causing persistent loss or delay.

Although active monitoring has been matter of interest in many research projects [174, 181, 197, 92, 163, 191, 162], extending it to multiclass networks [198, 162, 163, 191, 199, 200] is crucial and a topic requiring further study. As mentioned, in multiclass networks efficient strategies of in-band probing are fundamental in order to sense each class's performance without causing noticeable side effects on the class real traffic. To reduce intrusion and minimize probing impact, a single probing pattern should be able to capture simultaneously multiple QoS metrics of a class. To characterize this ability, the concept of *multipurpose* active monitoring is here introduced. Investigating multipurpose probing patterns is also an objective of this work.

In this context, relevant questions to be answered are: How to extend the monitoring process to a multiclass network environment, capturing each class QoS behavior and dynamics with minimal overhead? Can a probing pattern capture more than one metric accurately, according to the service class measuring requirements? Is there a trade-off among the simultaneous estimation of multiple QoS metrics? Finding answers for these questions is addressed in Section 7.2.2.

4.3.1 Probing patterns

The type of probing patterns used for metric estimation varies according to the metrics to be computed and the periodicity required for their evaluation. This variability involves changing both the time and space characteristics of the probing pattern. For instance, for measuring delay and loss related parameters continuously, simple and very low rate probing patterns have been in use in real and experimental network environments (e.g., 2 pps [92] or 4 pps [175][174]). For bandwidth estimation, several techniques such as Variable Packet Size (VPS), Packet Pair/Train Dispersion (PPTD), Self Loading Periodic Streams (SLoPS) and Trains of Packet Pairs (TOPP) have been proposed [201, 103, 179]. Common measurement tools based on these techniques [176, 202, 81, 203] use a high volume of packets (e.g., 100-5000 pkts) or probing rate and require a significant amount of time to obtain a singleton measure (e.g., 40-100 RTTs) [204]. This slow process impairs its use for continuous estimates due to the underlying overhead, being more appropriate for sparse measurements.

For continuous measurements, common methods for collecting sample metrics use either periodic or random sampling[6]. In *periodic sampling* measurements are made evenly spaced in time. Although being attractive for its simplicity, its eventual drawback is a possible synchronization with a periodic behavior either of the metric itself or induced by a network component. Moreover, periodic network perturbations resulting from probing itself can drive the network into a synchronization state, which may end up affecting the measure leading to biased metrics. In *random sampling*, such as Poisson or geometric sampling, the samples are taken at independent, randomly generated time intervals according to a statistical distribution. This avoids possible synchronization effects, yielding to unbiased samples [22]. The Poisson distribution, which leads to unpredictable sampling, is commonly used and recommended [22]. Despite having higher predictability, the uniform distribution is also used to bound the interval between samples, speeding up the convergence of the estimation resulting from sampling.

Initial results on per-class active monitoring [17], extended in Section 7.2, suggest that commonly accepted and used probing patterns may fail to capture simultaneously common performance metrics (see definitions in Table 6.3) in terms of shape and/or scale. Thus, in addition to periodic (CBR_P), Poisson (POI_P) probing streams and On-Off exponential streams ($EXPOO_P$), a new Back-to-Back On-Off probing source ($B2B_P$) with a deterministic On period and an Off period either deterministic or regulated by an Exponential, Pareto or Uniform distribution has also been developed and tested. The behavior of this $B2B_p$ probing source is controlled by three parameters: (i) duration of the On period, where probes are sent at constant rate; (ii) duration of the Off period, which may be deterministic or random; (iii) the probing rate, determining the number of packets generated within the On period. The configuration of these parameters determines the number of probing samples per second and how close back-to-back probes are in time during each sample. Figure 4.6 illustrates the behavior of this new probing source.

[6]These sampling approaches, when applied to active measurements, correspond to sending probe packets at constant or random rate. However, recall that due to interference of other traffic, the sending probing pattern is not likely to be maintained when the samples are collected.

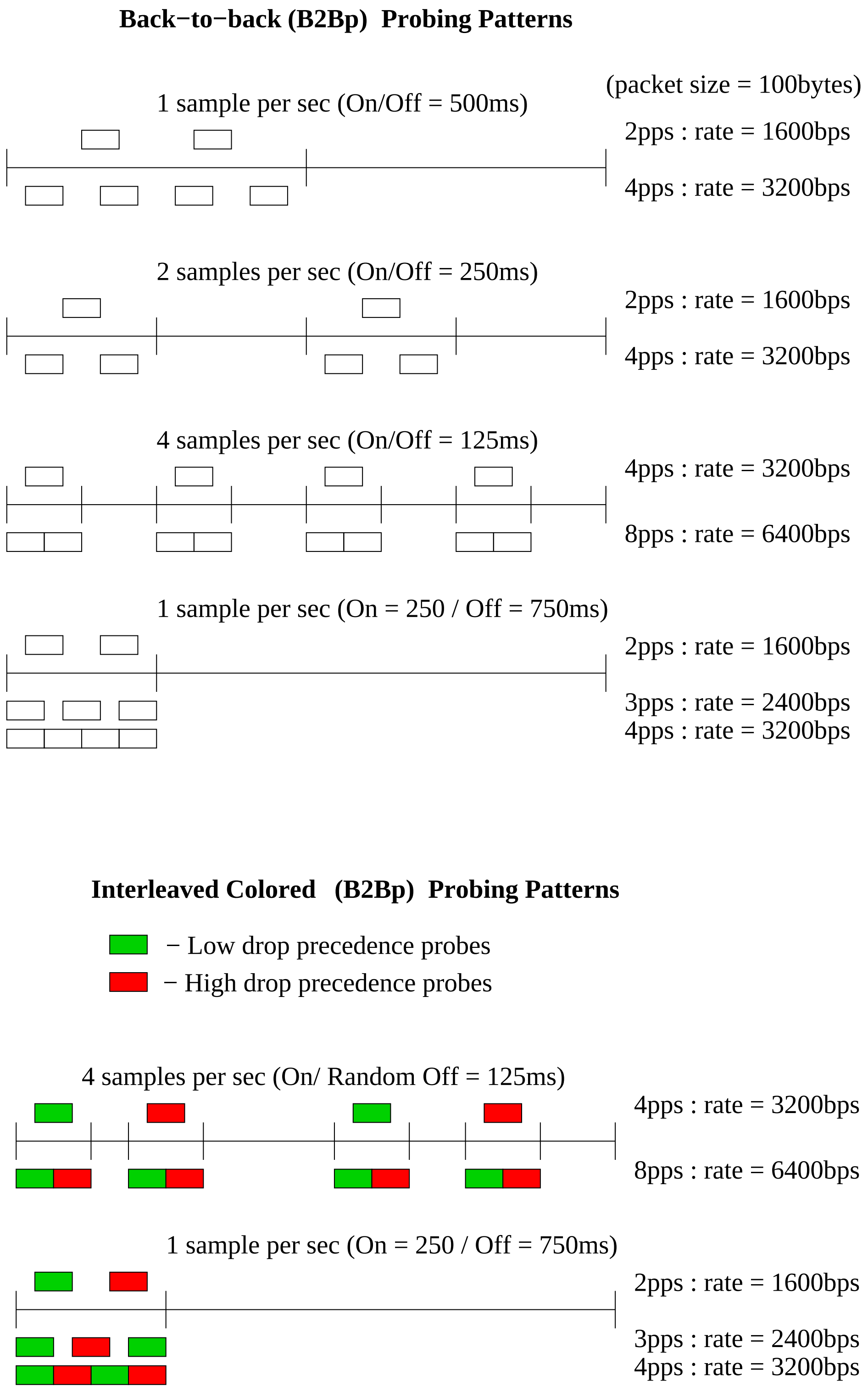

Back−to−back (B2Bp) Probing Patterns
(packet size = 100bytes)
1 sample per sec (On/Off = 500ms)
2pps : rate = 1600bps
4pps : rate = 3200bps
2 samples per sec (On/Off = 250ms)
2pps : rate = 1600bps
4pps : rate = 3200bps
4 samples per sec (On/Off = 125ms)
4pps : rate = 3200bps
8pps : rate = 6400bps
1 sample per sec (On = 250 / Off = 750ms)
2pps : rate = 1600bps
3pps : rate = 2400bps
4pps : rate = 3200bps
Interleaved Colored (B2Bp) Probing Patterns
🟩 − Low drop precedence probes
🟥 − High drop precedence probes
4 samples per sec (On/ Random Off = 125ms)
4pps : rate = 3200bps
8pps : rate = 6400bps
1 sample per sec (On = 250 / Off = 750ms)
2pps : rate = 1600bps
3pps : rate = 2400bps
4pps : rate = 3200bps

Figure 4.6: Proposed probing scheme

The resulting back-to-back probing streams aim at increasing probing sensitivity to queue variations by reducing the interpacket time between consecutive probes, while remaining simple and light. Once again, as probing needs to be carried out on a systematic way, overhead has to be tightly controlled to keep it deployable in real networks.

Moreover, a new approach of coloring probes, i.e., exploring the effect of marking probes with different drop precedences, using single color or interleaved color schemes, has also been explored (see Figure 4.6). This approach aims at exploring AQM actions in case of queue congestion and the different probabilities of packets reaching the network boundary. This may be particularly useful to sense packet loss in the network domain. For this purpose, a new policer/marker able to mark packets with an interleaved color scheme has also been developed. While single color mark schemes, i.e., schemes that send all probes as green or red packets, can be easily obtained resorting to the configuration parameters of existing policers/markers, to obtain an interleaved color scheme, where packets are marked red and green in a controlled way, has required the development of a new policer/marker.

The study of probing pattern characteristics and its accuracy for multiple metrics estimation in a multiclass test platform is further developed in Section 7.2.

4.4 Scalability considerations

A monitoring system where systematic measurements among a large number of measuring nodes are required may suffer scalability limitations, specially when active measurements take place. In fact, in a mesh measurement topology, the amount of data sent over the network, processed and stored increases quadratically to the number N of MPs, i.e., $O(N^2)$. This further stresses the need for efficient and light probing patterns justifying research on enhancing probing ability to be multipurpose [16].

Defining the borderline where scalability problems start to occur can be hard. As an example, RIPE TTM [92, 190] currently supports up to 200 test-boxes (MP); MPLS networks can support up to 40000 Label Switching Paths (LSPs) (200 nodes fully meshed), without problems [205]. In addition, to reduce the number of combinations and consequently the eventual scalability problems, peering groups of MP [190] or hierarchical regions [205] can be defined. These approaches are somehow followed in a measuring architecture that combines per-domain edge-to-edge performance measures to obtain a measure of end-to-end performance, as the one proposed in the present work. In [192] appropriate use of topology-based steering approaches and combined passive and active measurement methodologies are pointed to reduce the complexity of measuring the connections between edge nodes from $O(N^2)$ to $O(log(N))$.

In multiclass IP networks, where the amount of measurement data increases with the number of service classes and interfaces being monitored, building scalable monitoring systems is even more relevant. Research on this topic points out some principles to be followed, such as: the monitoring process granularity should be at aggregate level (PHB or path) and not at microflow level; the measures transmission overhead should be minimized using event notification and statistics summarization; the amount of synthetic or intrusive traffic should be reduced. Moreover, establishing a trade-off between the amount of synthetic traffic and sampling frequency, and combining hop-by-hop measurements when there is a large number of edge-to-edge combinations to monitor may contribute to increase scalability [162][7]. Finally, as stated in Section 4.2.2, to achieve more scalable monitoring systems active and passive measurements methodologies are usually combined [162, 192, 163, 193, 188].

Regarding the proposed AC model, two main aspects have been considered in order to improve QoS and SLS monitoring scalability. On the one side, measuring edge-to-edge services' performance is carried out at aggregate level (per-class). This means that QoS control is only performed at class level instead of SLS or flow level. This simplification stems from the fact that a service class comprises and bounds multiple SLSs and multiple flows on an edge-to-edge basis. At SLS level, the traffic load is the only parameter measured locally at ingress or egress nodes. In this way, SLS monitoring overhead is reduced (see also comments in Sections 2.2.2 and 5.1.1). On the other side, the use of multipurpose active monitoring brings potential advantages toward scalability.

As regards monitoring flexibility and portability, from an "operational perspective", the main modules of the proposed AC model - the monitoring module and the AC module (see Section 6.5) - although interrelated are independent. Thus, the monitoring process and its implementation details are hidden from the AC module and can be changed without compromising AC as long as edge-to-edge QoS measures for each class are provided. This allows to accommodate easily new developments in the research area of network QoS monitoring and new requirements of the network services being monitored.

[7]Although this approach increases processing efforts, the reduction on synthetic traffic and the improvement in scalability result from the fact that a hop measurement is potentially a constituent of several edge-to-edge paths.

4.5 Summary

In this chapter, the problematic of QoS and SLS monitoring has been discussed in order to sustain an important component of the proposed AC model. Starting by a high-level presentation of relevant characteristics of monitoring systems, the main research outcome regarding the definition of concrete metrics and measurement methodologies for QoS and SLS monitoring has been highlighted. The emphasis of the discussion has been given to the need for on-line monitoring in multiclass IP networks, as a way to provide up-to-date feedback to active network management and traffic control mechanisms, in particular to AC.

The suitability of active measurement methodologies for edge-to-edge on-line QoS monitoring purposes has motivated a more detailed discussion on this topic. In this context, the concept of multipurpose probing pattern has been introduced, with the objective of characterizing the ability of a single probing stream in capturing multiple QoS metrics of a service class simultaneously. This allows minimizing intrusive traffic and its impact on the class's real traffic. In addition, existing probing patterns have been discussed and a new colored probing pattern aiming at a better multipurpose QoS estimation has been proposed. Finally, the eventual scalability problems of an edge-to-edge monitoring process have been discussed and some principles for improving monitoring scalability have been pointed out.

Chapter 5

Proposed Admission Control Model

Defining an AC strategy for multiservice class-based networks constitutes a challenge as service classes have distinct characteristics and require different QoS assurance levels. As the service predictability required is closely related to the complexity and overhead of the AC strategy, finding a simple service-oriented AC model able to provide multiple QoS guarantees assumes a relevant role in controlling network resources and service levels efficiently.

Despite the existing proposals for AC discussed in Section 3.3, achieving an encompassing, yet feasible and lightweight AC model for CoS networks, able to control QoS and SLSs both intra and interdomain, is still an open issue. This is behind the motivation for the present work, as explained in Sections 1.1 and 3.5.

This chapter is entirely devoted to the presentation and specification of a new distributed AC model for multiservice class-based IP networks. This service-oriented model is proposed as a further step to pursue the objective outlined above. In this way, the main goals, underlying ideas and initial assumptions of the proposed AC model are firstly discussed. Then, the model architecture and generic operation are described. In order to provide a more detailed description of the model, the main entities of a network domain concerning multiservice AC, SLS and QoS management are formalized using an intuitive and expressive notation. This notation supports the intra and interdomain AC criteria specification. Finally, the key points and major hurdles of the model are analyzed and debated, emphasizing the problematic of handling concurrent AC.

5.1 Initial strategic considerations

To design an encompassing and lightweight AC model for CoS networks several initial aspects were identified as having major relevance. These aspects are as follows:

(i) *the model should be multiservice* - it should be able to control distinct network services and assurance levels, handling applications and services with different QoS requirements and traffic profiles;

(ii) *the model should be multidomain* - it should be able to operate both intradomain and end-to-end, controlling both the QoS levels in a domain and the share of existing SLS between domains. Although, in a first instance, intradomain AC is the major concern, covering the interdomain operation is also relevant in order to fulfill the applications' end-to-end QoS requirements;

(iii) *the underlying AC strategy should be efficient, scalable and flexible* - AC should be accomplished without adding significant overhead and complexity to the network control plane, contributing for an efficient management of network services and improving its ability to scale. The flexibility of the AC proposal as regards accommodating technological, service and application evolution goals should also be considered;

(iv) *the model should be feasible* - the model design should not be decoupled from its capacity to be deployed in real environments, i.e., it should be driven by simplicity, easy deployment and integration in the Internet, introducing minor changes to the CoS network operation.

The above design goals are particularly relevant when considering the deployment of the model in a large scale, across multiple administrative domains relying, eventually, on distinct solutions regarding service offering and provisioning.

5.1.1 The model underlying idea

Having in mind the strategic points mentioned above and the debate on current AC approaches presented in Section 3.2, the inherent simplicity, flexibility and adaptability of a distributed AC solution based on network monitoring assumes a clear advantage over other approaches. This advantage is further stressed when monitoring is carried out from an edge-to-edge perspective, as internal network control, topology and technologies are hidden from AC. Although such approach allows high abstraction of the network core complexity and heterogeneity, network traffic dynamics and QoS can yet be sensed and updated continuously through proper service metrics. However, as explained in Section 3.3.5, common EMBAC models have known disadvantages stemming from the introduction of per-application intrusive traffic and AC initial latency. Moreover, other edge-to-edge and end-to-end measurement-based AC approaches do not cover the control of SLSs. Overcoming these disadvantages will contribute to enhance the performance and functionality of AC.

In this context, an underlying idea of the proposed AC model is to take advantage of the need for on-line QoS and SLS monitoring in today's CoS networks and use the resulting monitoring information to perform distributed AC. This monitoring process carried out on a per-class and edge-to-edge basis allows a systematic view of each service class load, QoS levels and SLSs utilization in each domain, while facilitating SLSs auditing tasks. Performing AC at edge nodes using this feedback simplifies the network control plane, allows to make decisions on new flows' admittance with minimum latency and, generically, allows to manage QoS and SLSs. In this model, a domain is viewed as comprising distinct service classes encompassing accepted SLSs and flows with similar QoS needs (see Figure 5.1). Thus, from a QoS control perspective, controlling the QoS levels of service classes implicitly controls the QoS commitments of accepted SLSs. In this way, controlling SLSs is reduced to SLS utilization control. These aspects are fundamental to alleviate the amount of state information and control overhead, increasing the model scalability. When spanning multiple domains, collecting and accumulating the QoS measures available at each domain edge nodes will allow to compute the expected end-to-end QoS.

Another important underlying idea toward model simplicity and flexibility is to consider a certain degree of overprovisioning which, in practice, is often used and recommended [6, 206]. This is a relevant aspect to achieve a simple and manageable multiservice AC solution as it allows relaxing the AC process, while widening the range of service types covered by a monitoring-based AC solution. Introducing overprovisioning levels within the AC rules should consider the service guarantees to be provided, i.e., its definition should be service-dependent[1].

A discussion of the key points and major hurdles of the proposed AC strategy will be revisited in Sections 5.7 and 5.8, after the AC model description.

[1]The use of AC approaches for multiservice networks based on measurements has been later stressed in [207], where measurement-based AC is recommended both for real-time and elastic traffic. The advantage of using per-class overprovisioning ratios has also been recently stressed in [6].

AC perspectives

According to [10], two AC perspectives can be considered when an SLS is taken as reference:

(i) *flow AC* ensures that the admitted flows from a customer are within the capacity of the contracted SLSs;

(ii) *SLS AC* ensures that the accepted SLSs for a service type can be honored through proper service configuration and provisioning (see Figure 5.1).

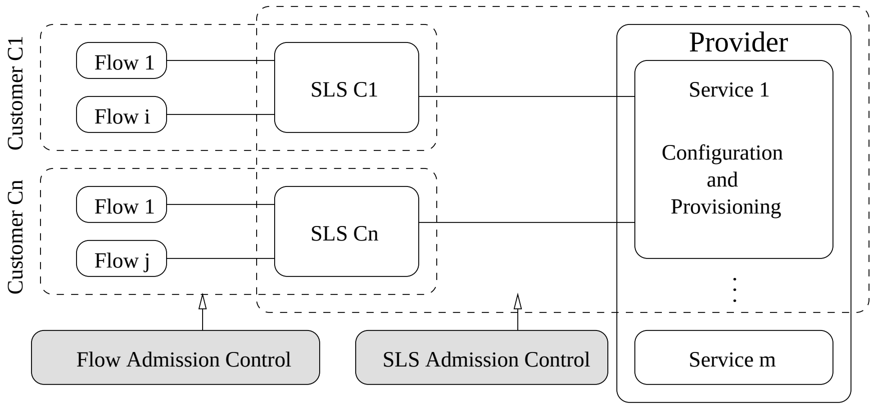


Figure 5.1: Flow AC and SLS AC

Although these are distinct AC perspectives, they follow similar principles. Whereas flow AC is based on the traffic profile and QoS objectives of a flow, SLS AC is based on the aggregate traffic profile and QoS objectives of the SLS. In fact, the semantics of the process is somehow equivalent, changing the time and space characteristics upon which the decision is made [2]. Therefore, the proposed model, defined and explored here for flow AC, is likely to be easily extended to SLS AC . However, dynamic SLS AC was left for future work (see Section 8.4).

5.1.2 Initial assumptions

This section reports a set of initial AC assumptions in order to clarify the forthcoming description of the AC model architecture. These are as follows:

[2]SLS AC involves a different AC decision timeliness, changes the type and amount of network state information to handle and involves (re)configuration tasks within domains.

(i) the admission control is carried out at flow level implicitly or explicitly depending on the type of applications. For applications involving multiple flows (e.g., composite applications such as videoconferencing) the overall admittance can be made following an application dependent criterion. As mentioned in Chapter 3, covering the general case of flow admission does not impair that other high-level AC heuristics may, in future, be in place;

(ii) the process of negotiation, acceptance and mapping of SLSs to the corresponding service classes has already occurred at the time that flow AC takes place. This implies a process of SLS validation and eventual qualitative to quantitative service requirements mapping [75, 18]. This means that an existing or new service class has to be found to encompass and bound the QoS parameters defined in each accepted SLS. The service class configuration and provisioning is also assumed to have been carried out throughout the domain following a static or dynamic approach;

(iii) the SLSs' parameters define the service to be provided in one direction, i.e., the context of an SLSs is unidirectional. However, note that bidirectional services/SLAs may be defined through two unidirectional SLS instances [69][3]. Similarly to SLSs, flow AC is handled unidirectionally;

(iv) in a first instance, flow AC occurs at ingress nodes. These nodes are able to identify the egress node that will be used by flows crossing the domain. Cases where this is not possible, e.g., whether topological information is not available or flows' destinations are not specified (e.g., multicast traffic), are discussed in Sections 5.6 and 5.8;

(v) although SLSs include the definition of a time scheduling period in which the service is due to be provided, flow AC decisions report to a present time period and the flow's duration respects the corresponding SLS time scheduling.

During this chapter and in Section 8.4 some of these assumptions are revisited.

[3] An SLA may include multiple SLSs, however, an SLS is usually related to a service class usage in one direction. In the context of AC, as the relevant part of an SLA is the SLS, from now on only the term SLS is used. Similarly to [5, 65], the administrative aspects of an SLA, e.g., pricing issues, are outside the scope of this work.

5.2 Model architecture

5.2.1 Involved research topics

In the AC model, admission decisions are made taking into account both the levels of QoS being offered for each service type and the corresponding SLSs utilization. Therefore, AC is performed resorting to QoS and SLS control equations, specifically defined according to each service characteristics. In this context, the model architecture strongly lays on research topics such as service definition, QoS/SLS monitoring and CoS traffic characterization to sustain the definition and operation of the AC decision criteria. Their interrelation is shown in Figure 5.2.

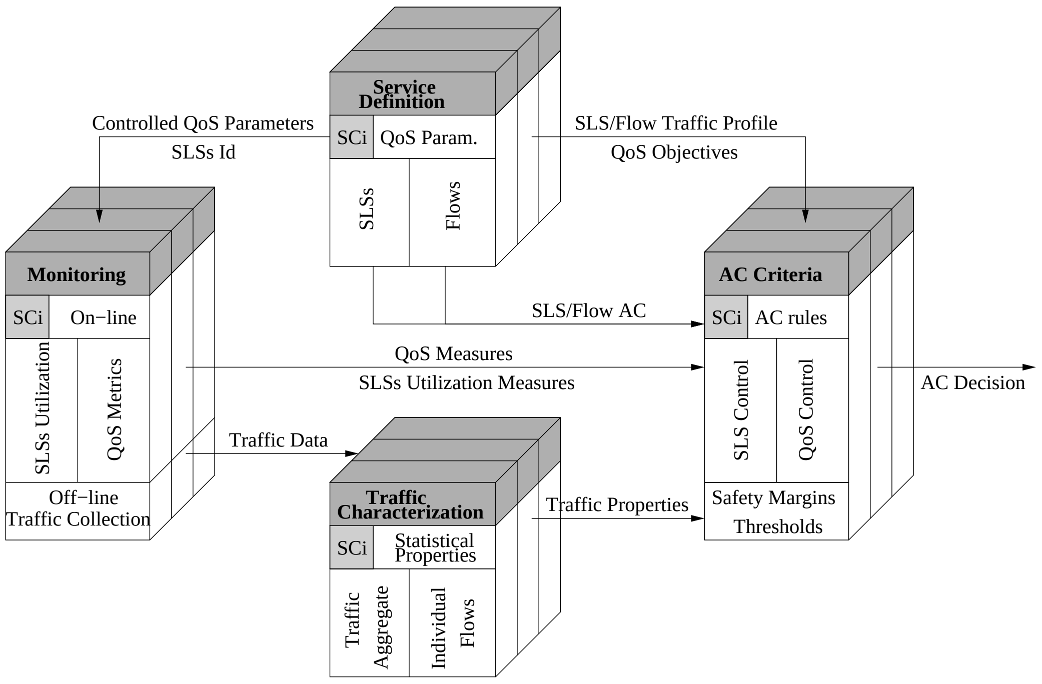


Figure 5.2: AC model architecture

Service definition, whose concept has been introduced in Section 2.2, formalized in Section 5.4 and instantiated in Section 6.1, involves the definition of basic services oriented to different application requirements, the definition of the relevant QoS parameters to control within each service type and the definition of SLSs' syntax and semantics. The traffic flows requiring admission can either belong to an SLS or not, as discussed in Section 5.5. Through systematic edge-to-edge measures of the identified QoS parameters and SLSs utilization, *on-line monitoring* keeps track of QoS and SLS status in the domain through well-defined metrics, providing feedback to drive

AC decisions. The problematic of this type of monitoring has been discussed in Section 4.2. As an *off-line monitoring* process, CoS traffic aggregates may also be collected for subsequent off-line analysis and characterization. As explained in Section 2.3, this analysis allows to determine the statistical properties of each class as a result of traffic aggregation [19] so that more realistic service-oriented AC rules, thresholds and safety margins can be established. The knowledge resulting from interrelating these areas and from comparing existing measurement-based or hybrid AC algorithms provides the basics for defining a multiservice *AC decision criteria*. Finally, the use of policy-based network management is being considered for managing all the involved model components. Security issues, such as authentication and authorization, are of undeniable relevance to be covered in future work.

5.3 Generic model operation

Before describing the generic model operation few remarks are made in order to clarify the description. In a transit domain, the way an SLS is viewed varies according to whether a client or service provider perspective is taken. For upstream SLSs, the domain acts as a service provider to the previous domain; for downstream SLSs the domain acts as a client of the next domain[4]. A set of upstreams SLSs with identical requirements share a service class in the domain. Whenever an upstream SLS requires a distinct specific service, in case of acceptance, a new service class has to be configured in the domain.

5.3.1 Intradomain operation

The main tasks involved in the proposed AC model and their location are illustrated in Figure 5.3. Apart from the usual classification and traffic conditioning functions (in white boxes) present in CoS networks, ingress nodes perform explicit or implicit AC depending on the application type and corresponding traffic class. Egress nodes perform on-line QoS monitoring and SLS control.

The *Ingress-Egress QoS Monitoring* task measures relevant parameters for each service (service metrics) using appropriate time scales and methodologies (see Section 6.3). The resulting measures are expected to reflect the service available from each ingress node.

[4]In the context of SLSs, the definition and establishment of upstream and downstream SLSs with adjacent domains is in conformance with the cascade approach for the support of interoperator IP-based services, which has the merit of being more realistic, i.e., in conformance with the Internet structure and operation, and more scalable than the source-based approach [1] (see also Section 2.2.1).

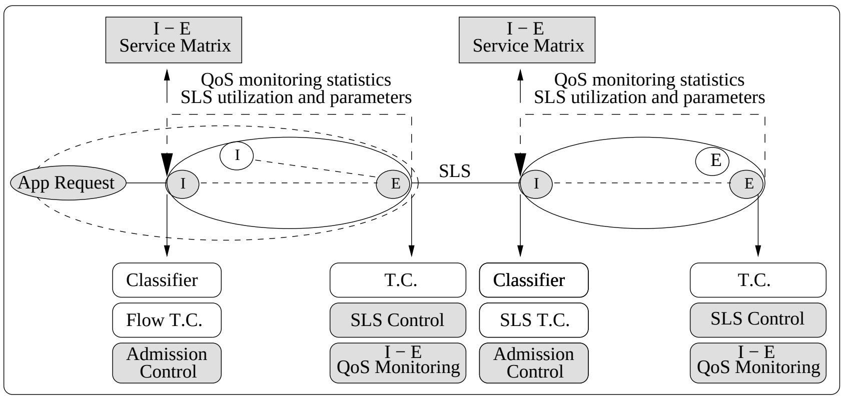


Figure 5.3: Location of tasks in a multiclass domain

The *SLS Control* task monitors the usage of downstream SLSs at each egress, to ensure that traffic to other domains does not exceed the negotiated profiles and packet drop will not occur due to a simple and indiscriminate TC process.

QoS monitoring statistics, SLS utilization and, eventually, other SLS parameters are then sent to the corresponding ingress routers to update an ingress-egress service matrix used for distributed AC and active service management. This notification may be carried out periodically, when a metric value or its variation exceeds a limit, or the SLS utilization exceeds a safety threshold. Although AC is considered to be carried out at network entrance, it is possible to decouple it between ingress and egress nodes, as debated in Section 5.6.1.

Explicit and Implicit AC

As the proposed model aims to be multiservice, explicit and implicit AC can be in place depending on the application or service characteristics. Explicit flow AC is oriented to applications able to signal the network with their traffic profile and QoS objectives. In this case, the AC decision requires two initial verifications (see Figure 5.4):

(i) *SLS Utilization Control* checks if the downstream SLS can accommodate the traffic profile of the new flow. Verifying if the upstream SLS can accommodate the new flow profile is optional. As the adjacent upstream domain is assumed to have controlled the corresponding downstream SLS traffic load, the current domain can control the upstream SLS aggregate using a simple TC mechanism (SLS TC);

(ii) *QoS Control* checks if, for the corresponding egress node and service, the domain QoS status allows a new flow entrance and if the domain QoS metrics and the previous measures (if any) fulfill the application QoS requirements[5].

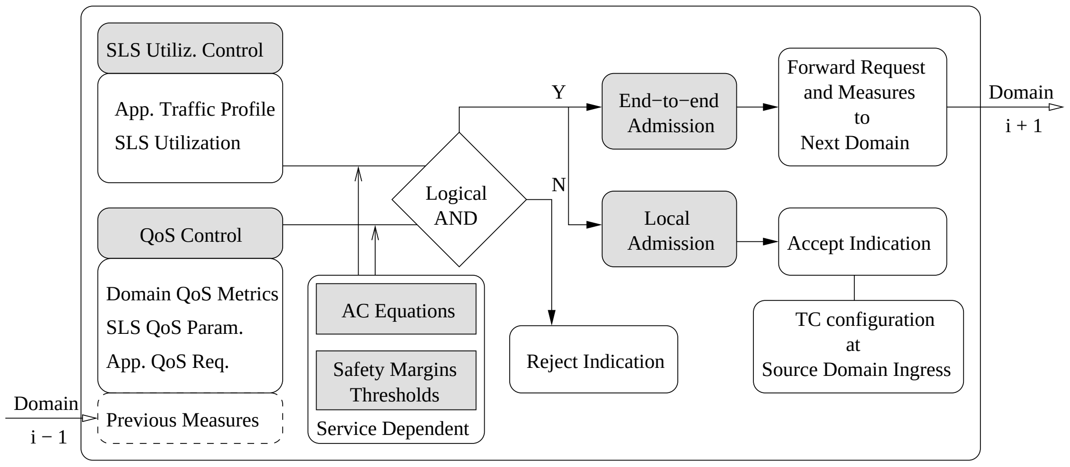


Figure 5.4: AC criterion

Each AC decision is based on a service-dependent AC equation, with safety margins and thresholds defined to ensure specific service guarantees (see examples in Section 6.2). For each class, admission thresholds must be stricter than the QoS objectives of the class, which in turn, must be stricter than the QoS requirements of SLSs and of all accepted flows, if specified. When a flow is accepted in the domain, the notification may be generated either locally (local admission) or remotely (end-to-end admission).

Local admission occurs mainly in the destination domain and the acceptance notification can also be used to configure TC at the source domain ingress router (Flow TC). Other cases where a local admission may be considered are in the source domain when no verification till the destination is required [85], or in a domain where the involved downstream SLSs reflects a service level for the specific destination[6].

[5]The QoS control check could account for the SLS QoS parameters negotiated downstream. This is, however, left for the next domain QoS control check. In addition, while domain QoS status is always verified, when the destination of the flow request is inside the domain, downstream SLS verification is not mandatory. In this case, defining intradomain SLSs will turn the AC process generic and independent of the destination's location.

[6]This covers the case of SLSs spanning multiple domains, i.e., of downstream SLSs for specific destinations. If the destination is outside the downstream domain, it is assumed that a pre-negotiation between all the involved downstream domains has already occurred. This may resort to either the *source* or the *cascade* SLSs business models (see Section 2.2.1). The use of the cascade approach is propose in [1, 89, 90], resulting in the concatenation of SLSs between peering ISPs, more precisely the concatenation of the involved Quality Classes, combined with a QoS/SLS-aware BGP interdomain routing to build or extend the local or intradomain Quality Classes to remote destinations.

End-to-end admission involves forwarding the AC request to next domain after adding the domain's QoS measures to the request (see section below).

Implicit AC is oriented to applications that do not signal the network, requiring therefore an implicit detection of flows. This implicit detection and consequent actions may fall within two distinct scenarios:

(i) the detection of a flow occurs on a per-domain basis and is treated locally according to each domain internal policies;

(ii) the detection of a flow triggers an explicit signaling process similar to the one mentioned for explicit AC.

The former case is, in general, applied in the context of adaptive TCP traffic [130]. This type of implicit AC will be restricted to domain QoS monitoring and SLS usage information, which means that neither specific flow's information nor measures from upstream domains are considered. Possible implicit reject actions at each domain are discarding of TCP SYN/SYN ACK packets or packet discarding based on flow accept/reject tables [130] (see also Section 3.3.6).

The latter case can be applied in the context of more demanding applications and services requiring per-domain and end-to-end service guarantees. In this case, the flow profile and QoS requirements for the explicit AC process have to be inferred from the flow type or high-level signaling protocols. This case will be treated in the same way as explicit AC.

5.3.2 End-to-end operation

The *end-to-end case* is viewed as a repetitive and cumulative process of admission control and available service computation[7] performed at ingress nodes (see Figure 5.5). At each domain, the ingress node decides if a flow can be accepted and, if so, the service metric values in the domain are added to the flow request to inform the downstream domain of the service available so far. Using the incoming and its own measures each domain performs AC. More precisely, verifying if each flow's QoS parameter target value can be satisfied involves considering the corresponding QoS parameter bound in the domain and the cumulative value computed so far. The way these values are handled depend on the type of parameter being controlled. For instance, delay parameters are addictive whereas loss ratio parameters are multiplicative. The last AC

[7]A cumulative or concatenation-based approach assumes that QoS parameters are estimated as average values, having independent distributions in different domains [81].

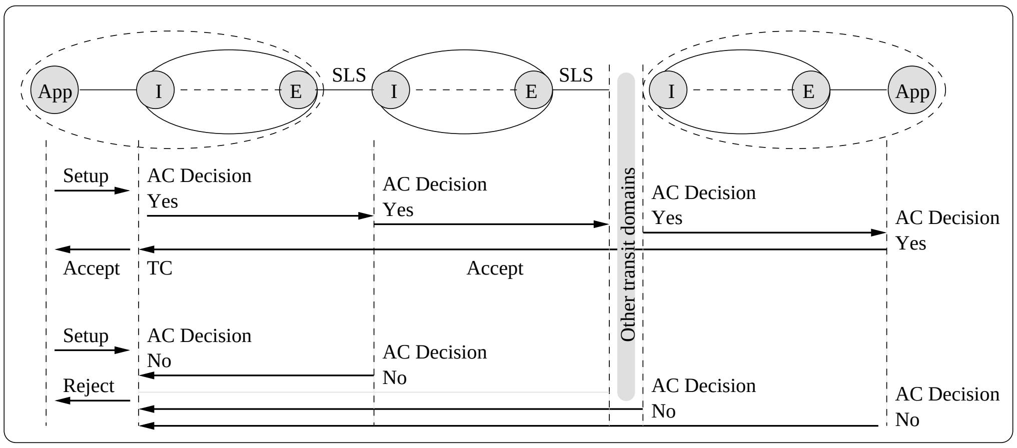


Figure 5.5: End-to-end AC operation

decision is made by the receiver in its own domain, which is viewed as a local admission. When a rejection occurs, the source is notified directly from the rejection point. This end-to-end solution leads to a generic and fluid AC model, which can be applied to source, destination and transit domains.

5.4 Specifying the AC model components

In order to specify the AC model and to provide a clear and detailed description of its operation in a multiclass and multidomain environment, the main network domain entities concerning multiservice AC, SLS and QoS management need to be formalized [11].

Taking into account the overview of the AC model operation described above, the main components of a network domain comprising multiple ingress and egress routers are specified regarding the provision of multiple services to customers (individuals or other domains). In such domain, the following entities are considered:

(i) service classes;

(ii) upstream SLSs;

(iii) downstream SLSs;

(iv) traffic flows.

Network resources are implicitly covered and controlled by edge-to-edge monitoring.

In this way, in the next sections, an intuitive and expressive notation is introduced to formalize these entities and to support the intra and interdomain AC criteria specification. When possible, the entities under specification use indexes based on the corresponding service class and involved ingress and egress nodes. As the AC model is class-based and operates edge-to-edge, this approach enriches the notation semantically, while keeping it intuitive. Appendix A provides a summary of the specified entities and their corresponding notation.

5.4.1 Service classes specification

Considering a multiclass domain D_x comprising N ingress nodes and M egress nodes, lets define $I^{D_x} = \{I_1, I_2, ..., I_N\}$ and $E^{D_x} = \{E_1, E_2, ..., E_M\}$ as the set of ingress and egress nodes, respectively[8]. For this domain, the set of supported service classes is represented as $SC^{D_x} = \{SC_1,\ SC_2, ...,\ SC_Y\}$. From a service management and provisioning point-of-view, the definition of a service class QoS levels includes identifying a set of QoS parameters under control and corresponding safety margins. Each parameter target value affected by this safety margin, will allow to establish a threshold for the parameter inside the domain. These QoS thresholds are used for triggering traffic control mechanisms such as AC, reducing the chance of QoS violation in the service class. Thus, for each class $SC_i \in SC^{D_x}$, the set of QoS parameters under control is defined as $P_{SC_i} = \{(P_{i,1}, \beta_{i,1}), ..., (P_{i,P}, \beta_{i,P})\}$ where each $P_{i,p} \in P_{SC_i}$ is the class parameter target value and $0 < \beta_{i,p} \leq 1$ is the parameter safety margin. Then, each parameter threshold is given by $T_{i,p} = \beta_{i,p} P_{i,p}$. The cardinality of this set depends on the QoS constraints of the class[9].

The service classes to be supported in domain D_x are closely related to the service levels negotiated with both upstream and downstream customers. In this context, for a class SC_i, the set of SLSs accepted in D_x coming from any upstream domain D_x^- is defined as $SLS_{SC_i}^{D_x^-} = \{SLS_{i,I_n} | I_n \in I^{D_x}\}$ and, in the same way, the set of SLSs negotiated with any downstream domain D_x^+ is defined as $SLS_{SC_i}^{D_x^+} = \{SLS_{i,E_m}^+ | E_m \in E^{D_x}\}$. Therefore, D_x is a service provider for D_x^- and a customer of D_x^+. Note that, SLS_{i,I_n} identifies a specific SLS accepted for SC_i with upstream domain D_x^-, connecting D_x through I_n, and SLS_{i,E_m}^+ identifies a specific SLS negotiated for SC_i with downstream domain D_x^+, accessible from D_x through E_m (see Figure 5.6)[10].

The case of flows entering D_x without pre-negotiated SLSs (usually dial-up users) is also covered, and the notation $\notin SLS$ is introduced for this purpose. The global rate share of these

[8]To simplify the notation, and without losing generality, each ingress or egress interface is treated as a virtually distinct ingress I_n or egress node E_m. Therefore, I^{D_x} and E^{D_x} include all ingress and egress interfaces to other

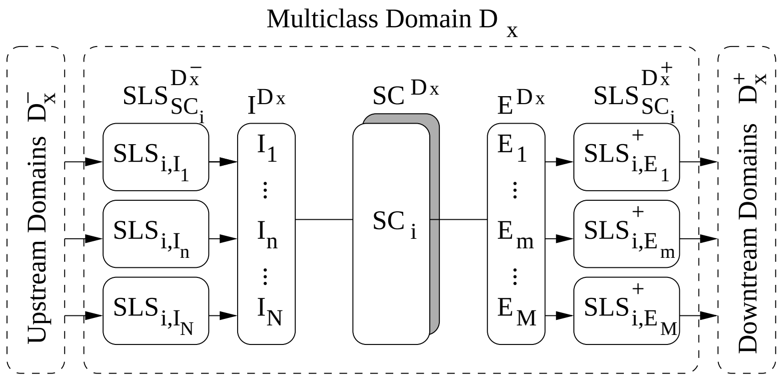


Figure 5.6: Domain main elements and notation

users is controlled by $R_{i,I_n}^{\notin SLS}$. Therefore, $R_{i,I_n}^{\notin SLS}$ is a rate-based parameter defined to limit traffic not sustained by a specific SLS, i.e., for flows $F_j \notin SLS_{i,I_n}$. This allows a better control of the rate share in D_x and SLS_{i,E_m}^+ utilization, while avoiding possible denial of service to flows $F_j \in SLS_{i,I_n}$.

When D_x acts as the source or destination domain, i.e., the end-systems are inside D_x, internal SLS_{i,I_n} and SLS_{i,E_m}^+ may also be defined in order to allow a generic AC criteria specification (see Section 5.5). However, this is not mandatory for the AC model operation.

5.4.2 Upstream SLSs specification

As stated in Section 2.2, the definition of SLSs, apart from being a key aspect for QoS provisioning, provides a valuable input for AC, in special, when admission spans multiple-domains. From an AC perspective, following the SLS template proposed in that section, an upstream SLS for

domains. An alternative notation identifying a specific interface k in a network node would be $I_{n,k}$ or $E_{m,k}$.

[9]Note that all (I_n, E_m) pairs within D_x share the same P_{SC_i} objectives. Defining QoS objectives per (I_n, E_m) can be easily accommodated turning P_{SC_i} into a $N * M$ matrix.

[10]In this specification, it is assumed that a specific upstream SLS has defined just one possible point of connection between domains D_x^- and D_x, which is I_n. When the scope of the SLS (see Section 5.4.2) defines more than one possible ingress interface, for instance (N:M), the SLS can be decomposed into N (1:M) SLSs, maintaining the above notation. Similarly, for a specific downstream SLS, a single E_m between domains D_x and D_x^+ is considered. When I_n provides access to more than one domain D_x^- (or individual customer), i.e., more than one upstream SLS for the same class may exist through I_n, one per client, an additional index would be required in order to identify each upstream SLS unambiguously (for instance $SLS_{i,I_n,s}$). The same would apply for E_m and corresponding downstream SLS notation. At this point, it is assumed that D_x negotiates just one SLS_{i,E_m}^+ with downstream domain D_x^+ for the service class SC_i. The same occurs between D_x^- and D_x regarding SLS_{i,I_n}.

Table 5.1: Common SLS_{i,I_n} elements

	Item	Notation	Example
1)	Scope	$SLS_{i,I_n} \rightarrow Scope$	$(I_n, E^{'})$
2)	Service ID	$SLS_{i,I_n} \rightarrow SC_{id}$	$DSCP$
3)	Traffic Profile	$SLS_{i,I_n} \rightarrow TrafficProfile$	$TB(R_{i,I_n}, b_{i,I_n})$
4)	Expected QoS	$SLS_{i,I_n} \rightarrow ExpectedQoS$	$IPTD_{i,I_n}, ipdv_{i,I_n}, IPLR_{i,I_n}$
5)	Validity	$SLS_{i,I_n} \rightarrow ServSched$	$[t_{i,I_n,0}, t_{i,I_n,f}]$

service class SC_i, i.e., SLS_{i,I_n}, should include elements such as those illustrated in Table 5.1[11]. In more detail:

1. $SLS_{i,I_n} \rightarrow Scope$ is specified as a pair $(I_n, E^{'})$ where the ingress node I_n is the access point of the upstream domain D_x^- to D_x and $E^{'} \subseteq E^{D_x}$ represents all possible egress nodes E_m providing access from D_x to D_x^+ for this SLS. At this point, the scope of $SLS_{i,I_n}$is limited to a single domain D_x, which is responsible for identifying $E^{'}$ according to the possible destination domains D_x^+ defined in the SLS_{i,I_n};

2. $SLS_{i,I_n} \rightarrow SC_{id}$ classifies and identifies the service type to be provided by D_x to packets belonging to SLS_{i,I_n}. The DSCP is a possible SC_{id} in Diffserv domains. Whenever a domain uses proprietary service identifiers, appropriate mapping is needed at domain boundaries;

3. $SLS_{i,I_n} \rightarrow TrafficProfile$ specifies the traffic aggregate characteristics of SLS_{i,I_n}, allowing to identify in or out-of-profile traffic. A policing algorithm is usually used to set the traffic profile and conditioning rules, which may include remarking or discarding traffic non-conforming with the defined SLS_{i,I_n}. For instance, when using a token bucket, the SLS traffic profile can be specified as $TB(R^{'}_{i,I_n}, b_{i,I_n})$ with mean rate $R^{'}_{i,I_n}$ and burst size b_{i,I_n}. Considering R_{i,I_n} as the aggregate rate established for SLS_{i,I_n} in the scope region (peak or mean), R_{i,I_n} can be expressed either as a global value or as a vector of rates $\vec{R}_{i,I_n} =< R_{i,(I_n,E_1)}, ..., R_{i,(I_n,E_m)} >$ depending on the scope of the SLS, i.e., taking all $E_m \in E'$. Handling a vector of rates may be particularly useful for transit domains which

[11]Two types of upstream SLS_{i,I_n} can be identified: (i) an individual SLS_{i,I_n} negotiated with a client/domain according to its specific needs; (ii) a collective SLS_{i,I_n} shared among several individual clients with similar contracts. Although these contracts are assumed individually, D_x controls collective SLS_{i,I_n} as a whole, receiving a treatment similar to the other type of SLS_{i,I_n}. A collective SLS might consist of clients having low-rate access contracts reaching D_x through, for instance, a virtual private or access network where each client subscribed rate is enforced.

want to pre-allocate specific resources for more demanding or high priority services[12]. When a single traffic profile for SLS_{i,I_n} is specified, $\vec{R}_{i,I_n}$ may be established following a D_x internal policy;

4. $SLS_{i,I_n} \rightarrow ExpectedQoS$ specifies the expected QoS parameters for SLS_{i,I_n}, represented by $P_{SLS_{i,I_n}} = \{P_{i,I_n,1}, ..., \ P_{i,I_n,P'}\}$, with $P_{SLS_{i,I_n}} \subseteq P_{SC_i}$. Note that, each QoS parameter $P_{i,I_n,p}$ value is bounded by the corresponding service class $P_{i,p}$, regardless the incoming I_n and accepted SLS_{i,I_n}. In other words, it is the QoS parameter target value for the class that bounds the corresponding SLS's expected QoS value. Depending on each parameter semantics, $P_{i,p}$ can either be an upper or lower bound. Embedding the expected SLS parameters values in the respective class parameter target values is of paramount importance as QoS and SLS control in the domain is clearly simplified. Examples of $P_{i,I_n,p}$ are $IPTD_{i,I_n}$, $ipdv_{i,I_n}$, $IPLR_{i,I_n}$;

5. $SLS_{i,I_n} \rightarrow ServSched$ determines the time interval $[t_{i,I_n,0}, t_{i,I_n,f}]$ in which the service is due to be scheduled, with $t_{i,I_n,0}$ expressing the SLS starting time and $t_{i,I_n,f}$ the SLS expiring time. This interval is recommended to be month-range [69] and/or time-slotted [66].

When considering the traffic profile as a vector of rates $\vec{R}_{i,I_n}$, an upstream SLS for service class SC_i can be defined as a matrix,

$$SLS_{i,I_n} = [SLS_{i,(I_n,E_1)}, ..., SLS_{i,(I_n,E_M)}] \tag{5.1}$$

where each $SLS_{i,(I_n,E_m)}$ element is null if $E_m \notin E'$, i.e., when E_m is outside the defined SLS scope. Considering this SLS_{i,I_n} definition and the set of upstream SLSs, i.e., $SLS_{SC_i}^{D_x^-}$, an ingress-to-egress matrix of accepted and active SLSs for a generic service class SC_i can be defined as

$$\Phi_{SC_i}^{SLS} = (\phi_{i,(n,m)}) \qquad\qquad \phi_{i,(n,m)} = SLS_{i,(I_n,E_m)} \tag{5.2}$$

An $SLS_{i,(I_n,E_m)}$ is effectively active whenever its negotiated scheduling period is valid, i.e., $t_{actual} \in [t_{i,I_n,0}, t_{i,I_n,f}]$. Therefore, when an element of $\Phi_{SC_i}^{SLS}$ is null, the corresponding SLS does not exist, is not yet active or has expired. $\Phi_{SC_i}^{SLS}$ allows to infer the expected traffic matrix

[12]This approach is considered in Geant IP Premium Service [69] where, for a limited number of well-known National Research and Education Networks (NRENs), SLS subscription allows specifying multiple traffic profiles depending on to which NREN an egress router provides access to.

for service class SC_i, which may then be used for current service provisioning in domain D_x[13]. When R_{i,I_n} is defined as a single and global rate value independently of each egress $E_m \in E'$, $\Phi^{SLS}_{SC_i} = (\phi_{i,n})$ where $\phi_{i,n} = SLS_{i,I_n}$.

5.4.3 Downstream SLSs specification

In a domain D_x, when defining and negotiating an SLS with a downstream domain D_x^+, i.e., an SLS^+_{i,E_m}, the contracted service from a particular egress node E_m should foresee the provision of adequate service levels taking into account all active SLSs going through egress E_m. From an E_m perspective, specifying a downstream SLS^+_{i,E_m} should follow the SLS template and notation introduced above for upstream SLSs, inserting the downstream identifier "$+$" and adapting the corresponding definitions accordingly. As an example, for a service class SC_i, R^+_{i,E_m}, $P^+_{i,E_m,p}$ and $[t^+_{i,E_m,0}, t^+_{i,E_m,f}]$ will represent the aggregated rate, the negotiated QoS parameter p and the service scheduling interval, respectively. In the same way, collecting $SLS^{D_x^+}_{SC_i}$ information an egress-based matrix can be defined,

$$\Phi^{SLS^+}_{SC_i} = (\phi^+_{i,m}) \qquad\qquad \phi^+_{i,m} = SLS^+_{i,E_m} \tag{5.3}$$

representing all accepted and active downstream SLSs. If an egress node E_m does not have a defined SLS^+ for class SC_i, $\phi^+_{i,m}$ is null. The negotiated traffic profile for $\forall SLS^+_{i,E_m} \in SLS^{D_x^+}_{SC_i}$ is given by $SLS^+_{i,E_m} \rightarrow TrafficProfile = \bigoplus_{k=1}^{N} \phi_{i,(k,m)}$, with the operator $\bigoplus$ denoting the aggregation of all accepted SLS_{i,I_n} in the domain for SC_i that may use the egress node E_m to leave domain D_x.

5.4.4 Flow specification

Depending on each application's ability for signaling its service requirements, traffic flows may undergo either implicit or explicit AC. For implicit AC, the relevant fields to consider include the source, destination and service class identifiers, i.e., Src_{id}, Dst_{id}, SC_{id}. For explicit AC, in addition to these fields, specifying a flow F_j includes defining the $TrafficProfile$, the required QoS parameters $ReqQoS$ and an optional $QoSTolerance$ factor. In addition, a specific field required for end-to-end AC operation is $AccQoS$; other optional fields, explained below, are I_{src}, SLS_{id} and D_{id}. In more detail, as for the SLS_{i,I_n} definition,

[13]In a medium or long-term service provisioning perspective, for forecasting the expected traffic, a more extended matrix including the set of expired and of accepted (but not yet active) SLSs may also be considered.

1. $F_j \rightarrow TrafficProfile$, identifying the flow's traffic profile, can be described by a token bucket $TB(r_j^{'}, b_j)$. The flow mean or peak rate r_j is taken according to the service type;

2. $F_j \rightarrow ReqQoS$, identifying the flow's QoS requirements (if any), can be defined associating a tolerance to each flow's parameter, i.e., defining a set of parameters $P_{F_j} = \{(P_{j,1}, \gamma_{j,1}), ..., (P_{j,P''}, \gamma_{j,P''})\}$, with $P_{F_j} \subseteq P_{SLS_{i,I_n}} \subseteq P_{SC_i}$. This subset inclusion also means that, each $P_{j,p}$ value must be bounded by the corresponding $P_{i,I_n,p}$ value (if applicable, i.e. if $F_j \in SLS_{i,I_n}$) which, in turn, must be bounded by the corresponding class target value $P_{i,p}$. The tolerance to $P_{j,p}$ degradation, expressed by $\gamma_{j,p}$, may be considered by the AC criteria;

3. $F_j \rightarrow AccQoS$ is used to accumulate QoS metric values in a multidomain end-to-end AC operation (see Section 5.5.3);

4. $F_j \rightarrow I_{src}$ is an optional field which allows to identify the source domain ingress node I_{src}. This is the only ingress node that may need to be self-identified when receiving AC response notification messages for per-flow TC configuration purposes. SLS and domain identifiers, $F_j \rightarrow SLS_{id}$ and $F_j \rightarrow D_{id}$, are also optional fields useful to handle interdomain authentication and authorization issues.

5.4.5 Monitoring and controlling per-class QoS metrics

As mentioned, the proposed service control model resorts to on-line measurements to obtain a systematic view of the network service levels and resource occupation. Thus, for service class SC_i and ingress node I_n, a dynamic ingress-egress service matrix used to control QoS levels and support AC decisions is defined as

$$\Psi_{SC_i}^{QoS} = (\psi_{i,(n,m)}) \tag{5.4}$$

Note that at each I_n, for each SC_i, this matrix has a single line $(1 * m)$, i.e., i and n are constants and m varies identifying the egress node E_m, corresponding to the measurements between the involved (I_n, E_m) pairs. Service data in the matrix $\Psi_{SC_i}^{QoS}$ is provided by egress nodes which send monitoring updates at each measurement time interval Δt_i. This data includes the class's QoS parameters measured from an (I_n, E_m) perspective, i.e., $\psi_{i,(n,m)} \rightarrow P_p = \tilde{P}_{i,(I_n,E_m),p}$. Using this measured data and corresponding class thresholds, a QoS status indicator defined as

$\psi_{i,(n,m)} \rightarrow AC\_Status_{\Delta t_i}$ is computed and then used by AC for determining if incoming traffic from I_n to E_m can be accepted in Δt_i (see QoS control rule in Section 5.5.2).

The measured traffic load of SLS_{i,I_n} and SLS^+_{i,E_m} (aggregate SLS utilization) measured at I_n and E_m, respectively, might be included in the corresponding matrices $\Phi^{SLS}_{SC_i}$ and $\Phi^{SLS+}_{SC_i}$ or, alternatively, stored with other QoS monitoring data in $\Psi^{QoS}_{SC_i}$. This latter option is considered more appropriate taking into account the short-term updating nature of this monitoring matrix, making it more suitable to maintain traffic load measures obtained at each Δt_i. When the measures are not egress dependent, e.g., a single value $\tilde{R}_{i,I_n}$ is measured, $\psi_{i,n}$ is used denoting that m assumes a “don’t care” status, avoiding redundant data in $\Psi^{QoS}_{SC_i}$. Examples of relevant edge-to-edge QoS parameters to be measured and the respective equations are defined in Table 6.3.

5.5 Specifying the AC criteria

The definition of an AC criterion involves establishing the rules which determine the acceptance or rejection of flows. In the proposed model, the service-dependent AC criteria are generically measurement-based controlling both the QoS levels in the domain and the utilization of existing SLSs (see Figure 5.4), which leads to the specification of two types of rules: (i) rate-based SLS control rules; (ii) QoS parameters control rules. The specification of these rules follows the notation introduced in Section 5.4.

5.5.1 Rate-based SLS control rules

For each ingress node $I_n \in I^{D_x}$ and each egress node $E_m \in E^{D_x}$ one or more SLSs can be in place. However, as mentioned earlier, for a specific service class SC_i within D_x, a single SLS is negotiated with an upstream D^-_x or downstream D^+_x domain. As each SLS_{i,I_n} and SLS^+_{i,E_m} have specified a negotiated rate, R_{i,I_n} and R^+_{i,E_m} respectively, a rate-based Measure-Sum (MS) algorithm can be applied to control SLSs utilization at each network edge node[14]. This algorithm

[14]Following the discussion on measurement-based algorithms performance (see Appendix C) and taking into consideration the trade-off between the results obtained by the Measure Sum (MS) algorithm in [99, 105, 208] and its semantics, easy to understand and apply, the MS algorithm is used to control the SLSs utilization at network edges. To enforce achieving a pre-defined QoS target performance in a CoS domain, this rule is complemented by a measurement-based QoS control rule, triggered by thresholds to the QoS controlled parameters of each service class (see Section 5.5.2). The evaluation of the AC criteria performed in Section 7.3 extends the performance results of the MS algorithm to an edge-to-edge multiservice test scenario, involving flows with distinct traffic characteristics and descriptors.

takes both rate estimates and the flow traffic description to verify if a new flow can be admitted, i.e., if it fits within the corresponding SLS.

Explicit AC

At each ingress node I_n, verifying if a new flow $F_j \in SLS_{i,I_n}$ can be admitted involves testing if the SLS_{i,I_n} can accommodate the new flow traffic profile, i.e.,

$$\tilde{R}_{i,(I_n,*)} + r_j \leq \beta_{i,I_n} R_{i,I_n} \tag{5.5}$$

In Eq. (5.5), $\tilde{R}_{i,(I_n,*)}$ is the current measured load or estimated rate of flows using SLS_{i,I_n}; r_j is the rate specified by the new flow F_j; β_{i,I_n} (with $0 < \beta_{i,I_n} \leq 1$) is a safety margin or utilization target defined for the negotiated rate R_{i,I_n} for SLS_{i,I_n}[15]. When R_{i,I_n} is viewed as a vector depending on a subset of egress nodes in the domain $(E' \subseteq E^{D_x})$, the following rule is applied,

$$\tilde{R}_{i,(I_n,E_m)} + r_j \leq \beta_{i,(I_n,E_m)} R_{i,(I_n,E_m)} \tag{5.6}$$

When the destination of flow F_j is outside D_x, verifying if the new flow can be admitted also involves testing if the downstream SLS^{+}_{i,E_m} can accommodate the new flow traffic profile, i.e.,

$$\tilde{R}^{+}_{i,(*,E_m)} + r_j \leq \beta^{+}_{i,E_m} R^{+}_{i,E_m} \tag{5.7}$$

In Eq. (5.7), $\tilde{R}^{+}_{i,(*,E_m)}$ is the current measured load or estimated rate of flows using SLS^{+}_{i,E_m}, considering all ingress-to-E_m estimated rates of flows going through E_m , i.e.,

$$\tilde{R}^{+}_{i,(*,Em)} = \sum_{k=1}^{N} \tilde{r}_{i,(I_k,E_m)} \tag{5.8}$$

r_j is the rate specified by the new flow F_j; β^{+}_{i,E_m} (with $0 < \beta^{+}_{i,E_m} \leq 1$) is the safety margin for the rate R^{+}_{i,E_m} defined for SLS^{+}_{i,E_m}. Recall that this safety margin determines the degree of overprovisioning for the corresponding SC_i. The value of β^{+}_{i,E_m} may result from high-level domain policies defined at service class level, instead of being defined at SLS level.

When D_x is a transit domain, verifying if the upstream SLS_{i,I_n} can accommodate the new flow profile (Eq. (5.5)) is optional. In fact, assuming that the upstream domain D^{-}_x controls

[15]In the MS equations presented in this section, $\beta_{i,*}$ is said to represent a safety margin or utilization target defined for the rate parameter $R_{i,*}$. More precisely, $\beta_{i,*} R_{i,*}$ represents a target rate which includes a safety margin given by $(1 - \beta_{i,*})$. $\beta_{i,*}$ represents then the utilization target and implicitly a safety margin. To simplify the notation and the description, $\beta_{i,*}$ is generically referred as a safety margin.

the corresponding downstream SLS traffic load through a process equivalent to the one ruled by Eq. (5.7), domain D_x can control SLS_{i,I_n} using a simple TC mechanism based on the negotiated traffic profile specification for the aggregate. In optimal conditions, R^+_{i,E_m} would be dimensioned in order to absorb all accepted $R_{i,(I_n,E_m)}$ without problem. This would also make Eq. (5.7) optional. However, one must consider that: (i) not all flows are supported by an SLS; (ii) when statistical multiplexing is considered, the dimensioning of R^+_{i,E_m} can be below $\sum_{k=1}^{N} R_{i,(I_k,E_m)}$. Moreover, $R_{i,(I_n,E_m)}$ may not be known in advance. For source and destination domains, unless internal SLS_{i,I_n} and SLS_{i,E_m} are defined, Eqs. (5.5) and (5.7) may not apply either. In particular for transit domains, when Eq. (5.5) determines a positive AC decision and Eq. (5.7) refuses the flow, SLS_{i,I_n} commitments have been violated.

The rate control rules for the admission of flows not sustained by an SLS, i.e., $F_j \notin SLS_{i,I_n}$, resort to Eq. (5.7) and the measured rate $\tilde{R}^{\notin SLS}_{i,I_n}$. This is controlled by an expression similar to Eq. (5.5), i.e.,

$$\tilde{R}^{\notin SLS}_{i,(I_n,*)} + r_j \leq \beta^{\notin}_{i,I_n} R^{\notin SLS}_{i,I_n} \tag{5.9}$$

Once again, when the rate $R^{\notin SLS}_{i,I_n}$ is specified depending on each E_m, a rule similar to Eq.(5.6) is applied.

Implicit AC

The equations defined above, which take into account both the rate estimates and the flow traffic profile, can be easily applied to implicit AC scenarios. For a service class SC_i under implicit AC, as flows are unable to describe r_j, the SLS control equations defined above become similar to the QoS control equation (Eq. (5.10)), considering $P_{i,p}$ as a rate-based parameter. Therefore, traffic flows are accepted or rejected implicitly according to the value of the variable $AC\_Status_{\Delta t_i}$ computed once in Δt_i. Additionally, a variable $Adm\_Flows_{\Delta t_i}$ may constrain the number of flows which can be implicitly accepted in Δt_i.

5.5.2 QoS parameters control rules

When controlling the QoS levels in a domain, the QoS parameters and corresponding thresholds can vary depending on each service class SC_i commitments, the statistical properties of the traffic and the safety margins.

At each ingress node I_n, the $AC\_Status_{\Delta t_i}$ variable, used to control the admission of new flows in the monitoring interval Δt_i, is updated after checking the controlled parameters $P_{i,p}$ of

SC_i against the corresponding pre-defined threshold $T_{i,p}$, i.e.,

$$\forall (P_{i,p}, \beta_{i,p}) \in P_{SC_i} : \tilde{P}_{i,p} \leq T_{i,p} \tag{5.10}$$

where $\tilde{P}_{i,p}$ represents the measured value of $P_{i,p}$ for Δt_i and $T_{i,p}$, as explained in Section 5.4.1, reflects a safety margin $\beta_{i,p}$ to the QoS parameter target value, i.e.,

$$T_{i,p} = \beta_{i,p} P_{i,p} \tag{5.11}$$

Eq. (5.10)[16] is not flow dependent, i.e., it is checked once during Δt_i to determine the variable $AC\_Status_{\Delta t_i}$, for each (I_n, E_m) pair. The $AC\_Status_{\Delta t_i}$ - `accept` - indicates that the measured QoS levels for SC_i are in conformance with the QoS objectives and, therefore, new flows can be accepted. The $AC\_Status_{\Delta t_i}$ - `reject` - indicates that no more flows should be accepted until the class recovers and restores the QoS target values. This will only be checked at Δt_{i+1}[17].

In practice, the QoS control rules are applied on an ingress-egress basis using monitoring data stored in the QoS matrix $\Psi^{QoS}_{SC_i}$ available at each I_n. Other possible scenarios for handling monitoring data are presented in Section 5.6.1.

5.5.3 End-to-end AC rules

Assuming a consistent mapping between the service classes in domains D_x^-, D_x and D_x^+, when AC is taken from an end-to-end perspective making an AC decision at ingress node I_n of domain D_x involves considering the following rule:

$$\forall P_{j,p} \in P_{F_j} : (\mathtt{op}_1\ (P_{j,p}^{acc^-}, P_{i,p}))\ \mathtt{op}_2\ (\gamma_{j,p} P_{j,p}) \tag{5.12}$$

where each flow requested QoS parameter $P_{j,p}$, allowing a tolerance factor $\gamma_{j,p}$, is checked against the cumulative value computed for the parameter when crossing previous domains, $P_{j,p}^{acc^-}$, affected by the corresponding target value of $P_{i,p}$[18] within domain D_x.

[16]While for most of the relevant QoS parameters a flow is accepted when Eq. 5.10 is satisfied, the $\leq$ operator can be different if the controlled parameter is, for instance, the available bandwidth.

[17]When the metric update scheme is also triggered by an excessive variation of metric value, more than one QoS Control check may occur during Δt_i.

[18]Note that $\tilde{P}_{i,p}$ could also be used in the cumulative process of metric computation instead of $P_{i,p}$. This option would lead to less stable AC decisions and end-to-end available service computation. Despite being more con-

Depending on each parameter semantics, $\mathtt{op}_1$ and $\mathtt{op}_2$ may express different operations, i.e., $\mathtt{op}_1 \in \{add \mid sub \mid max \mid min \mid mul \mid f^{spec}\}$ and $\mathtt{op}_2 \in \{\leq \mid < \mid \geq \mid > \mid =\}$. If the flow can be accepted in D_x, the new available service computation to be included in the flow request is given by

$$P_{j,p}^{acc} = \mathtt{op}_1\,(P_{j,p}^{acc^-}, P_{i,p}) \tag{5.13}$$

To clarify the use of Eq. (5.12) and Eq. (5.13), lets consider the following examples, where the type of the QoS parameter under control varies:

1. $P_{j,p}$ is a delay parameter - a positive AC decision occurs when $add(P_{j,p}^{acc^-}, P_{i,p}) \leq \gamma_{j,p} P_{j,p}$. When $\gamma_{j,p}$ is defined as a percentage of QoS degradation (tolerance) then the right side of this equation becomes $(1+\gamma_{j,p})P_{j,p}$;

2. $P_{j,p}$ is a loss ratio parameter - considering $0 \leq P_{j,p}, P_{i,p} \leq 1$, the computation of Eq. (5.12) and AC requires a specific multiplicative function, i.e., $\mathtt{op}_1 = f^{spec}$. Knowing that a sequence of individual nodes with loss ratio $IndLoss$ has a total loss ratio given by $TotalLoss = 1 - \prod(1 - IndLoss)$, the cumulative computation of $TotalLoss$ in domain D_x is given by[19]

   $$P_{j,p}^{acc} = 1 - ((1 - P_{j,p}^{acc^-})(1 - P_{i,p})) \tag{5.14}$$

   For very low values of $P_{j,p}^{acc^-}$ and $P_{i,p}$, Eq. (5.14) may be simplified, i.e., $P_{j,p}^{acc} \simeq P_{j,p}^{acc^-} + P_{i,p}$ and the multiplicative function ($\mathtt{op}_1 = f^{spec}$) can be changed to an additive function ($\mathtt{op}_1 = add$);

3. $P_{j,p}$ is a rate parameter - for rate-based parameters, taking the minimum rate ($\mathtt{op}_1 = min$) is common, and Eq. (5.13) can be used to carry the minimum available rate for SC_i across all the involved domains up to the destination.

servative, taking $P_{i,p}$, i.e., the class parameter target value, allows more robust, stable and reliable AC decisions. Once again, it should be noticed that a cumulative process for end-to-end QoS computation is consistent with the cascade approach pointed out in the SLSs business model definitions provided in Section 2.2. The cumulative QoS computation explored here at flow level can be extended to SLS level.

[19]Assuming that $1 - P_{j,p}^{acc^-}$ represents the traffic entering domain D_x and $P_{i,p}$ is the target loss ratio in D_x, the traffic leaving D_x is given by $(1 - P_{j,p}^{acc^-})(1 - P_{i,p})$. So the cumulative computation of loss ratio after crossing D_x is $1 - (1 - P_{j,p}^{acc^-})(1 - P_{i,p})$.

5.5.4 Additional remarks on the AC criteria

Apart from syntax differences between rate-based SLS rules (Eqs. (5.5) , (5.7) and (5.9)) and QoS control rule (Eq. (5.10)), they also target different contexts. While the former are checked for the admittance of each new flow, Eq. (5.10) is not flow dependent, i.e., it is checked once during Δt_i to determine the value of $AC\_Status_{\Delta t_i}$.

While for a service class SC_i with explicit AC, if F_j is accepted at I_n, the rate estimated variables can be updated in Δt_i according to r_j information[20], for a service class with implicit AC, if a F_j is accepted at I_n, as r_j is unknown, only the number of flows that can be accepted in Δt_i ($Adm\_Flows_{\Delta t_i}$) needs to be decremented by one (when applicable). In this context, Eqs.(5.5) , (5.7) and (5.9) only need to be computed once in Δt_i. This means that these equations follow indeed the syntax and semantics of the QoS control rules, and may also determine the value of $AC\_Status_{\Delta t_i}$. In this way, classes using implicit AC only deal with the variables $AC\_Status_{\Delta t_i}$ and $Adm\_Flows_{\Delta t_i}$. For service classes based on PHBs such as Lower Effort (LE) [64], where no SLSs rate and QoS target values are expected to be defined, SLS and QoS control may not apply.

Table 5.2: AC criteria summary

AC	F_j	Rate Control	QoS Control	E2E Control
Explicit	$\in SLS_{i,I_n}$	Eq. (5.5) and Eq. (5.7)	$AC\_Status_{\Delta t_i}$ (given by Eq. (5.10))	Eq. (5.12)
	$\notin SLS_{i,I_n}$	Eq. (5.9) and Eq. (5.7)		
Implicit	$\in SLS_{i,I_n}$	$AC\_Status_{\Delta t_i}$ and/or $Adm\_Flows_{\Delta t_i}$		n.a.
	$\notin SLS_{i,I_n}$	$AC\_Status_{\Delta t_i}$ and/or $Adm\_Flows_{\Delta t_i}$		

Table 5.2 summarizes the AC equations which support the AC decisions made in a domain D_x. As mentioned in Section 5.5.1, some of the rate equations are optional or do not apply, and in most of the cases, controlling rate can be reduced to R^+_{i,E_m} control (Eq. (5.7)). Figure 5.7 illustrates the AC criteria summary for the explicit AC case. An algorithmic description of the explicit or implicit AC decision process is provided in Appendix B.

[20]During Δt_i, only the rate-based measures $\tilde{R}^{\notin SLS}_{i,I_n}$, $\tilde{R}_{i,I_n}$ and $\tilde{R}^+_{i,E_m}$ can change as they are updated at each I_n according to r_j of a new admitted flow (if using explicit AC). Update rate estimations leads to a more conservative AC as the rates of new flows are considered in the traffic load estimation but the compensation effect of flows terminating during the same Δt_i is not taken into account. Keeping the rate estimation unchanged during Δt_i explores this compensation effect but may increase overacceptance levels. The impact of both situations in the performance of the AC criteria will be explored in Chapter 7.

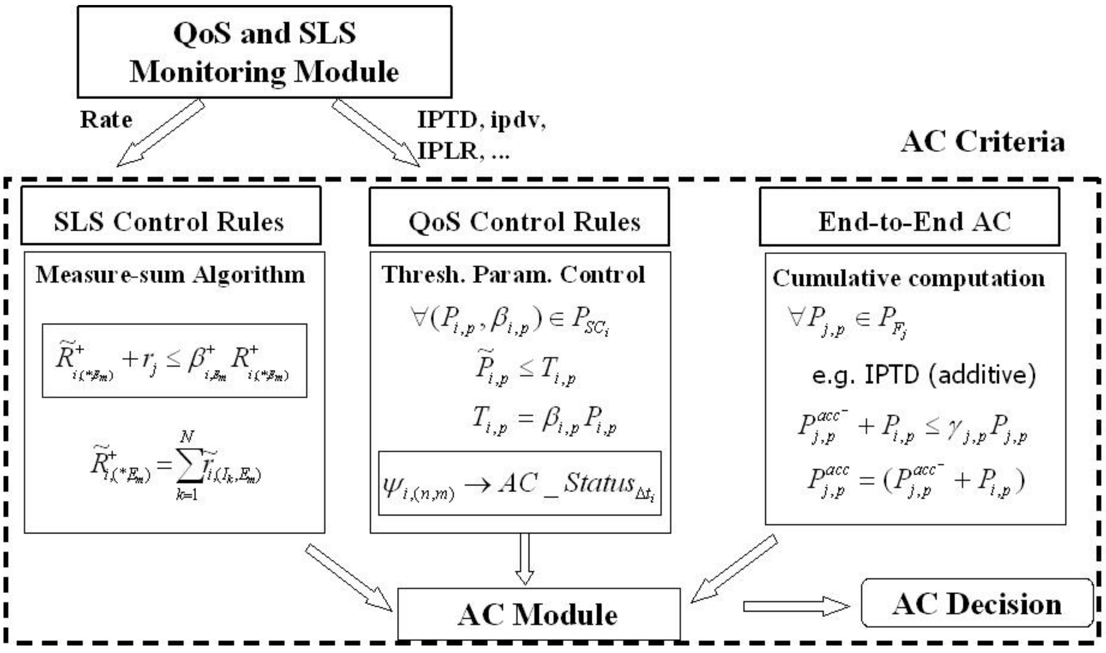


Figure 5.7: Explicit AC criteria summary

5.6 State information and signaling

When proposing or enhancing a traffic control mechanism, the state information and signaling involved need to be carefully assessed. In this way, this section provides a reflection on the characteristics (e.g., type, volume, location, dynamics) of state information and signaling required to support the operation of the proposed AC model. The discussion considers the model's operation described in Sections 5.3 and 5.5, and the distribution of AC and monitoring tasks in the domain represented in Figure 5.3[21].

As regards the state information, the discussion is focused essentially on the information required at network edges to support the distributed AC model, disregarding whether or not a central management entity is used to maintain a global view of network status, both in static and dynamic terms. It is important to note that, even if such entity is in place, the traffic control and service management relying on the proposed AC model has an entirely distributed nature. This means that edge nodes have enough autonomy to perform AC without resorting to any other decision point, at least during each time interval Δt_i. The same reasoning is valid if any

[21]When AC is decoupled between ingress and egress nodes or undertaken from the latter ones (which will be discussed in Sections 5.6.1 and 5.8.1), the state information at ingress and the signaling involved are simplified.

form of centralized policy-based management is in use. The following debate also abstracts implementation details such as the concrete data structures in which the state information is stored, despite sometimes referring to them as a matrix or a vector.

5.6.1 State information

Table 5.3 provides an encompassing view of the state information required, illustrating its location and update regularity (semi-static, dynamic). The volume of data involved is determined by the number of edge nodes, service classes, controlled parameters and negotiated SLSs, being reflected by the corresponding indexes according to the notation defined in Section 5.4. In this table, in each service matrix, the index in bold represents the variable index. As an example, for a SC_i, $\psi_{i,(n,\mathbf{m})}$ and $\psi_{i,(\mathbf{n},m)}$ represents a single line matrix at I_n and a single column matrix at E_m, respectively.

Table 5.3: State information at edge nodes

	Semi-static		Dynamic
	Service Class (SC_i)	Negot. SLSs ($\Phi^{SLS}_{SC_i}$ and $\Phi^{SLS^+}_{SC_i}$)	QoS and SLS Monit. ($\Psi^{QoS}_{SC_i}$)
Ingress I_n	QoS parameters and thresholds P_{SC_i}	SLS_{i,I_n}: $\phi_{i,n}$ or $\phi_{i,(n,\mathbf{m})}$	$\tilde{R}_{i,I_n}$: $\psi_{i,n}$ or $\psi_{i,(n,\mathbf{m})}$
			$\tilde{P}_{i,p}$: $\psi_{i,(n,\mathbf{m})}$
		SLS^+_{i,E_m}: $\phi^+_{i,\mathbf{m}}$	$\tilde{R}^+_{i,E_m}$: $\psi_{i,(n,\mathbf{m})}$
Egress E_m	QoS metrics P_{SC_i}	SLS^+_{i,E_m}: $\phi^+_{i,m}$	$\tilde{R}^+_{i,E_m}$: $\psi_{i,m}$
			$\tilde{P}_{i,p}$: $\psi_{i,(\mathbf{n},m)}$

The state information maintained at ingress nodes aims at supporting AC decisions according to the defined QoS and SLS control equations. Moreover, although not being specific for AC, ingress nodes may also require domain topological and routing information to determine the egress node that will be used, for instance, when accessing the downstream domain. The state information held at egress nodes is essentially related to monitoring domain QoS and downstream SLSs' utilization. Part of this data or the corresponding AC status indication ($AC\_Status_{\Delta t_i}$) may then be sent to ingress nodes. When upstream SLSs require monitoring specificities depending on egress nodes, these nodes may also include the relevant SLS_{i,I_n}data to satisfy those specificities. In addition to the state information included in Table 5.3 and topological data, other relevant data to maintain on a service class basis is the policies to be applied in the domain as regards, for instance, resource allocation and usage (e.g., bandwidth sharing, authorization and authentication information).

The state information illustrated in Table 5.3 can be considerably reduced giving that:

- from the semi-static information about negotiated SLS_{i,I_n} and SLS^{+}_{i,E_m}, only the relevant fields for AC and monitoring need to be considered at ingress and egress nodes, respectively. As far as AC is concerned, in addition to information for classification and service scope assessment, the defined rates $R_{i,I_n}$and R^{+}_{i,E_m} are the most relevant variables to be maintained and controlled at ingress nodes. As mentioned before, the negotiated QoS parameters are bounded and controlled at service class level;

- $SLS^{+}_{i,E_m}$and $\tilde{R}^{+}_{i,E_m}$data at ingress nodes (presented in dark gray in the table) could be avoided if AC is decoupled between I_n and E_m, regarding rate-based SLS control rules. In fact, as SLS_{i,I_n} is related to I_n and SLS^{+}_{i,E_m} to E_m, Eq. (5.5) could be evaluated at I_n and Eq. (5.7) evaluated at E_m. Being conceptually correct, this decoupling process reduces the state information required at ingress nodes and simplifies the control of concurrent AC (see Section *5.8.1*);

- $\tilde{P}_{i,p}$ monitoring data (presented in light gray in the table), provided by egress to ingress nodes, is used to assess the domain's QoS status in Δt_i ($\psi_{i,(n,m)} \rightarrow AC\_Status_{\Delta t_i}$) based on QoS control rules (Eq. 5.10). To avoid a full dissemination of QoS measures and to decrease the amount of state at ingress nodes, egress nodes could compute $\psi_{i,(n,m)} \rightarrow AC\_Status_{\Delta t_i}$ passing it to the corresponding ingress I_n. This means that each I_n would perform AC without knowing the concrete metric values. This solution avoids the replication of monitoring data, however, when QoS measures are also available at I_n handling bidirectional AC is simplified (see details in Section 8.4) . In the limit, QoS control rules and accumulated QoS verification (Eq. 5.10 and Eq. 5.12) could also be transferred to E_m. This would avoid both metric dissemination from E_m to I_n and topological information at I_n for E_m identification[22]. However, this solution requires that each flow conveys an identifier of the involved I_n so that each E_m is able to check the corresponding $\psi_{i,(n,m)} \rightarrow AC\_Status_{\Delta t_i}$. These two approaches for QoS control at egress nodes involve bringing the service class QoS controlling information, i.e, $(P_{i,p}, \beta_{i,p}) \in P_{SC_i}$, into each E_m.

Having discussed these topics, the decision of decoupling AC decisions between I_n and E_m should also consider the additional computational burden of performing AC at E_m, as new flows'

[22]In addition, when the flow destination is not completely specified, it may be difficult to determine at I_n which E_m will be used.

identification and AC processing are required in addition to monitoring. Maintaining AC at I_n and monitoring at E_m is a solution that allows to balance the computational overhead of monitoring and AC tasks. Thus, in the ongoing study, AC is performed at I_n and monitoring at E_m. Studying the impact of the remaining pointed solutions on AC model performance was left for further study. Finally, it is important to note that, the control rules defined in the AC criteria can be applied irrespectively of the degree of AC decoupling between edge nodes. This means that they can be applied at ingress or egress nodes according to the location of the state information, stressing the AC model flexibility.

5.6.2 AC and monitoring signaling

Signaling is here discussed at two levels. At one level, intrinsic to explicit AC, signaling is used by applications to express flows' traffic profile and QoS requirements. The AC model takes advantage of this signaling process to propagate cumulative QoS indication across multiple domains. Recall that the AC model does not intend to use this signaling process to allocate resources or maintain per-flow state information, instead, it allows each domain to decide upon flow admittance and, simultaneously, conveying the expectable QoS along the path toward destination. For this purpose, signaling must include:

- a service request primitive able to specify traffic profile and QoS requirements, and to gather cumulative QoS information;
- a service response primitive reporting service acceptance or rejection notification.

Considering an optional refreshing primitive for evaluating the previously assessed and accepted QoS conditions, keeping also track of the edge nodes in the path would allow to detect major routing changes, i.e., changes in the traversed domains and QoS deviations[23].

Proposing or developing a specific signaling protocol is outside the scope of this work and somehow unnecessary. Existing signaling protocols can be used or adapted. For instance, RSVP

[23]There is no guarantee that the path used for the flow data remains the same used for the flow request. In particular for intradomain route changes, this may not be problematic providing that the new path maintains the same QoS characteristics. In fact, the new metrics will reflect the load changes and AC at edges will act accordingly. Interdomain path changes, involving other crossed domains, are a particular challenge as the new route may represent a clear change in the end-to-end available service. The problem is simplified as no per-flow state is kept, thus less state information updates are needed, and interdomain routes tend to be more stable, but degradation may still occur.

To cope with these possible causes of QoS degradation, notification/feedback mechanisms to allow fast re-establishing or renegotiating of services/SLSs under the new conditions may be required. These topics are discussed in Section 8.4 as future work.

supports detailed flow specification, allows registering the QoS along the path and the path itself and, as a soft-state protocol, has a built-in refreshing mechanism. Nevertheless, in the context of the present work, RSVP messages only need to be processed at ingress nodes, and effective resource reservations, per-node and per-flow state information or symmetric response paths are dispensable.

This reasoning is sustained by the principle that the AC model is integrally based on on-line monitoring and service-oriented state information, where SLSs traffic profiles are the granularity of "reservations" within each domain. To follow these directions, when a domain D_x decides upon a new flow request positively, the rate of the incoming flow should be immediately accounted for the corresponding SLSs rate measurements until it can be sensed in following measurements intervals ($\Delta t_{i+1,\ldots}$). Counting on the new flow before end-to-end admission is completed avoids symmetric paths for effective reservations but may lead to rate overestimation in D_x. In fact, when a downstream domain D_x^+ rejects the flow, the updates on rate measures in upstream domains become incorrect. However, the self-corrective nature of systematic monitoring will adjust those measures accordingly. This "pre-reservation" principle is in-line with the model underlying idea of resorting to overprovisioning to relax AC and increase resilience to QoS degradation.

A sender-initiated approach where the signaling messages do not need to follow the entire path to destination and keep track of the way back is, in this way, more suitable than a receiver-oriented approach such as RSVP. More recently, the functionality and versatility of signaling protocols within NSIS framework [135], in special, the sender-initiated path-coupled case where signaling messages are routed and processed only at specific nodes in the data path may be particularly suitable to support the AC model operation.

At other level, in the context of network monitoring, signaling is required to disseminate edge-to-edge QoS measures and the SLSs occupancy in the domain. In this work, the metrics are evaluated and propagated periodically each time interval Δt_i. Metrics' dissemination may also be triggered when a QoS metric, its variation or the SLS utilization exceed a threshold. This signaling process should include mechanisms to increase the monitoring resilience to lost monitoring updates, similarly to routing protocols. As regards implementation, the signaling process itself may rely on capabilities of existing protocols, such as ICMP, to propagate QoS monitoring information from egress to ingress nodes. The use of alternative ways of metrics computation and dissemination, including the use of multicast IP to achieve a more efficient distribution, is left for future work (see Section 8.4).

5.7 Model strengths

Having detailed the proposed AC model along this chapter, this section highlights the most important features of the model, reflecting also the fulfillment of the initial goals. Conceptually, some of the features represent an added value facing other current AC proposals.

5.7.1 Model major key points

In summary, the major key points identified are as follows:

(i) only edge nodes are involved, i.e., the network core is kept unchanged and treated as a black box. This provides a convenient level of abstraction and independence from network core complexity and heterogeneity;

(ii) the state information is service and (I_n, E_m) based which, apart from leading to reduced state information, is particularly suitable for SLS auditing. Per-flow state information is only kept at the source domain ingress router for TC (when applicable), while other downstream domains may maintain TC based on the SLS aggregated traffic profile, as usual;

(iii) the control of the SLSs negotiated QoS parameters is embedded in the QoS control of the corresponding service classes, reducing the amount of SLSs dynamic state information and control overhead. This important inclusion rule also applies to the control of the flows' expected QoS;

(iv) the signaling process for intra and interdomain operation is simple, horizontal and fluid. The flow AC request is used both for per-domain AC and for end-to-end available service computation along the data path, and no soft/hard state behavior and symmetric routing paths are imposed;

(v) the systematic use of on-line monitoring for traffic load and QoS metrics' estimation in a per-class basis, while allowing an adaptive service management, avoids per-application intrusive traffic to obtain measures and reduces AC latency as measures are available on-line. Furthermore, systematic measurements have an intrinsic auto-corrective nature, allowing to detect short or long-term traffic fluctuations depending on the measurement time unit or interval, and implicitly take into account the effect of cross-traffic and other internally generated traffic (e.g., routing, management, multicast traffic);

(vi) different service types, QoS parameters and SLSs can be controlled simultaneously in a distributed and simple fashion. Note that, usually, controlling QoS and SLSs is only covered in centralized and "heavier" AC approaches;

(vii) the AC model provides enough flexibility to accommodate technological, service and application evolution. Important aspects contributing for the model's flexibility are: (i) the service-dependent nature of AC rules and adjustable parameterization; (ii) the ability to be decoupled between ingress and egress nodes; (iii) the conceptual modular independence between AC and monitoring tasks, which increases their ability to integrate new developments and improvements.

5.7.2 Fulfillment of initial goals

Having in mind the initial goals identified in Section 5.1 as regards achieving an encompassing and lightweight service-dependent AC strategy, the proposed AC model fulfills those goals as the following characteristics are verified:

- *multiservice* - depending on the characteristics of each service class, AC decisions are made implicitly or explicitly resorting to a service-oriented AC criteria which involve AC equations, safety margins, QoS parameters and thresholds adjusted to each class characteristics. The measurement methodologies and time granularity used in the measurement process can also be service-oriented and defined to achieve different accuracy levels. The AC model allows to define more or less relaxed AC criteria and safety margins depending on the service level guarantee to be provided and on the intrinsic traffic characteristics of each service class. All these configurable aspects of the AC criteria also increase its ability to accommodate new service classes defined according to the requirements of emergent applications and services;

- *multidomain* - the AC model can be deployed in a single domain as well as it may span multiple domains involving, eventually, distinct strategies and technologies in the provision of services with differentiated QoS. Moreover, the simple and systematic interdomain approach proposed, illustrated in Figures 5.4 and 5.5, does not impair the model to be adjusted to specific service policies and other particularities of each domain, increasing its flexibility both intradomain and end-to-end;

- *low overhead of the control strategy* - the AC model, relying on edge-to-edge on-line QoS monitoring, avoids extra control mechanisms in the network core and simplifies the network control plane. In fact, AC and monitoring are the only new tasks accomplished at edge nodes. Note that, controlling SLSs at service class level also simplifies the underlying control task. Apart from the required QoS and SLS monitoring state information maintained at network boundaries, which is also relevant to assist other network control and management tasks than AC, the amount of additional state information is minimized as no individual or aggregated flow state is kept in the core and edge nodes. Despite handling individual flows, edge nodes only keep aggregated information at service/SLS level. Moreover, the model does not imply the use of specific intra and interdomain signaling, e.g., in the explicit AC case, the flow AC request may be used for end-to-end signaling. As there is no per-flow state information maintained about individual reservations, the usual signaling refreshment/teardown process is avoided. All these aspects contribute positively for reducing the overhead of the control strategy and for increasing the model ability to scale;

- *easy of integration and deployment* - the AC model does not require particular changes to each domain underlying a service class model. For instance, in Diffserv domains, both PHBs and PDBs can follow IETF recommendations and be deployed as recommended. The required changes are at the service control level performed at edge nodes regarding AC and monitoring tasks. As mentioned, the network core is kept unchanged and, as it is viewed as a black box, different internal strategies and mechanisms for service implementation and generic network operation can be accommodated. In this way, from the end-to-end perspective, the model does not force the involved domain to adopt an uniform technological solution. This flexibility along with the above properties facilitate the integration and deployment of the model in IP networks;

- *efficiency* - although assessing the efficiency of the model is matter of study in Chapter 7, it will be shown that the proposed AC solution provides a good compromise between an efficient use of network resources and the service levels provided, even for demanding traffic classes.

5.7.3 Comparison with other measurement-based AC approaches

Although measurement or monitoring-based AC is not a new concept, the way: (i) AC criteria and monitoring information are proposed and articulated for controlling QoS and SLSs; (ii) it is extended to multiservice environments; (iii) end-to-end AC and available service computation is accomplished, are novel contributions. A comparative study of the conceptual model with other measurement-based AC approaches is justified to further highlight its characteristics.

As debated in Section 3.3.5, classical MBAC solutions perform flow AC in all the nodes along the path and focus mainly on assessing accurate estimates of each node or class load and on defining efficient AC decision algorithms. Thus, a solution to perform flow AC intradomain and end-to-end using this approach will involve AC, state information and changes in all network nodes, which need to implement, preferably, an uniform or consistent AC criteria. In practice, this is difficult to achieve and fails several of the initial defined goals. Moreover, the predictability and service guarantees achieved [106] are not adequate to support service classes requiring strict guarantees.

Although MBAC/EMBAC approaches do not offer deterministic guarantees, the proposed model design, while being measurement-based, has been oriented to CoS domains where different service level guarantees need to be fulfilled. As mentioned, through systematic control of each service class QoS parameters upper bounds and SLSs utilization levels, and through properly defined safety margins reflecting controlled levels of overprovisioning, the aim is to apply the simplicity and flexibility aspects of measurement-based solutions to the control of multiple service classes, assuring, if possible, QoS requirements of more demanding services.

EMBAC solutions are more closely related to the proposed model design as they only involve edge nodes or end-systems and have an edge-to-edge or end-to-end nature. In active EMBAC strategies, the end-to-end approach is even simpler giving that interdomain communication is not needed, the control tasks at edge routers are reduced or inexistent and no particular changes in the network are required. Despite the simplicity of the process, probing traffic is injected in the network in a per-application basis and the initial latency of the probing process can be significant. In addition, stealing and thrashing regimes may occur [106].

As mentioned before, in the proposed model, the probing traffic associated with active measurement methodologies (when used) is injected in a per-class basis, which reduces overhead and allows a tighter control of intrusive traffic. The initial latency is also reduced as the metrics computed for AC are available for on-line decisions since the beginning of the corresponding Δt_i. Moreover, the stability, predictability and security of the provided services are improved as the AC decision process is left for each domain according to the monitoring QoS levels and SLSs commitments. The reliability of the AC decision and of the information about the expected QoS conveyed up to the destination is also improved as QoS parameter thresholds are properly controlled in each domain, instead of resulting from an instantaneous and less predictable view of the network status. In addition, and particularly in CoS networks, when the probing process and the AC decision are left to end-systems, other control mechanisms need to be implemented to rule the amount of probing traffic injected in the network simultaneously and to control sources not well-behaved[24].

Although both the present AC proposal and other EMBAC approaches target the problem of flow AC and end-to-end operation, comparing them just based on these aspects is rather limited. In fact, the proposed model controls relevant management aspects of multiservice networks in a per-domain basis, such as domain QoS levels, SLSs usage and auditing. The same considerations can be drawn when comparing the AC model with the edge-to-edge AC proposal based on aggregate traffic envelopes [122, 123]. Although both solutions assess the available service edge-to-edge to make an AC decision, [122, 123] involve a proprietary monitoring approach [147], do not address SLS control and do not provide a feasible and scalable end-to-end AC. The main advantages and limitations of other AC solutions have been pointed out in Section 3.4.

5.8 Major hurdles and solutions

A distributed edge-to-edge AC model based on monitoring, although having the advantages expressed in the previous section, poses several hurdles that need to be faced.

First of all, as an edge-to-edge approach, the AC model overhead is closely related to the number of ingress and egress nodes, i.e., the cardinality of I^{D_x} and E^{D_x}. This overhead is mainly due to handling per-service ingress-to-egress monitoring and related state information (see a more detailed discussion in Section 4.4). For improving monitoring scalability, SLS QoS control is embedded in the service class control and efficient multipurpose probing patterns are under research. In addition, when considering the end-to-end operation, splitting or bringing monitoring and AC granularity to the domain level reduces the problem dimension in the same way as, for instance, OSPF routing and MPLS consider areas or regions to reduce complexity and increase their ability to scale.

[24]As mentioned in Section 3.3.5, when several sources send probing traffic simultaneously, problems caused by probes stealing bandwidth from established flows and denial of service situations (trashing regime) may occur. In CoS networks, especially when probing is carried out in-band, excessive probing may cause degradation of each class real traffic performance and interference/stealing between classes. Sources that send excessive probing traffic or make positive AC decisions even when the metrics point out in opposite direction are examples of sources not well-behaved.

Edge-to-edge monitoring also launches additional challenges to parameter estimation and control. For instance, controlling the available bandwidth or capacity in a single link or node-by-node is a fairly simple process, however, controlling it edge-to-edge is not straightforward as the available bandwidth, capacity or network bottlenecks vary dynamically over time[25]. When the network core is hidden from measurements, identifying a specific congestion node or link responsible for degrading QoS metrics is also difficult to achieve. For controlling the network core performance, internal strategies, for instance, based on SNMP or on QoS-aware routing techniques, should be implemented to complement the edge-to-edge control. Although the AC model is independent of those strategies, the more efficient they are, the better the edge-to-edge QoS is.

Secondly, when AC is carried out at ingress nodes based on the flow's specified destination, topological and routing information for egress identification is needed. Moreover, when flows are not completely specified, for instance, the end-system destination is unknown (e.g., multicast traffic), E_m selection poses additional challenges. The simplest solution to avoid the dependence on topology-aware routing protocols and to deal with flow's incomplete information is to perform AC at egress nodes, which can be easily attained in the proposed model. Within a domain, the presence of multiple active routes and load balancing between a (I_n, E_m) pair does not pose particular difficulties to the AC model;

Thirdly, distributed AC may involve multiple ingress routers making concurrent AC decisions. Therefore, dealing with concurrency is a key aspect as otherwise over or false acceptance may occur. This problem can be reduced resorting to the definition of per-service safety margins to absorb load fluctuations, complemented by more elaborated solutions to limit simultaneous AC decisions. Due to the relevance of this topic, Section 5.8.1 is entirely centered on the problematic of handling concurrent AC.

An additional aspect of concern is how to foresee the impact a new flow acceptance will have on the existing network resources and current QoS measurements. In order to keep the AC model simple, the impact of new flows is accommodated within the rate-based control rules by defining overprovisioning levels, and also by defining and tuning proper safety margins for the QoS parameters under control.

As regards the model implementation, several aspects of the monitoring process and of the AC criteria may affect the effectiveness and efficiency of the proposed solution. Both the peri-

[25] A discussion on methodologies and tools for estimating the path capacity and available bandwidth is provided in [179, 103, 81] and Section 4.3.1.

odicity of measurements and corresponding updates assume particular relevance. Besides their impact on monitoring overhead due to intrusion, state information and metrics computation effort, they determine the validity of information used in AC. According to [99], the length of the measurement intervals and the way new flows are treated affect significantly the performance of MBAC algorithms (see details in Appendix C). A discussion on possible solutions for measures update has been carried out in Sections 5.6.2 and 8.4. The impact of the measurement time interval is evaluated in Section 7.3.7. As regards the AC criteria, assessing the adequacy of AC equations and tuning the corresponding thresholds and safety margins for each service type according to the service level guarantees to provide are important aspects to test. The tuning and performance evaluation of the monitoring process and the AC criteria are covered in Chapter 7.

Other aspects to study related to AC being monitoring-based include: (i) *parameter mapping* - dealing with qualitative parameters (of service classes, SLSs or traffic flows) and mapping those parameters into quantitative parameters for service class control [75, 18]; SLS metrics also need to be mapped into perceptible parameters both at network and at application levels [81, 65]; (ii) *load forecasting* - monitoring-based AC approaches also make difficult the forecast of future network loads and the processing of AC requests referring to a future time scheduling. When the estimation of future loads is required, the state information of accepted SLSs for the corresponding time period and historical data is the only information available to sustain an AC decision; (iii) *fairness of the AC decision* - facing the usual tendency of MBAC algorithms in favoring small flows or flows that traverse small paths [209], defining a fairness criterion and evaluate and enhance AC policies to fulfill the established criterion are relevant topics to study. A preliminary study on the fairness of the proposed AC model is provided in Section 7.3.6.

Broader topics left for future research (see discussion in Section 8.4) include handling: (i) policy-based management and security issues; (ii) dynamic negotiation of SLSs and SLS AC; (iii) bi-directional AC; (iv) multicast and composite applications; (v) route change; (vi) multipath options at domains boundaries; (vii) mobility.

5.8.1 Handling concurrency

A distributed AC model may involve multiple ingress routers making concurrent AC decisions. Therefore, dealing with concurrency is a key aspect to avoid over or false acceptance. In fact, within a measurement time interval Δt_i, each ingress node I_n makes AC decisions based on measures estimated for the interval, without knowing the contribution of other ingress nodes to the metrics variation until Δt_{i+1}, i.e., when the next measuring update takes place[26].

The presence of concurrency affects both the measured utilization of the rate related variables (e.g., $\tilde{R}^+_{i,E_m}$) shared among ingress nodes and the QoS measures. Note that, although these QoS measures reflect the available service between each (I_n, E_m) pair, the links in the corresponding path may carry traffic resulting from a different pair of nodes. Therefore, the acceptance decisions at any other ingress node $I_{n'} \neq I_n$ may affect the measured QoS for a specific (I_n, E_m) pair. The problem of mis-acceptance within each service class can be reduced resorting to larger safety margins (e.g., β^+_{i,E_m}, $\beta_{i,p}$) to absorb the effect of traffic load fluctuations resulting both from the inherent statistical properties of traffic and from concurrent AC. Here, to reduce or solve the negative effects of concurrent AC might have on service offering, more elaborated, not mutually exclusive, solutions are explored and debated such as:

(i) the definition of a concurrency index based on the number of concurrent ingress nodes, affecting explicitly the rate control rules;

(ii) a token-based system to rule and limit the number of simultaneous AC decisions;

(iii) a rate-based credit system to control each I_n admission capacity.

The following topics explore these scenarios regarding the control of SLS^+_{i,E_m} utilization [15].

Initial AC scenario

In the case of explicit AC, it is considered that satisfying the inequality $\tilde{R}^+_{i,(*,E_m)} + r_j \leq \beta^+_{i,E_m} R^+_{i,E_m}$ determines a positive AC decision. When a new flow acceptance occurs, $\tilde{R}^+_{i,(*,E_m)}$ can be updated by considering r_j at the corresponding I_n, assuring that I_n does not accept more traffic than the estimated available rate for SLS^+_{i,E_m} during Δt_i. However, assuming that other concurrent ingress nodes are in place, the total new load is temporarily unknown and the available rate at SLS^+_{i,E_m} may be exceeded.

Concurrency index

Considering $\ddot{I}$ the set of concurrent ingress nodes sharing a common SLS^+_{i,E_m}, the estimation of SLS^+_{i,E_m} available rate for Δt_i can be protected by a concurrency index χ_{i,E_m}, which depends on

[26]In order to maintain simplicity, reduce overhead and latency associated with the exchange of control information, during Δt_i each I_n only knows the initial measures provided by each E_m for that time interval and its own contribution for the rate metric variation.

the cardinality of $\ddot{I}$, i.e., $|\ddot{I}|$. In this way, explicit flow AC is ruled by

$$r_j \leq \frac{\beta^{+}_{i,E_m} R^{+}_{i,E_m} - \tilde{R}^{+}_{i,(*,E_m)}}{\chi_{i,E_m}} \tag{5.15}$$

where $\beta_{i,E_m} R^{+}_{i,E_m} - \tilde{R}^{+}_{i,(*,E_m)}$ represents the estimated available rate of SLS^{+}_{i,E_m} to be shared among all concurrent ingress nodes. In the case of implicit AC, a similar use of χ_{i,E_m} can be applied.

Token-based system

Other possible solution to control the number of concurrent ingress nodes performing AC decisions may follow a token-based system, where the level of concurrency allowed is determined by the number of tokens available. In this system, only ingress nodes holding a token can accept new flows in Δt_i. At the limit, when a single token is available in the system, no concurrency is allowed. Nevertheless, if during Δt_i the tokens pass through several ingress nodes, the SLS^{+}_{i,E_m} utilization can change without common knowledge of all concurrent nodes ($\ddot{I}$). Consequently, overacceptance may still occur. To cope with this, tokens can be used to carry SLS^{+}_{i,E_m} updates. If the token assignment remains unchanged during Δt_i, this time interval needs to be carefully defined as it influences directly the domain QoS stability and load balancing, and the AC latency at ingress nodes without tokens.

Apart from the conceptual simplicity of a token-based model to control concurrency, this method reduces the problem but does not solve it completely. Additionally, the signaling required for token exchange among ingress nodes and the time required for I_n to get a token, which depends on the number of available tokens and the number of concurrent nodes $|\ddot{I}|$, may be prohibitive.

Rate-based credit system

To reduce the underlying drawbacks of a token-based system, the strategic view an egress node may have of the aggregate measured rate $\tilde{r}_{i,(I_n,E_m)}$ can be used to implement a rate-based credit system to control the bandwidth usage of ingress nodes and, implicitly, concurrency.

Following the defined AC model strategy, in the proposed rate-based credit system, the monitoring information obtained at egress node E_m is used to control the amount of credits assigned to I_n, from an (I_n, E_m) and service class SC_i perspective. Each egress E_m manages a pool of unused credits in order to distribute spare resources (bandwidth) dynamically as a complement to a static credit assignment initially defined, considering the ingress nodes grouped into distinct topological areas. The amount of available credits to be shared by ingress nodes which want to reach a specific egress E_m, therefore controlled by this one, should consider: (i) the network topology, the underlying bottleneck capacity[27] and core multiplexing effects; (ii) the bandwidth sharing policies among classes [54]; (iii) the accepted SLS_{i,I_n} and the corresponding expected traffic matrix Φ_{SCi}^{SLS}; (iv) the SLS_{i,E_m}^{+} negotiated rate or the capacity allocated at E_m for SC_i; (v) a safety margin of unused credits at each I_n to assure that I_n has a controlled autonomy to make acceptance decisions during Δt_i.

At each Δt_i, ingress nodes may receive new credits using the QoS metric dissemination process. When an egress node E_m provides new measures to an ingress node I_n, it can distribute new credits too, i.e., no specific or additional control messages are needed (see Figure 5.8). This strategy avoids several drawbacks of the solution proposed in [54], such as horizontal sharing of credits, use of specific signaling between ingress nodes and holding to many unused resources at each I_n.

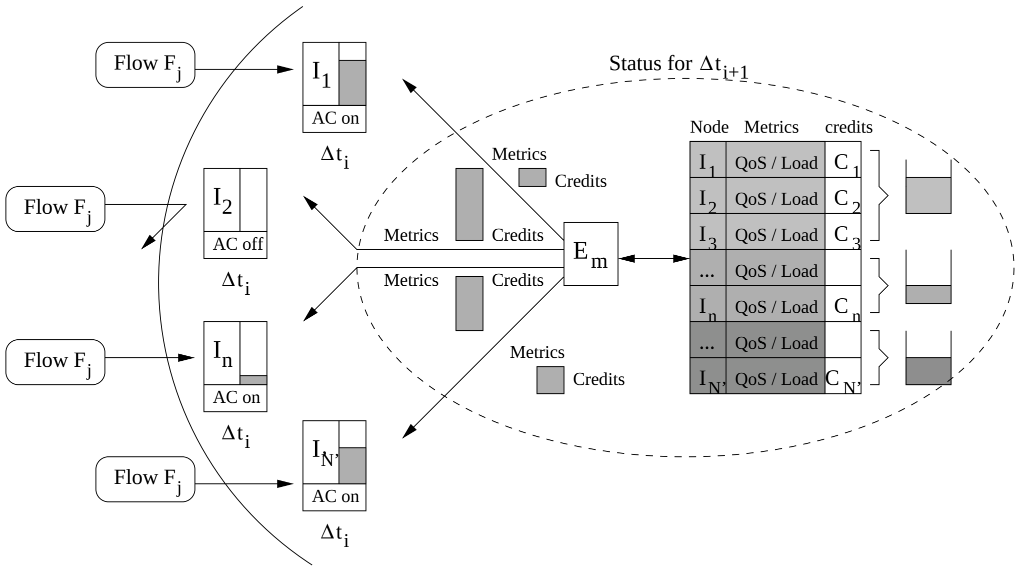


Figure 5.8: Rate-oriented credit system

[27]Network bottleneck can be hard to define as it changes dynamically. Different pairs of (I_n, E_m) may share and be limited in rate by a known bottleneck link; however, a new bottleneck may occur in a different place depending on traffic load and (I_n, E_m) pairs involved. This concept is not new and is usually expressed by metrics such as available capacity and available bandwidth. For an initial credit assignment, the available capacity should determine the bottleneck link between (I_n, E_m).

Algorithm 1: Measurement-based Credit Management

```
/* Available Rate Credits at $I_n$ for $SC_i$ at the end of $\Delta t_i$ */
$RC^{avail}_{i,(I_n,E_m)} = RC_{i,(I_n,E_m)} - \tilde{r}_{i,(I_n,E_m)}$

/* Updating credits for $\Delta t_{i+1}$ */
        /* if $RC^{avail}_{i,(I_n,E_m)} < \beta_{i,RC}$: credits under limit, new credits are distributed */
        /* if $RC^{avail}_{i,(I_n,E_m)} > \beta_{i,RC}$: credits over limit, excess credits return to the pool */
        /* if $RC^{avail}_{i,(I_n,E_m)} < 0$: $RC_{i,(I_n,E_m)}$ underestimated, new credits are distributed */
$RC^{new}_{i,(I_n,E_m)} = \beta_{i,RC} - RC^{avail}_{i,(I_n,E_m)}$
$CredPool_{i,E_m} = CredPool_{i,E_m} - RC^{new}_{i,(I_n,E_m)}$
$RC_{i,(I_n,E_m)} = RC_{i,(I_n,E_m)} + RC^{new}_{i,(I_n,E_m)}$
```

Notation:

$RC_{i,(I_n,E_m)}$: rate credits available at I_n for SC_i; E_m maintains this information to determine $RC^{new}_{i,(I_n,E_m)}$
$RC^{avail}_{i,(I_n,E_m)}$: remaining credits at I_n according to the estimated rate usage $\tilde{r}_{i,(I_n,E_m)}$
$RC^{new}_{i,(I_n,E_m)}$: credits update for Δt_{i+1}
$\beta_{i,RC}$: safety margin of unused credits at ingress nodes for SC_i. It is service-dependent and defined in bps
$CredPool_{i,E_m}$: pool of credits at E_m for SC_i, shared among $\ddot{I} \subseteq I^{D_x}$ concurrent nodes

The management of credits can be either measurement-based or explicit, with credits being captured and released according to SLS_{i,I_n} acceptance and termination. A possible measurement-based approach for managing the distribution of rate credits is detailed in Algorithm 1.

In an explicit approach, two scenarios can be devised:

- each ingress node I_n informs explicitly the egress node E_m of the amount of credits captured or released, keeping the credits captive during the service scheduling period defined in their SLS_{i,I_n};
- each egress E_m uses the measured rate $\tilde{r}_{i,(I_n,E_m)}$ to determine when I_n needs additional credits, waiting for an explicit teardown before releasing credits previously assigned. This avoids removing temporarily unused credits of SLSs still active, assuring that new incoming flows $F_j \in SLS_{i,I_n}$ have credits available.

At domain egress nodes, the amount of available credits in the pool may change for different reasons:

- credits are increased when: (i) the negotiated rate R^{+}_{i,E_m} and/or the links' capacity are upgraded; (ii) an SLS_{i,I_n} having E_m within its scope expires (explicit case, with I_n returning credits back); (iii) the egress E_m senses a rate utilization decrease at I_n, recovering excess credits (measurement-based case);

- the amount of available credits is decreased in favor of one I_n when: (i) I_n is running out of credits, i.e., its previous credit assignment is reaching an usage limit; this can be sensed by egress E_m when measuring the rate $\tilde{r}_{i,(I_n,E_m)}$ or (ii) an explicit request occurs from I_n[28].

Decoupling AC decisions

Controlling R^+_{i,E_m} utilization during Δt_i and, consequently, concurrency on SLS^+_{i,E_m} can be simplified if the AC module and corresponding tasks are divided between ingress and egress nodes. Instead of controlling the rates R_{i,I_n}, $R^{\notin SLS}_{i,I_n}$ and R^+_{i,E_m}at I_n, the control of R^+_{i,E_m} can be passed to E_m. For example, a flow request $F_j \in SLS_{i,I_n}$ crossing the domain D_x is accepted at I_n if Eqs. (5.5) and (5.10) are satisfied. When arriving at egress E_m, F_j is accepted and may be forward to the next domain if Eq. (5.7) is satisfied. When it is rejected at E_m, a reject notification due to R^+_{i,E_m} underestimation or by an incorrectly defined statistical multiplexing factor may be reported[29]. This corresponds to a case of violating SLS_{i,I_n} commitments.

Decoupling AC between I_n and E_m nodes, apart from being conceptually correct as SLS_{i,I_n} is related to I_n and SLS^+_{i,E_m} to E_m, brings other clear advantage. In fact, the overacceptance or concurrency control of R^+_{i,E_m} during Δt_i becomes straightforward. Since each egress node E_m can have a global view of all new flow requests trying to use SLS^+_{i,E_m}, for all I_n, it can update the previous $\tilde{R}^+_{i,E_m}$ estimation in Δt_i accordingly. This means that, when E_m accepts a new flow it can update $\tilde{R}^+_{i,E_m}$ to $\tilde{R}^+_{i,E_m} - r_j$, maintaining an updated view of global SLS^+_{i,E_m} occupancy. In this way, overacceptance as regards R^+_{i,E_m} cannot occur.

As discussed in Section 5.6.1, the decision of decoupling AC decisions between I_n and E_m, apart from the concurrency debate, should consider the computational overhead balance between (I_n, E_m) QoS monitoring and AC tasks, and the required state information at edge nodes.

When egress nodes perform AC regarding SLS^+_{i,E_m}, the credit strategy may still be useful to control each I_n rate share, SLS AC, traffic entering I_n not involving an SLS^+_{i,E_m} and, indirectly, the QoS levels in the involved paths.

[28]Specific requests of credits from I_n to E_m during Δt_i can also be considered, however, it changes the initial concept and assumption of viewing Δt_i as a black box, reflecting a measurement steady state.

[29]Note that when a flow is rejected at E_m, $\tilde{R}_{i,I_n}$ remains overestimated till Δt_{i+1}, as its rate r_j is incorrectly accounted for.

5.9 Summary

In this chapter, a service-oriented distributed AC model for managing QoS and SLSs in multiclass and multidomain environments has been proposed and specified. Initially, the model's major goals and assumptions have been highlighted before presenting the model's architecture and interrelated areas. As explained, explicit or implicit AC decisions are made based on feedback from edge-to-edge on-line measurements of service-specific QoS parameters and SLS utilization. This allows a dynamic control of services and resources, while abstracting from network inherent complexity and heterogeneity.

Resorting to an intuitive and expressive notation, multiservice domain entities such as service classes, upstream and downstream SLSs, and traffic flows have been specified in order to formalize service-dependent AC rules. These rules allow a flexible and self-adaptive control of QoS levels and SLS usage both intra and interdomain.

The major conceptual virtues and difficulties inherent to the proposed AC model have been identified and debated, pointing out ways of overcoming those difficulties. Still in a conceptual context, the present proposal has been compared with related work in the field. The problematic of handling multiple AC requests simultaneously due to the distributed nature of the AC model has been debated and some approaches for controlling concurrency suggested.

Chapter 6

AC Model Implementation Issues

This chapter details issues regarding the AC model implementation considering the architecture presented in Section 5.2. This involves the definition of a limited set of service classes with distinct QoS requirements and the configuration of corresponding traffic handling policies. For each service class, the AC criterion is defined and parameterized according to the SLSs and QoS parameters to be controlled, the safety margins and thresholds to use. The monitoring implementation decisions involve defining appropriate metrics for the QoS parameters under control, measurement methodologies and measurement time intervals. As far as active measurements are concerned, the probing sources are defined and adjusted to the characteristics of each service class.

After describing the topics above, the motivation for using a simulation environment to test the AC model is presented. When detailing the simulation prototype, aspects such as the simulation topology and internal structure, the adopted source models, the concrete service and AC configuration are presented and discussed. Finally, additional issues regarding the implementation and validation of the simulation prototype are also presented.

6.1 Definition of service classes

The definition of the service classes to be supported in a multiclass network domain is closely related to the applications and services to be handled and the traffic classification strategy adopted. Despite the subjective aspects a classification strategy might have, above all, it should be defined according to the traffic characteristics and QoS requirements of those applications and services. The relevance of having a consistent view of services has motivated efforts to establish guidelines for the definition and configuration of differentiated service classes, relating these classes with their practical use.

Taking into consideration the debate in Section 2.1.2 and current IETF service configuration guidelines [41, 9], three initial service classes are defined. As basic policy, TCP and UDP traffic are treated separately, being UDP traffic further divided according to its QoS requirements.

Service Class 1 (SC1), oriented to conversational services, provides a high quality service guarantee and is supported by the EF PHB [57]. This class may comprise traffic with hard real-time constraints such as VoIP or circuit emulation over IP [41, 9]. Due to the high priority treatment this class requires in each network node, which may starve low priority classes, the access to the corresponding service is tightly controlled. In the service model, SC1 takes a reference value of 10% of the bottleneck link capacity as an upper bound for the admissible traffic load. For this service, the AC criterion will be explicit following a conservative approach (see Section 6.2). At network entrance, TC gives a severe treatment on excess traffic, i.e., SC1 traffic is policed using a TB that drops all non-conforming packets.

Service Class 2 (SC2), oriented to a range of multimedia streaming services with soft real-time constraints, provides a predictive service with low delay, low loss and minimum bandwidth guarantee and is supported by the AF PHB [62, 5]. This class may comprise audio and video streaming or webcasting [41, 9]. For this service, the AC criterion will be less conservative, taking more advantage of statistical multiplexing. TC will act upon SC2 traffic following a srTCM [42]. In SC1 and SC2 the AC criteria, apart from considering the flow traffic profile description, take into account measures of network loss and delay of those classes attending to their relevance for the supported conversational and streaming applications.

Service Class 3 (SC3) oriented to elastic data applications, generically, supports TCP adaptive traffic. Depending on the nature of TCP flows (e.g., high throughput vs. undifferentiated traffic), this class can be implemented using the AF or DF PHB [24, 4]. Detailed classification rules for TCP differentiation, e.g., handling short and long-lived connections separately, will be considered in the future. The resulting service classes may take the remaining AF classes of this PHB group. For service SC3, the AC criterion will be implicit and relaxed. Giving the nature of TCP traffic and associated congestion control mechanism, IP packet loss will be considered the parameter under control. As for SC2, SC3 traffic is policed and marked using a srTCM.

The service classes described above, and summarized in Table 6.1, are implemented in the domain routers resorting to a class-based queuing differentiation mechanism, where queues are served according to a hybrid work-conserving PQ-WRR scheduling mechanism. The active management of the queues regarding early packet discard is based on RIO-C [52].

Table 6.1: Definition of service classes

Class	Service Level	Traffic type	PHB	AC	Policing	Scheduling
SC1	guaranteed	UDP	EF	explicit & conservative	drop on excess	strict priority
SC2	predictive	UDP	AF	explicit & flexible	3 color marker	rate-based
SC3	best-effort	TCP	BE	implicit & relaxed	3 color marker	rate-based

6.2 AC criteria parameterization

In this section, the equations of the AC criteria are revisited so that a concrete parameterization adjusted to each specific service class is defined. This parameterization involves defining, for each class, the parameters under control and the limits for AC. The choice of the controlled QoS parameters cannot be dissociated from the type of applications to be supported and the user-visible metrics. The assignment of adequate values for the corresponding thresholds, apart from the user perceived QoS and service objectives, has to take into account the network topology characteristics (e.g., number of nodes and their spacial distribution, propagation delay and queuing delay) and the statistical properties of the traffic. In the same way, the rate limits for AC, in addition to the network topology and traffic properties, should consider the service guarantee levels to be provided (and thus consistent overprovisioning levels), the bandwidth sharing policies and the medium/long-term expected traffic matrix. These multiple aspects emphasize the need for service-dependent AC criteria.

As detailed in Section 5.5, the AC criteria involves SLS utilization control rules and QoS parameter control rules. For the control of SLS utilization, the MS algorithm has been chosen. This measurement-based algorithm takes both the rate estimate and flow traffic description to verify if a new flow can be accommodated within the utilization threshold defined for SLS_{i,I_n}, SLS^{+}_{i,E_m} or for $F_j \notin SLS_{i,I_n}$ (see Section 5.5). These thresholds consider a safety margin, β_{i,I_n} or β^{+}_{i,E_m} or $\beta^{\notin}_{i,I_n}$to be applied to the negotiated rate R_{i,I_n} , R^{+}_{i,E_m} or $R^{\notin SLS}_{i,I_n}$. Although, in the future, distinct algorithms might be considered for distinct service classes, at present, the size of the safety margins and the flows/SLSs' peak or mean rate used in the MS algorithm determine the conservativeness of the SLS control rules applied to each class. For QoS control, depending on the service class, both the QoS parameters and their corresponding targets can vary. More precisely, as stated in Eq. (5.10), a new flow is accepted in Δt_i if the controlled parameters P_{SCi} of class SC_i checked against the corresponding pre-defined thresholds $T_{i,p}$ determine a positive acceptance status for Δt_i. Once again, each $T_{i,p}$ is affected by a safety margin $0 < \beta_{i,p} \leq 1$ to the parameter bound, as shown in Eq. (5.11). Tuning these limits, making them useful and realistic indicators of the overall QoS status is a fundamental aspect for AC, as explained in Section 7.2.3.

Table 6.2: AC criteria parameters

	Flow Inputs		Network Inputs	SLS Util. Control		QoS Parameter Control	
Class	T.Desc.	QoS	Measures	Parameter	Method	Parameter	Method
SC1	peak rate	if any	rate, IPTD, ipdv, IPLR	rate	MS	IPTD, ipdv, IPLR	thresh.
SC2	mean rate	if any	rate, IPTD, IPLR	rate	MS	IPTD, IPLR	thresh.
SC3	n.a.	n.a.	rate, IPLR	rate	thresh.	IPLR	thresh.

According to the service definition provided in Section 6.1, AC for service classes SC1 and SC2 uses the two types of rules mentioned above. As illustrated in Table 6.2, for SC1, a more conservative criterion is taken considering the worst-case scenario (e.g., flow peak rates, concurrent AC at other ingress nodes and optimistic performance measures), for which larger safety margins and tighter thresholds should be defined. The controlled QoS parameters for SC1 are IPTD (similar to OWD), ipdv and IPLR (similar to OWPL), whose definitions provided in Section 4.2.1 are summarized in Table 6.3. These one-way QoS parameters are considered the most critical for the real-time services supported in this class[1]. AC for SC2, being more flexible, takes the flow mean rate for SLS control and IPTD and IPLR for QoS control. For SC3, oriented to TCP traffic, AC is implicit and decisions are based essentially on IPLR control. This QoS parameter influences the goodput or BTC of TCP sessions, which is a common measure of the quality of TCP based applications. Recall that, due to the nature of TCP traffic, where a flow does not have a pre-defined rate, Eq. (5.7) is applied as a threshold for the estimated rate.

The estimation mechanisms for the parameters under control and the time granularity used in the estimation are discussed in Section 6.3. Due to the close relation to the network topology characteristics, the concrete values for the safety margins and thresholds applied to each service class AC equations are detailed along with the description of the simulation scenario.

[1]In particular, ipdv provides an indication about the level of buffers' occupancy within the network resulting from variations of the traffic conditions [178]. The need for controlling ipdv in a per-domain basis is however arguable. On the one side, some argue that buffering at source and destination will suffice [210]. Moreover, ipdv in a domain may be compensated when crossing other downstream domains. On the other side, buffering at end-systems only solves the problem when the variations in delay do not exceed certain limits. In the present context, controlling ipdv per-domain, intends to provide indications of the variability of buffers' occupancy in the domain so that traffic control mechanisms such as AC may be triggered accordingly.

6.3 Monitoring decisions

Although being decoupled from the AC process itself, monitoring is a critical component of the model as it is used for active QoS and SLS control. For active control, monitoring has to be on-line [190, 74] in order to provide feedback reflecting the current network conditions so that proper control decisions can be made in useful time.

In this study, the objective of on-line monitoring is twofold. First, it provides inputs for the AC decision module and corresponding MBAC algorithms, which apart from flow traffic profile and/or QoS requirements information, require a realistic view of the service classes' status and performance. Therefore, several parameters need to be defined and estimated in order to drive AC decisions. Second, it allows SLS and QoS auditing in the domain [14].

The on-line monitoring implementation options are discussed below, regarding the definition of controlled QoS and SLS metrics, measurement methodologies and estimation methods to be applied.

Controlled QoS and SLS metrics

In the previous section, several edge-to-edge QoS and SLS parameters have been identified to be controlled at each egress monitoring module. Considering [22, 167, 169, 168, 165] inputs, the corresponding metrics are defined in Table 6.3 for a measurement time interval Δt_i. The mean value of each metric in Δt_i, measured for an ingress-egress (I_n, E_m) pair and service class SC_i, is controlled by the AC module as described in Sections 5.4.5 and 5.5. The estimation of SLS^+_{i,E_m} usage is not ingress dependent, therefore it is not controlled necessarily on an ingress-egress basis.

Measurement methodology

For each class, the metrics in Table 6.3 are estimated and controlled resorting to passive and active measurements. Comparing the outcome of both approaches allows to assess and tune the probing process, as discussed in Section 7.2.2. In more detail, passive measurements consist of evaluating the QoS metrics for each measurement interval Δt_i, using the traffic aggregate comprising active flows within service class SC_i. A similar evaluation is performed for active measurements, but in this case, only the probing traffic embedded in each service class is considered. For active measurements, the type of packets used to evaluate the metrics (*packet of*

Table 6.3: Controlled QoS and SLS parameters and corresponding metrics

Rate Parameters	
Rate r (bps)	$r_{i,\Delta t_i} = (\sum bits\_recv_i)_{\Delta t_i}/\Delta t_i$
Utilization U	$U_{i,\Delta t_i} = r_{i,\Delta t_i}/C$
Delay Parameters (s)	
IP Transfer Delay ($IPTD$)	$IPTD_{i,pkt} = t_{E_m,pkt} - t_{I_n,pkt}$
Mean IPTD ($\overline{IPTD}$)	$\overline{IPTD}_{i,\Delta t_i} = (\sum IPTD_{i,pkt}/\sum pkts\_recv_i)_{\Delta t_i}$
Maximum IPTD ($IPTD^{max}$)	$IPTD^{max}_{i,\Delta t_i} = max(IPTD_{i,pkt})_{\Delta t_i}$
Minimum IPTD ($IPTD^{min}$)	$IPTD^{min}_{i,\Delta t_i} = min(IPTD_{i,pkt})_{\Delta t_i}$
Inst. Packet Delay Var.[2] ($ipdv$)	$ipdv_{i,2pkt} = IPTD_{i,pkt} - IPTD_{i,pkt-1}$
Mean ipdv ($\overline{ipdv}$)	$\overline{ipdv}_{i,\Delta t_i} = (\sum \lvert ipdv_{i,2pkt}\rvert/\sum pkts\_recv_i)_{\Delta t_i}$
Signed mean ipdv ($\overline{ipdv^s}$)	$\overline{ipdv^s}_{i,\Delta t_i} = (\sum ipdv_{i,2pkt}/\sum pkts\_recv_i)_{\Delta t_i}$
Maximum ipdv ($ipdv^{max}$)	$ipdv^{max}_{i,\Delta t_i} = max(ipdv_{i,2pkt})_{\Delta t_i}$
Minimum ipdv ($ipdv^{min}$)	$ipdv^{min}_{i,\Delta t_i} = min(ipdv_{i,2pkt})_{\Delta t_i}$
Loss parameters	
IP Loss Ratio ($Total\ IPLR$)	$IPLR_{i,tot} = tot\_pkts\_lost_i/tot\_pkts\_sent_i$
IP Loss Ratio in Δt_i ($IPLR$)	$IPLR_{i,\Delta t_i} = (\sum pkts\_lost_i/\sum pkts\_sent_i)_{\Delta t_i}$

type P) are, in most cases, UDP packets of 100 bytes, and the *Type-P* probing stream follows distinct patterns (e.g., CBR_P, POI_P, $EXPOO_P$, $B2B_P$) as discussed in Section 4.3.1. Section 7.2.2 explores the adequacy of different probing solutions for the simultaneous estimation of the considered metrics, and includes tests with TCP probing (FTP_P) and distinct packet sizes.

Parameter estimation mechanisms

According to Section 4.2.2, apart from the measurement methodology itself, the value of each metric to be used in Δt_i can be evaluated resorting to distinct estimation methods such as *Time-Window*, *Point Sample* and *Exponential Averaging*. These methods are here applied to edge-to-edge measurements.

For SLS utilization control, the traffic load of the SLS is the parameter to be estimated. The estimated value $\tilde{R}^{+}_{i,E_m}$, which corresponds to the current aggregate rate of the SLS, is obtained resorting to the three estimation mechanisms mentioned above in order to assess which of them reflects the real network load more closely (see Section 7.2.3). In order to obtain a statistically meaningful number of samples, following [105, 121] guidelines, the relation between the win-

[2]Two variants of mean ipdv have been considered: (i) signed $\overline{ipdv^s}$; (ii) module $\overline{ipdv}$. The former captures the increasing or decreasing tendency of ipdv in Δt_i, however, it loses the real amplitude of ipdv variations as positive and negative ipdv values smooth or cancel each other. The latter captures the mean amplitude of ipdv variations during Δt_i. $ipdv^{min}$ and $ipdv^{max}$ complement the information provided by mean statistics. Establishing alarms based on pre-defined variations on the metrics' values may be explored in the future.

dow size T and the sampling period S should be $T/S \geq 10$ with $S > 100L/C$, for a packet size of L bits transmitted at rate C.

For QoS control, the point sample method is used. However, as in [211], for each sampling period S (equivalent to Δt_i), independently of which estimation method is in use, the metric takes an average instead of an instantaneous value. For the passive measurement methodology, this corresponds to consider all packets in a class[3]. As regards the active measurement methodology, only the probing packets are used. Additionally, as the estimates are edge-to-edge, the dimensioning of S considers the one-way delay and not the packet transmission time.

6.4 Implementing the AC model in a simulation platform

6.4.1 Modeling approaches

The study of computer networks may follow several modeling techniques depending on aspects such as the nature of the problem to be solved or the ease of access to the systems to be studied. When an experimental study is not feasible either because the involved systems are still under development, their cost is prohibitive or setting up a real testing environment is not possible, analytical and/or simulation modeling is commonly used [212, 213].

Analytical models are a powerful and precise tool to evaluate, for instance, the behavior, conformance and performance of network systems and protocols. However, when the systems are too complex, involving a large number of variables, the analysis usually leads to models that are analytically intractable unless substantial simplifying approximations are made. Examples of common assumptions are: (i) the system under study has infinite buffering capacity; (ii) the traffic sources generate independent and identically distributed streams; (iii) no other network traffic is in transit, i.e., the system is isolated; (iv) the network infrastructure is error free; or (v) the network does not implement any traffic control actions. However, in practice, network nodes have limited buffering capacity, today's network traffic is likely to be highly correlated and undergo some form of conditioning control, and retransmissions are likely to occur due to lost or corrupted packets. Therefore, assumptions such as the ones mentioned above may limit considerably the scope of the results, leading sometimes to analytical models that do not reflect or are far from the reality.

[3]This may be too demanding, especially in high-speed networks due to large traffic volume and reduced packet processing time. In the present context, the aim is to tune the probing process.

Alternatively, computer simulations constitute a very useful and flexible modeling tool. In fact, the main advantages of using simulation models lay on the following: (i) simulation models are simpler to devise and handle than analytical models; (ii) multiple test configurations can be easily tested by changing or updating the simulation scenario; (iii) when compared to analytical modeling, simulation allows an easier evaluation of a system dynamics and behavior. The use of simulation is therefore very appealing as it opens a wide range of different test scenarios without adding too much complexity to the study. A problem usually pointed out to simulation approaches is that for some statistics or rare events the simulation needs to run over very long periods, which may make it impracticable. The use of hybrid models is sometimes adopted [214].

In this study, apart from the flexibility it provides, simulation is justified by the scope and complex nature of the problem to solve. In fact, although initially a single domain simulation model is under consideration, there are multiple variables and test scenarios involved. In addition, testing a full implementation of the AC model prototype in real networks would be difficult to accomplish mainly due to administrative impairments and limitations in performing test measurements in operational network equipment.

6.4.2 Choosing the simulation platform

Giving that a full discussion of simulation languages and tools falls outside the scope of this thesis, the debate will concentrate briefly on two major open-source simulation packages, particularly oriented to study multiple aspects of computer networks and related protocols. These simulation packages provide a comprehensive support for simulation modeling as they fully include basic event-driven simulation facilities, an extensive set of reusable networking components, and support for high-level simulation programming, debugging and animation.

The Objective Modular Network Testbed in C++ (OMNeT++) [215] is a event-driven simulation environment that provides a generic, modular, component-based architecture for modeling. Components or modules are programmed in C++, then assembled into larger components and models using a high-level network description language (NED). Due to its modular and open architecture, the simulation kernel and models can be embedded into user applications easily. OMNeT++ is open-source, provides extensive graphical user interface support and includes many protocols of the TCP/IP stack, IPv6, MPLS, and frameworks for mobile and ad-hoc network simulations.

The Network Simulator (NS-2) [216] developed within the VINT Project [217, 218] is a widely used open-source simulation platform. NS-2 is an object-oriented event-driven simulator with the core written in C++ and an OTcl interpreter as a front-end [219]. The C++ programming level is suitable for detailed protocol implementation, where the running time of handling packet headers and performing protocol functionality is rather relevant. At OTcl programming level, the code can be changed more easily but runs slower than C++. Therefore, it is suitable for high-level modeling of network aspects that involve varying parameters and configurations in order to explore a large number of simulation scenarios. Currently, from many contributions worldwide, NS-2 covers a wide range of networking modules providing a comprehensive support of the TCP/IP protocol stack, including several transport and routing protocols both for unicast and multicast environments. NS-2 also supports mobile IPv4 and IPv6, ad-hoc and satellite networking.

Although OMNeT++ has been appointed as a better structured simulation platform, allowing a modular and hierarchical design supported by an enhanced interactive graphical environment [220], NS-2 includes more specific communications protocol facilities. In particular, the module comprising the main components for implementing Diffserv networks[4] has been a key factor for choosing NS-2 for the present work.

6.5 Simulation model

To test the proposed AC model in a multiclass domain, a simulation prototype was devised and set up based on the NS-2 platform [216]. The design of this simulation prototype cannot be decoupled from the main objectives of the experiments which are mainly: (i) the assessment and tuning of the monitoring process as a whole, with emphasis on the active measurement methodology; (ii) the evaluation of the AC criteria ability to meet service commitments efficiently.

In this context, the simulation model internal structure, the adopted topology, the traffic source models adjusted to each service class characteristics and the configuration of the AC model are described next. The parameterization provided in this description is generically used throughout the experiments included in Chapter 7. According to the particularities of each test scenario, a different parameterization for the tested variables is sometimes explored and detailed in the corresponding test scenario taxonomy.

[4]The Diffserv model, developed initially by a team from Nortel Networks, was included in NS-2.1b8 version.

6.5.1 Simulation model internal structure

The concretization of the simulation prototype involves identifying the functional modules to implement and the relevant characteristics of each one influencing on the AC model behavior. In addition, the inputs or configurable aspects of each module and corresponding outputs also need to be carefully established in order to pursue the main objectives of the tests. In other words, the resulting simulation model should be versatile enough, allowing to access both the monitoring process and the AC criteria efficiency under a wide range of test scenarios.

Concretely, after setting up of the network topology (see Section 6.5.2) and resorting to the Differentiated Services Module embedded in NS-2, the developed simulation model implements three functional interrelated modules - Automatic Source Generation Module, AC Decision Module, and QoS and SLS Monitoring Module. Considering an (I_n, E_m) pair, Figure 6.1 presents a simplified diagram of the simulation model architecture, including the relation between these modules and main underlying functions and variables. The two modules represented in gray are recursive being responsible for the dynamic behavior of traffic source generation and monitoring. A brief description of each module is provided next.

- *Automatic Source Generation Module* - This recursive module is responsible for the automatic start up and tear down of traffic sources for each service class (flow initiation and departure), simulating the normal network traffic dynamics. It allows a per-class distinct parameterization of the traffic sources characteristics, as regards the source model distribution and related parameters, the flow arrival process and the flow holding time process. For each class, the acceptance and start of each new flow is conditioned by the status of the AC decision variables (QoS-Accept-Status ($AC\_Status_{\Delta t_i}$), SLS-Accept-Status, #Adm-Flows ($Adm\_Flows_{\Delta t_i}$)) defined and updated by the AC decision and monitoring modules. When accepted, for explicit AC, the new flow rate can be used to update the SLS-Accept-Status at the corresponding ingress node; for implicit AC, the #Adm-Flows can be updated. The output variables related to this module provide information about the number of active flows, the number of accepted/rejected flows on a continuous basis and per time interval. Probing sources are also defined per-class but statically activated at the beginning of the simulation.

- *AC Decision Module* - This module, enclosing the QoS control module and the SLS utilization control module, is responsible for implementing the AC decision rules defined in

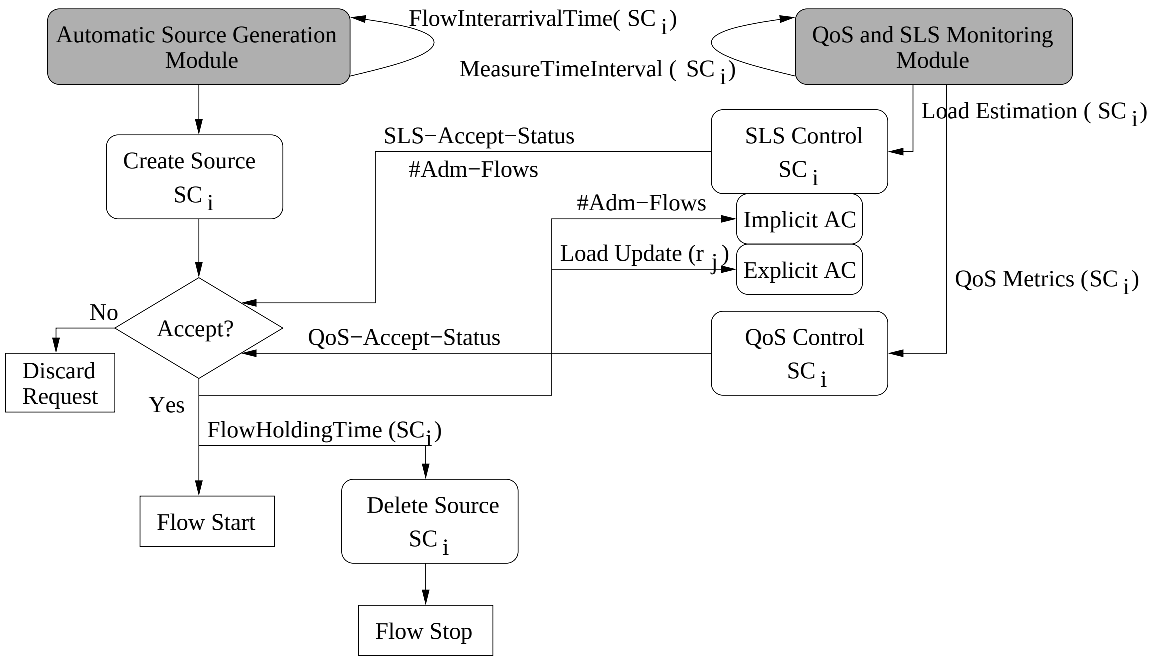


Figure 6.1: Simulation model diagram

Section 5.5. In particular, the QoS control module implements Eq. (5.10) evaluating it once in each Δt_i resorting both to the measures provided by the QoS and SLS Monitoring Module and to configurable QoS thresholds. For each new flow requesting admission to classes with explicit AC, the SLS utilization control module implements Eq. (5.7); for classes with implicit AC it controls the SLS rate usage (once in each Δt_i) and the number of admissible flows $Adm\_Flows_{\Delta t_i}$. The parameterization of these equations is service-dependent and their evaluation determine the value of the variables QoS-Accept-Status, SLS-Accept-Status, and #Adm-Flows, which constrain the admission of new flows generated by the Automatic Source Generation Module.

- *QoS and SLS Monitoring Module* - This module, developed mainly at C++ level, is responsible for the computation of the QoS and SLS metrics defined in Table 6.3. It resorts to the capacity of NS to attach *traffic sink* agents to destination nodes for packets receiving and processing. In particular, the *LossMonitor* and *TCPSink* agents have been enhanced with new facilities to perform the computation of the desired metrics. At TCL level, a recursive monitoring module, called each Δt_i, receives the metrics, providing them as inputs for the on-line AC Decision Module and as output for off-line processing. In particular, the estimated rate usage of each SLS for Δt_i, $\tilde{R}^{+}_{i,E_m}$, used by the SLS utilization control module can be alternatively calculated resorting to the three parameter estimation methods defined in Section 6.3. At C++ level, the QoS metrics are continuously evaluated for each received packet in order to allow a more detailed off-line analysis of the AC model performance with respect to QoS violations at packet, flow and class level. In order to access and tune the active monitoring process, the QoS metrics are computed separately using the real traffic within each class (passive monitoring) and the corresponding probing traffic (active monitoring). The passive and active measurement outcome can be used on-line to drive AC and cross-checked off-line for monitoring evaluation purposes.

Modules interrelation and independence

As referred in Section 4.4, for flexibility and portability reasons, the monitoring module and the AC module, although being interrelated, are independent. Therefore, the monitoring process and its implementation details are hidden from the AC module, which means that new developments on network performance monitoring and new requirements on the network services being monitored can be accommodated easily without compromising AC. In the same way, the algorithms used in the AC criteria can be improved or changed without interfering with the monitoring module, unless the changes involve new monitoring facilities such as measuring different QoS metrics.

6.5.2 Simulation topology

The simulation topology is illustrated in Figure 6.2. A simple initial configuration has been adopted in order to pursue the objectives defined above and to allow a macro and microanalysis of the model behavior. The network domain consists of ingress routers I_1, I_2, a multiclass network core initially composed by a core router C_1 and an edge router E_1. The service classes SC1, SC2 and SC3 are implemented in all the domain nodes. While I_1 multiplexes three types of sources, each type mapped to a different class, I_2 is used to inject concurrent or cross traffic. This allows to evaluate concurrency effects on distributed AC and assess the impact of cross traffic on the AC model performance. Despite its simplicity, this topology allows to emulate a wide range of test scenarios (see details on Sections 7.2.1 and 7.3.1), including relevant aspects of real environments. For instance, the scenarios with cross traffic allow to contemplate the presence of unmeasured traffic within the core, having an impact on the domain's QoS and load but without being explicitly measured by E_1 SLS rate control rules. To assess the model scalability (discussed in Section 7.5) and end-to-end behavior a more complex scenario should

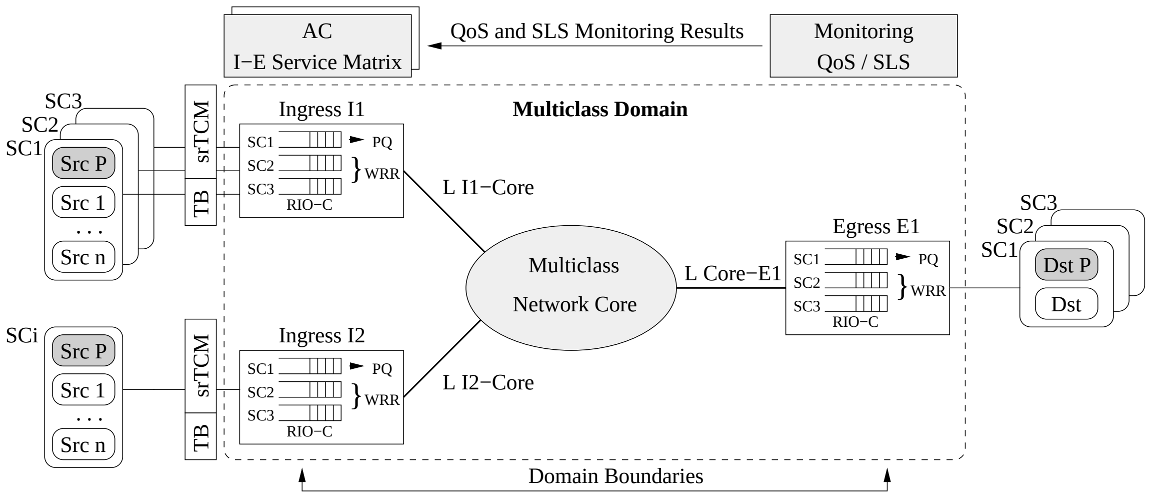


Figure 6.2: Simulation topology

be considered.

The domain routers implement the service classes according to a hybrid PQ-WRR(2,1) scheduling discipline, with RIO-C as AQM mechanism. The PQ-WRR(2,1) discipline applies to the highest priority class (SC1) a strict priority treatment with a tight limit on a pre-defined rate (10% of the link capacity), whereas the queues of the remaining class (SC2, SC3) are served with a 2 to 1 proportionality. Each class queue is 150 packets long. The domain internodal links capacity is 34Mbps, with a 15ms propagation delay. $L_{C1,E1}$ link works as a bottleneck in this network topology. At network entrance, SC1 is policed and marked using a TB which controls both rate and burst size, whereas SC2 and SC3 are policed and marked using a srTCM [42]. The access links to the domain boundaries are configured so that intradomain measurements are not affected. Table 6.4 summarizes the parameters used in the topology configuration.

Table 6.4: Network topology configuration

Links	Delay	Capacity	Queues	AQM	Qsize	Scheduler	Policer
$L_{I1,C1}$	15ms	34Mbps	$Q_{I1,C1}$	RIO-C	150 pkts	PQ-WRR(2,1)	n.a.
$L_{I2,C1}$	15ms	34Mbps	$Q_{I2,C1}$	RIO-C	150 pkts	PQ-WRR(2,1)	n.a.
$L_{C1,E1}$	15ms	34Mbps	$Q_{C1,E1}$	RIO-C	150 pkts	PQ-WRR(2,1)	n.a.
L_{access}	0ms	100Mbps	n.a.	n.a	n.a.	n.a.	TB,srTCM

6.5.3 Source models

Generically, three source models have been considered: Constant Bit Rate (CBR) sources, Exponential on-off ($EXPOO$) and Pareto on-off (PAR) sources. $EXPOO$ sources have exponential distributed sojourn on-off times, where during the on period packets are generated at fixed rate r kbps. PAR sources follow the same behavior but now ruled by a Pareto distribution with a shape factor α. PAR sources with $1 < \alpha < 2$ under aggregation will allow to generate traffic exhibiting long-range dependence. SC1, SC2 and SC3 traffic is generated resorting to the source models specified and parameterized according to Table 6.5. While SC1 comprises UDP traffic sources with low rates (r) and small packet sizes (l) reflecting voice-like traffic, SC2 also comprises UDP traffic with higher rates and larger packet sizes as generated by other real-time applications with higher variability. SC3 comprises long-lived high throughput TCP traffic, from FTP protocol. Some tests consider other TCP (Telnet) and UDP traffic in this class too. The flow interarrival and holding times are exponentially distributed. In [13], a distinct parameterization of traffic sources was considered for the defined service classes.

Table 6.5: Traffic sources configuration

Class	Protocol	Src Type	Src Param.: r(kbps);l(bytes);on/off(ms)	Inter. Time	Hold. Time
SC1	UDP	CBR_{SC1}	(r=23, l=120)	0.3-2s	90s
	UDP	$EXPOO_{SC1}$	(r=64, l=120, on=0.96,off=1.69)	0.3-2s	90s
	UDP	PAR_{SC1}	(r=64, l=120, on=0.96,off=1.69, α=1.5)	0.3-2s	90s
SC2	UDP	CBR_{SC2}	(r=128, l=512)	0.5-2s	120s
	UDP	$EXPOO_{SC2}$	(r=256, l=512, on=off=500)	0.5-2s	120s
	UDP	PAR_{SC2}	(r=256, l=512, on=off=500, α=1.5)	0.5-2s	120s
SC3	TCP	FTP App.	(r=unspecified, l=512)	0.5-2s	180s
	TCP	TELNET App.	(r=unspecified, l=512)	0.5-2s	180s
SC3	UDP	CBR_{SC3}	(r=256, l=512)	0.5-2s	180s
	UDP	$EXPOO_{SC3}$	(r=512, l=512, on=off=500)	0.5-2s	180s
	UDP	PAR_{SC3}	(r=512, l=512, on=off=500, α=1.5)	0.5-2s	180s
Probing	UDP	CBR_P	(r=1.6-variable, l=100)	1 src	sim. dur.
	UDP	POI_P	(r=1.6-variable, l=100, Poisson)	1 src	sim. dur.
	UDP	$EXPOO_P$	(r=1.6-variable, l=100, on/off=exp.)	1 src	sim. dur.
	UDP	$B2B_P$	(r=1.6-variable, l=100, on=det./off=unif.)	1 src	sim. dur.
	TCP	FTP_P	(r=variable, l=100)	1 src	sim. dur.

As regards probing, as mentioned in Section 4.3.1, five types of probing sources were considered: periodic (CBR_P); Poisson (POI_P); exponential on-off ($EXPOO_P$); back-to-back hybrid on-off ($B2B_P$) and a TCP-based source (FTP_P). For each (I_n, E_m) pair, a single probing source is embedded in each service class, i.e., an in-band probing source type is defined to measure the class behavior. The probing sources considered and their generic characteristics are indicated in Table 6.5 [16]. In Chapter 7, Table 7.2 specifies in detail the probing characteristics used in each of the test scenarios defined for active monitoring evaluation.

6.5.4 Service and AC Configuration

Table 6.6 illustrates the main parameters used to configure the AC rules used for controlling both SLS utilization and domain QoS levels. Three downstream SLSs have been considered, one per service class, with a negotiated rate (R^+_{i,E_m}) defined according to the traffic load share intended for the corresponding class in the domain. The MS algorithm, which rules SLS utilization, has specific utilization target (β^+_{i,E_m}) values depending on how conservative the AC decisions must be. For instance, a $\beta^+_{i,E_m} = 0.85$ corresponds to impose a safety margin of 15% to absorb load fluctuations and optimistic measures. This value can be viewed as a degree of overprovisioning. At present, these values are defined empirically and will be tunned throughout the simulation tests in order to assure each service class commitments. In the future, a formal relation between them and the statistical properties of service class traffic, such as the degree of burstiness and LRD, will be explored.

The AC thresholds $T_{i,p}$ which rule the control of each class QoS levels in the domain are set taking into account the domain topology dimensioning, queuing and propagation delays, and perceived QoS upper bounds for common applications and services (see Section 2.2). As shown in Table 6.6, the parameterization of the AC rules is service-dependent and larger β^+_{i,E_m} and tighter $T_{i,p}$ are defined for more demanding classes.

Table 6.6: Service parameter configuration

Class	SLS Rate R^+_{i,E_m} (% share)	Safety Margin β^+_{i,E_m}	QoS Parameter	Threshold $T_{i,p}$
SC1	3.4Mbps (10%)	large (0.85)	(IPTD,ipdv,IPLR)	(35ms,1ms,10^{-4})
SC2	17.0Mbps (50%)	medium (0.90)	(IPTD,IPLR)	(50ms,10^{-3})
SC3	13.6Mbps (40%)	small (1.0)	(IPLR)	(10^{-1})

6.6 Model validation

The validation of the simulation model, as a multistage process, has required running a large number of simulations for verifying the consistency and correct behavior of the implemented model. The validation process was accomplished through detailed observation, analysis and cross-checking of specific output data and traces collected from the following sources:

- trace and monitor NS facilities [219]- the two primary types of monitoring objects supported by NS - *traces and monitors* - were configured in order to trace the progression of packets belonging to each flow, class and ingress node (*traces*) and record counts of relevant quantities such as bytes, packets and loss associated with all traffic or per-flow (*monitors*). In particular, *flow monitors* were configured to gather per-flow statistics helping the validation of the Automatic Traffic Source Generation module;

- placement of debugging checkpoints in critical parts of the developed code - resorting to runtime data, the value of state variables, the interaction among modules, intermediate/final results and strategic counters were verified;

- output files from the TCL code and C++ code - the relevant output data from the distinct modules was stored in files to be processed and analyzed off-line;

- graphical results - the graphical representation and consequent analysis of the simulation results allowed a first and rapid identification of a specific behavior or value deserving a more detailed verification and/or explanation.

This integrated and incremental analysis of the simulation results allowed the verification of the implemented model regarding:

- the simulation topology and parameterization;

- the correct initiation and departure of traffic flows for each class and their corresponding profile;

- the obtained measures at packet level, flow level and class level both continuously and per measurement time interval Δt_i;

- the AC status variables and AC decisions facing the involved parameters;

- the correct behavior of each module individually and of the simulation dynamics as a whole.

6.7 Additional issues on model implementation

Apart from the developed simulation model involving the described main functional modules, new functions have been added to NS-2 libraries in order to support the specificities needed for the defined set of tests. In some cases, the facilities of existing functions have been extended and, when necessary, new functions have been created. In more detail,

- to support the dynamic generation and simultaneous treatment of several TCP flows, the TCP implementation (TCP-Tahoe) has been modified in order to distinguish between distinct TCP flows and corresponding acknowledgment;
- to support the QoS and SLS Monitoring module, the *LossMonitor* agent has been improved for contemplating the computation of the required metrics;
- to support the set of tests related to the evaluation of the active monitoring process, new probing source models (POI_p and $B2B_p$) and policers/markers for interleaved coloring of probes have been developed.

Finally, several scripts were written to assist the off-line treatment and analysis of the simulations' output files. Other tools used to complement this off-line analysis were gnumeric [221] and gnuplot [222].

6.8 Summary

In this chapter, the main aspects concerning the implementation of the AC model have been identified and discussed. These aspects, aiming at developing a prototype to evaluate both the monitoring and AC criteria performance, have included the definition of: (i) the characteristics of the service classes and controlling policies; (ii) the AC criteria parameterization involving service-dependent safety margins and thresholds; (iii) the QoS and SLS parameters to monitor and the measurement methodologies. To sustain these definitions and the corresponding choice of policies and parameters, an analysis of current work and guidelines on these topics has been carried out, not only in this chapter but also throughout Chapters 2, 3 and 4.

Resorting to the NS-2 simulation platform, a multiservice network simulation prototype embedding the proposed AC model has been developed and configured accordingly. The main aspects regarding the implementation and validation of the simulation prototype have also been discussed.

Chapter 7

Test Scenarios and Results

Generically, an AC proposal needs to be sustained by a set of well-defined and target tests allowing to: (i) evaluate the performance of the proposed solution; (ii) identify and handle unexpected or critical aspects of the model behavior; (iii) identify the limitations and aspects that need further study. In special, evaluating the performance of the solution should be carried out both at macro level, e.g., studying the domain and classes' behavior, and at micro level, e.g., covering packet analysis and tuning of algorithms and corresponding parameters.

In the context of the present work, these tests intend to provide a proof-of-concept of the proposed AC model as regards its self-adaptive ability to control QoS and SLSs in multiclass IP networks, assessing the AC criteria effectiveness in satisfying service commitments and the network utilization levels achieved. In addition, attending to the discussion on multiclass QoS monitoring challenges provided in Section 4.3 and on existing measurement methodologies, several tests are planned to evaluate the adequacy of active measurements for edge-to-edge multipurpose QoS estimation[1].

Thus, in this chapter, after detailing the objectives of the tests, multiple testing scenarios are devised in order to evaluate both the active measurement methodology and the proposed AC criteria. The debate focuses mainly on the evaluation results of these two related components of the AC model, covering also relevant issues regarding the deployment of the model in a large scale.

[1]Although the proposed AC model is not tied to a particular measurement methodology (providing that the necessary metrics are evaluated and made available regularly to drive AC decisions), several advantages have been pointed out concerning the use of active measurements for edge-to-edge QoS monitoring (see Section 4.2.2).

Table 7.1: SLS and QoS control

SLS Control Rule (Eq.(5.7))				
Class	Monitoring Inputs $\tilde{R}^{+}_{i,(*,E_m)}$	Flow Inputs r_j	SLS Rate R^{+}_{i,E_m} (share %)	Safety Margin β^{+}_{i,E_m}
SC1	Traffic load	peak rate	3.4Mbps (10%)	0.85
SC2	Traffic load	mean rate	17.0Mbps (50%)	0.90[2]
SC3	Traffic load	n.a.	13.6Mbps (40%)	1.0

QoS Control Rule (Eq.(5.10))			
Class	Monitoring Inputs $\tilde{P}_{i,p}$	Flow Inputs	QoS Param. Thresh. $T_{i,p}$
SC1	IPTD, ipdv, IPLR	if available	$35ms; 1ms; 10^{-4}$
SC2	IPTD, IPLR	if available	$50ms; n.a.; 10^{-3}$
SC3	IPLR	n.a.	$n.a.; n.a.; 10^{-1}$

7.1 Main objectives of the tests

The main objectives of testing the proposed AC model in a multiclass domain are twofold. In a first stage, the aim is to assess the active measurement methodology, including the multipurpose probing process and the parameters' estimation mechanisms. Both the characteristics of probing patterns and the probing ability to capture each class behavior are studied aiming at a multipurpose QoS estimation [16]. In addition, a comparison of the estimation mechanisms TW, Avg_PS and EA is carried out in order to evaluate which one provides the most realistic estimate of each class and SLS load [12]. In a second stage, the proposed AC criteria are evaluated as regards their ability to assure that each service class QoS commitments are not violated, while assessing both SLSs and global network utilization [11]. This evaluation is carried out using distinct test scenarios, varying the parameters in the AC rules and the traffic conditions.

In order to pursue these objectives, the simulation prototype described in Section 6.5 is used throughout the experiments taking into account the implementation decisions and parameters defined along Chapter 6. In particular, the service-dependent AC rules parameterization is summarized in Table 7.1.

As initial configuration three downstream SLSs, one per service class, are considered. The choice of SLS rate shares (R^{+}_{i,E_m}), safety margins (β^{+}_{i,E_m}) and QoS parameters thresholds ($T_{i,p}$) are defined in the right hand side of Table 7.1. As shown, larger β^{+}_{i,E_m} and tighter $T_{i,p}$ are defined for more demanding classes[3]. In more detail, according to Eq. 5.7 and Eq. 5.10, SC1 traffic is

[2]The tests presented in Section 7.2 use a threshold of 0.95.

[3]The safety margin β^{+}_{i,E_m} can be viewed and used in two distinct ways: (i) as a safety margin in the utilization of

blocked when the sum of the rate estimate $\tilde{R}^{+}_{i,(*,E_m)}$ and the flow's peak rate r_j is above 85% of the rate share defined in SLS^{+}_{i,E_m}, i.e., R^{+}_{i,E_m}, or any of the controlled QoS parameters $\tilde{P}_{i,p}$ exceeds its pre-defined threshold $T_{i,p}$. For SC2, a safety margin of 10% , which corresponds to a β^{+}_{i,E_m} of 90% is defined and the flow's mean rate is now used. SC3 does not include any safety margin and the controlled parameter is IPLR. For SC3, the maximum number of active flows in a given time interval, i.e., $Adm\_flows_{\Delta t_i}$, is set to one hundred flows (see details in Section 7.3.3). As said before, the AC thresholds $T_{i,p}$ are set taking into account the domain topology and perceived QoS upper bounds for common applications and services. This initial configuration may lead to eventual QoS degradation or service violation that, from a test perspective, constitutes a useful scenario to verify the model's behavior and the ability of probing to detect it.

The results presented in the following sections were obtained running a large number of simulations of about ten minutes each, after discarding an initial convergence period. Simulations up to forty minutes were also carried out in order to verify the consistency of the behavior under evaluation.

7.2 Evaluation of the active measurement methodology

Ideally, probing should be able to reflect both the shape and the scale of the relevant metrics identified for each class so that its behavior is correctly captured with reduced intrusion. If this is accomplished, probing can provide valuable inputs both for SLS auditing in the domain and for active network control tasks, such as AC.

The main objective of these tests is to determine and tune adequate multipurpose probing patterns for the defined service classes. To pursue this objective and assess the suitability and effectiveness of multipurpose in-band probing patterns in measuring the QoS parameters defined in Table 7.1[4], several alternative probing schemes varying space and time properties of probing patterns are explored. These include the probing distribution, rate, drop precedence (color) and

R^{+}_{i,E_m} (downstream overprovisioning level), defined to absorb traffic fluctuations resulting from natural and/or induced properties of traffic (e.g., presence of concurrency), avoiding overutilization and, consequently, indiscriminate packet discard at E_m; (ii) as a degree of overprovisioning that is necessary to keep inside the domain (internal overprovisioning level), for SC_i utilization. Exploring β^{+}_{i,E_m} in the latter context is facilitated by the relation between the global SLS^{+}_{i,E_m} share, i.e., when considering all SC_i, and the domain bottleneck link. In practice, this relation can be provided by the expected traffic matrix $\Phi^{SLS}_{i,(n,m)}$, topological information and internal services policies.

[4]Note that, the probing rate cannot be directly compared to the class rate. For bandwidth estimation, specific probing techniques need to be used [201, 103].

packet size, in a per-class basis. The approach of coloring probes aims at exploring AQM actions in case of queue congestion and different probabilities of packets reaching the network boundary.

In the analysis of the measurement results, the probing measurement outcome is cross-checked against the corresponding measures using the real traffic within each class, i.e., active and passive measurement results are compared. For the different service classes and QoS parameters, this verification process is carried out resorting to a direct comparison of graphical results (pictorial proof) and statistical analysis of collected measurement samples.

7.2.1 Test scenarios taxonomy

Table 7.2 summarizes the planned test scenarios exploring different characteristics of probing patterns. For instance, while Test1, Test2 and Test6 study the impact of probing rate, color and packet size on multiple metrics' estimation, respectively, Test3 and Test5 intend to study and enhance probing ability to overcome identified limitations when estimating multiple metrics [17]. Apart from Test4, which uses a TCP probing stream in SC3, the remaining testing scenarios use UDP probing streams in all classes. As defined in Table 6.5, the types of sources considered are $EXPOO$ in $SC1$ and $SC2$, and $FTP\ App$ in $SC3$, with flow interarrivals of 300ms for SC1, and 500ms for SC2 and SC3. The measurement time interval Δt_i is 5s and the measures of IPTD, ipdv and IPLR report to mean values in that time interval, according to Table 6.3. The following sections will further explain each test scenario and detail the corresponding results.

Table 7.2: Test scenarios taxonomy - monitoring evaluation

Test	Tested	Probing pattern characteristics				I-E Total
Scen.	Variable	Distrib.	Mean rate (pps)	Color	PktSize (B)	Overhead (%C)
Test1	Rate	POI_P	2 to 192	green	100	0.014 to 1.4
Test2	Color	POI_P	2 to 192	red	100	0.014 to 1.4
Test3	IPTD vs IPLR	POI_P	2 to 192	interleaved	100	0.014 to 1.4
Test4	TCP Probing	FTP_P	n.a.	green,red,inter.	100	variable
Test5	ipdv	$B2B_P$	8 and 24	interleaved	100	0.06 and 0.17
Test6	Probe size	POI_P	4	red	100 and 512	0.03 and 0.15

7.2.2 Tuning multipurpose probing patterns

Test1 - Matching IPTD, ipdv and IPLR

Random sampling has been recommended as a convenient technique for systematic measurements of one-way delay, jitter and loss related metrics [22, 167, 168, 169]. Based on these directives, some monitoring systems [92, 174] resort to Poisson traffic with light probing rates, e.g., 2 or 4 pps, aiming at estimating several QoS metrics.

In [17], considering a multiclass Diffserv domain, these Poisson probing patterns were used in-band (per-class) and marked with low drop precedence (green) to refrain the network to discard them in presence of congestion. The initial results assessing the measurements' accuracy show that while IPTD metrics can be closely captured (shape and scale) for those probing rates, ipdv and IPLR are not measured properly. In particular, probing clearly overestimates ipdv and misses most of IPLR events, unless heavy loss occurs. As ipdv is a consecutive packet measure, probing gaps lead to higher measures as consequence of queue occupancy variations. These results suggest the use of alternative probing patterns with smaller probing gaps to better sense ipdv and of different coloring schemes to increase probing sensitivity to network congestion and loss events[5].

An immediate and intuitive approach to improve estimations is to increase the sampling frequency without disregarding the overhead introduced. In this way, as specified for Test1 (see Table 7.2), for each class, the Poisson probing rate was progressively increased from 2 to 192 pps. For the number of classes considered, the maximum overhead introduced per ingress-egress pair ranges approximately from 0.01 to 1.4% of the bottleneck link capacity (34Mbps), i.e., the probing rate of each class varies from 1.6 to 153.6kbps. Note that, for classes with low bandwidth share and high priority treatment such as SC1, these values might be relevant when considering multiple ingress-egress pairs. The results from active measurements revealed that the captured behavior is distinct for the classes SC1, SC2 and SC3, and the improvement observed in QoS metrics' estimation resulting from a probing rate increase also differs among the classes, as illustrated by Figures 7.1 and 7.2[6].

[5]Apart from Poisson, periodic and exponential on-off patterns were also tested. It was noticed that, for the probing rates under test, the captured metrics' behavior and their trends are equivalent. However, for similar probing rates and coloring, a periodic pattern leads to a slightly better metrics' estimation than Poisson and high correlation factors between class and probing measurement outcome.

[6]Although the metrics for AC are service-dependent and defined according to Table 7.1, to obtain a more encompassing view of probing results, IPTD, ipdv and IPLR metrics are evaluated for the three classes in use.

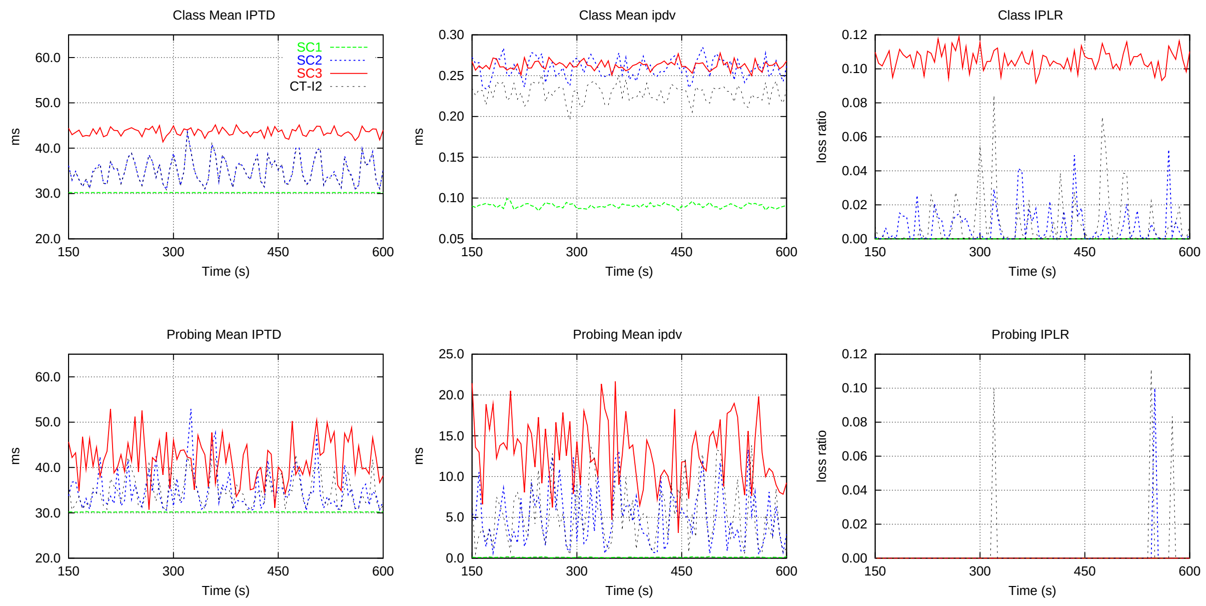


Figure 7.1: Comparison of class and probing measurements (Test1 @ 2pps)

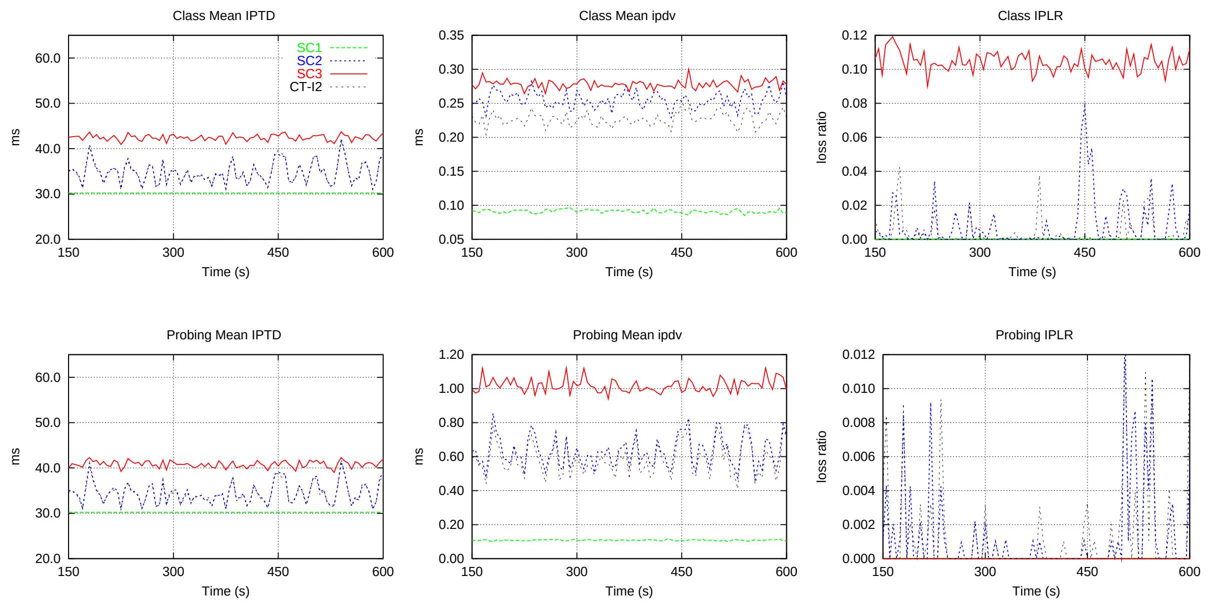


Figure 7.2: Comparison of class and probing measurements (Test1 @ 192pps)

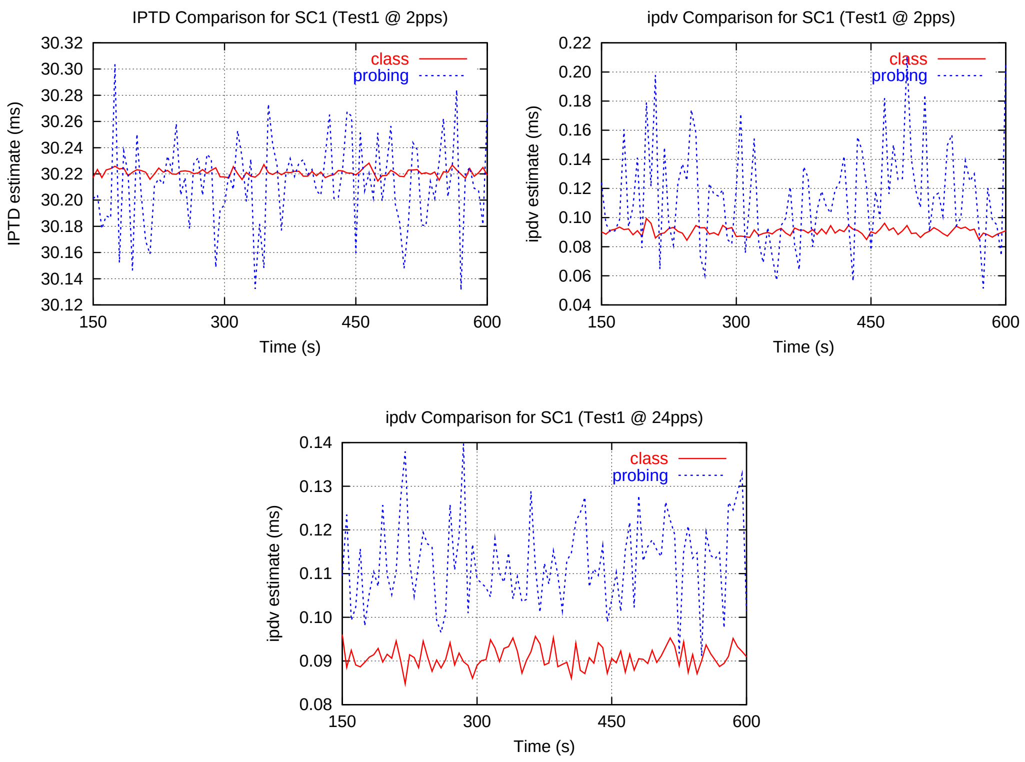


Figure 7.3: Comparison of class and probing measurements for SC1 (Test1 @ 2 and 24pps)

SC1 is a very stable traffic class with IPTD and ipdv tightly controlled without suffering any loss, thus, probing is able to approximate this behavior for a probing rate as small as 2pps. In more detail, as illustrated in Figure 7.3 (Test1 @ 2pps), the estimated probing values are delimited within a range of 0.1 ms around IPTD and ipdv class estimates. This is obviously a small variation in scale, in particular for IPTD. However, the shape of probing and class estimates is not well adjusted. As Figure 7.3 (Test1 @ 24pps) shows, increasing probing rate to 24pps clearly brings probing close to the class shape, with an overestimation upper bound of 0.05ms. A similar improvement in IPTD shape and scale is only met for higher probing rates. For instance, at 192pps, ipdv and IPTD probing estimations differ in 0.01ms from the class. Despite that, the intrusion cost introduced is too high to be considered, i.e., the trade-off between intrusion and accuracy is not worth.

Considering the less strict nature of service class SC2, for a probing rate of 2pps, IPTD is also fairly well captured (see Figure 7.4). However, a significant decrease on ipdv overestimation (less than one order of magnitude) is only achieved for the higher probing rates under test (see example in Figure 7.6(d,d')). IPLR also benefits from probing rate increase as loss is gradually better

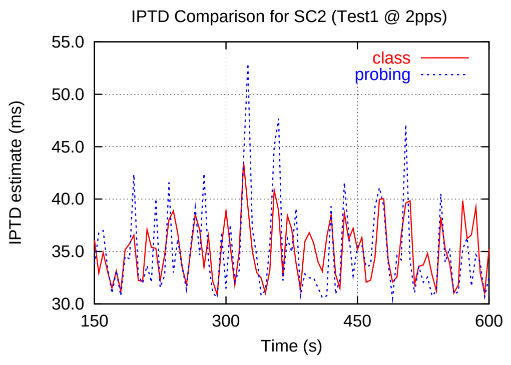


Figure 7.4: Comparison of class and probing measurements for SC2 (Test1 @ 2pps)

detected, although a deficit on IPLR scale estimation of approximately one order of magnitude is still present.

For the lower probing rates, the behavior of SC3 is clearly the worst captured as regards the three metrics under control. While IPTD and ipdv benefit from a probing rate increase, IPLR events are completely missed even at 192pps.

In summary, Test1 allows to conclude that increasing probing rate, *per se*, is not enough to overcome QoS metric estimation mismatches. Despite the tendency to improve IPTD and ipdv accuracy, the overhead introduced and the failure of IPLR estimation suggest exploring other probing characteristics as either alternative or complementary approaches.

Test2 and Test3 - Exploring probe coloring

Probe coloring is proposed and studied here as a method of improving IPLR estimation. For the conditions stated in Test2, when changing the drop precedence of probing packets from low to high, i.e., coloring probes from green to red, a significant improvement in IPLR sensitivity was noticed even for a probing rate of 2pps. This improvement is reflected in a better detection of class loss events, however, IPLR scale is clearly overestimated and IPTD slightly underestimated (see Figure 7.5). This behavior is justified by the AQM action on probes' precedence. In fact, when queue congestion increases, red probes are the first to be dropped and the previously high-delayed green probes are now mostly discarded. As a consequence, on average, IPTD estimation is slightly degraded, while loss detection is improved. The scale magnifying error in IPLR estimation is justified by the huge difference between the total number of probes and class packets in Δt_i. Increasing the rate of red probes revealed fruitful for SC3 IPLR scale accuracy, but for

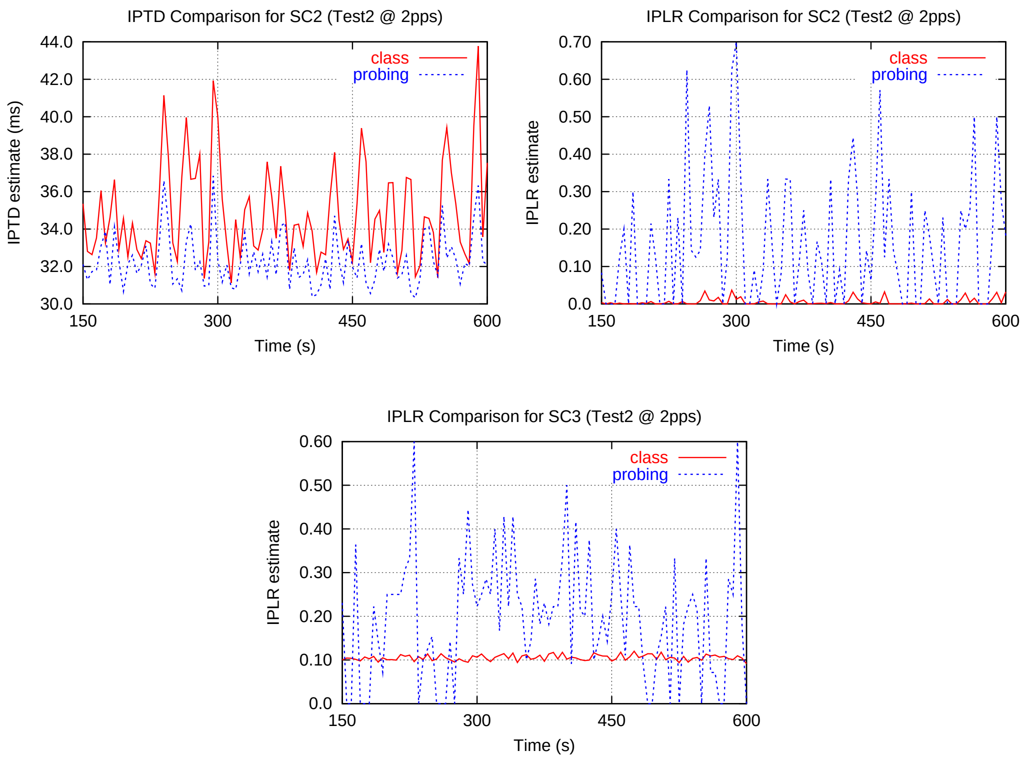


Figure 7.5: Comparison of class and probing measurements for SC2 and SC3 (Test2 @ 2pps)

SC2 the previous scale problems remain evident without noticeable improvement. This is due to the different nature of loss in SC2 (more sparse) and SC3 (more regular), and the volume of red packets in those classes. The side effects on IPTD estimation are not completely removed either, when higher rates of red probes are used.

In order to improve the compromise between IPLR and IPTD estimation and to adjust IPLR scale, probing patterns with an interleaved coloring scheme are tested, i.e., green and red packets are sent alternately according to a pre-defined distribution (see Test3 details). Comparing to Test1 outcome, a interleaved probing pattern of 2pps brings significant improvement on IPLR estimation for all traffic classes. Moreover, the degradation of IPTD estimation and IPLR overestimation noticed in Test2 is now much less pronounced. These positive results are further enhanced for higher probing rates where the accuracy of all metrics is increased, as exemplified in Figure 7.6 (a,a’) and (b,b’) for a probing rate of 24pps. Despite that, for SC2, IPLR still remains overestimated (see Figure 7.6(c,c’)). As in Test1, ipdv estimates converge for probing rates above 96pps (see example in Figure 7.6(d,d’) for 192pps). Generically, SC3 is the class that strongly benefits from interleaved probing, reaching a good compromise in the metrics’

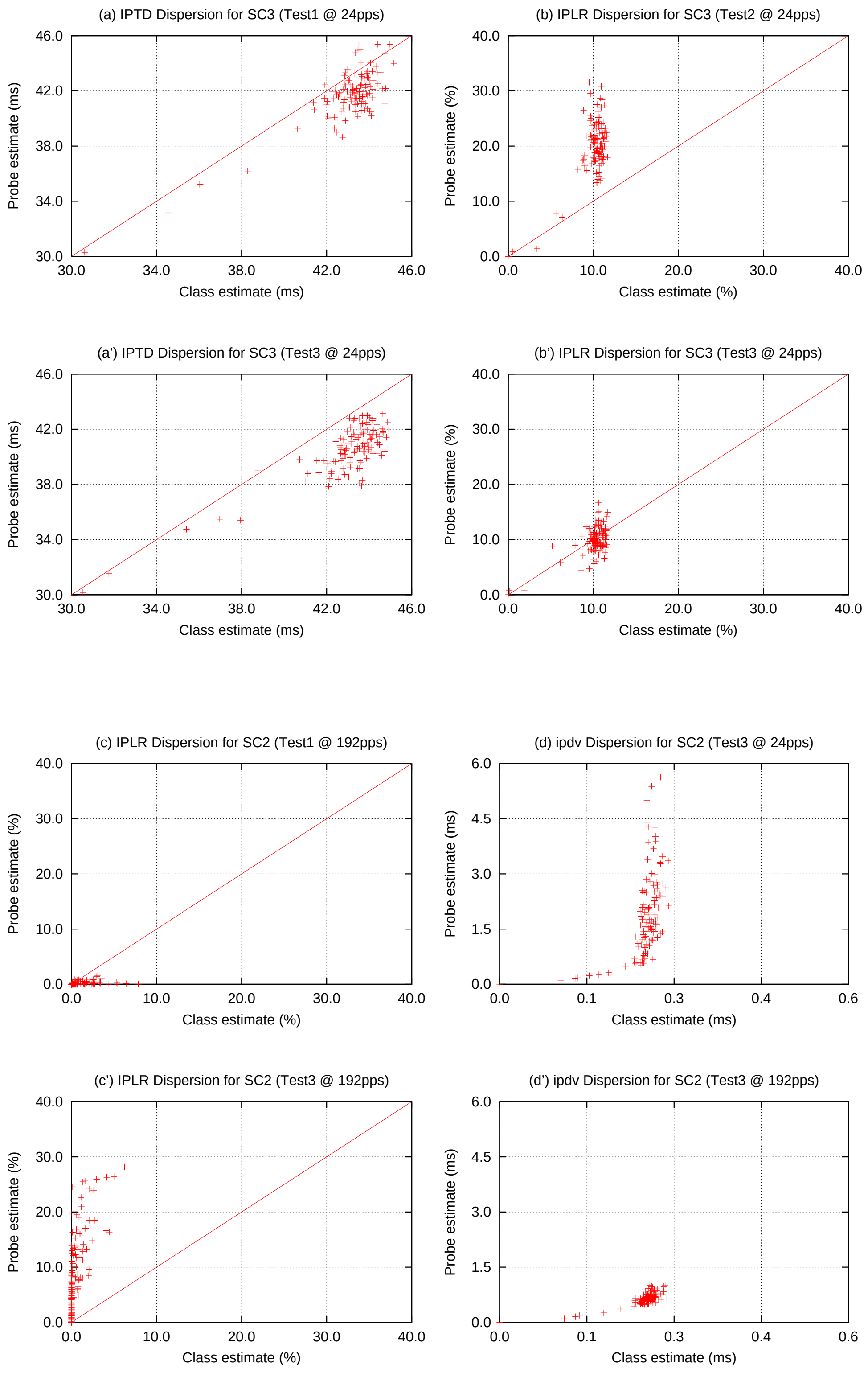


Figure 7.6: Dispersion of (a,a') IPTD for SC3 - green and interleaved @ 24pps; (b,b') IPLR for SC3 - red and interleaved @ 24pps; (c,c') IPLR for SC2 - green and interleaved @ 192pps; (d,d') ipdv for SC2 - interleaved @ 24 and 192pps

estimation for a probing rate of 24pps.

Test2 and Test3 allow to conclude that coloring probes can be particularly useful to provide both an indication of network congestion (through loss detection) and feedback to traffic control mechanisms, for very low probing rates. For SLS auditing and traffic control mechanisms requiring accurate quantitative inputs, higher colored probing rates are needed. SC2 IPLR scale is however difficult to meet, not benefiting significantly from that rate increase.

Test4 - TCP probing

As SC3 is oriented to TCP traffic, Test3 has been extended so that an FTP probing source is now considered in this class (Test4), approximating the probing to the class traffic characteristics. The results show that the color of this type of probing stream is even more relevant than of UDP probing (Test1,Test2,Test3). The color is relevant both for the estimate accuracy and for the probing overhead. Once again, green FTP probes are not able to detect loss in SC3 and the probing rate may reach a worrying 2Mbps rate, i.e., 15% of the class bandwidth share. This may occur when the probing source does not experience any loss and keeps taking over bandwidth of other TCP flows that either adapt or terminate. Red FTP probes are far less bandwidth demanding (30kbps) with the cost of emphasizing the problems identified in Test2. As for Test3, an interleaved color FTP probing pattern leads to a better compromise between overhead (0.4%) and accuracy.

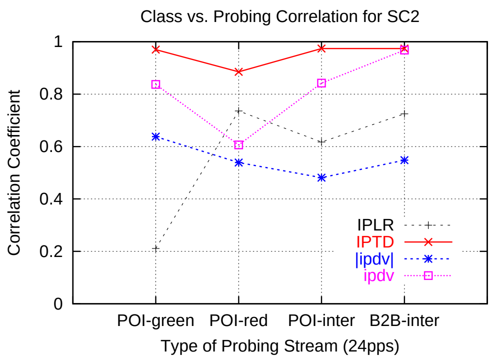
Test5 - Improving ipdv estimation

Generically, it was found that ipdv is a rather sensitive metric to network load and its variability. The results illustrated in Test1 and Test3 show that ipdv scale for the classes SC2 and SC3 is difficult to obtain regardless of the test probing rate considered. While small ipdv variations are magnified by probing, ipdv mismatch under the different probing rates suggests that queuing delay oscillations persist across multiple time scales. For moderate loads, ipdv is more closely measured as the queues remain in a reasonable steady state [17].

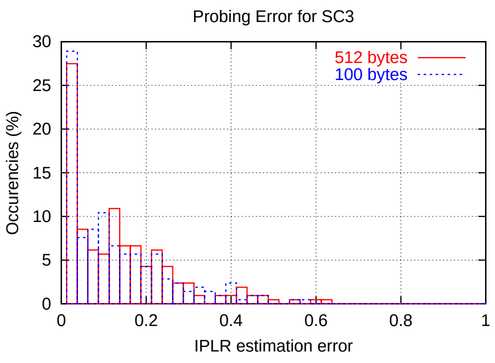
As decreasing the interpacket gaps through a probing rate increase did not successfully solve ipdv scale estimation, a new probing pattern was considered which on average tries to keep regular and light the mean probing rate while reducing interpacket gaps. The new probing pattern $B2B_P$ (see Section 4.3.1) acts as a back-to-back on-off source, where the number of packets inside the on period and the on/off sojourn times are configurable. The rate and duration of the on period determines the amount and how close the probes are in the sample event; the off period can be either deterministic or random. The use of a non-deterministic off period avoids possible network synchronization effects [22].

Test5 considers interleaved $B2B_P$ probing sources generating 8 and 24pps, respectively, with on and off periods of 125ms, i.e., corresponding to four back-to-back bursts. It was noticed that, when compared to POI_P with similar rates, interleaved $B2B_P$ probing streams lead to better estimates of ipdv scale, also with better results on IPTD and IPLR. This improvement is notorious in the experiment with probing at 24pps as shown in Figure 7.7(a), where the correlation coefficient between class and probing outcome is evaluated for all QoS metrics and all test scenarios previously considered.

Further tests exploring $B2B_P$ functionality to improve multipurpose estimation are left for future study.



(a)



(b)

Figure 7.7: (a) Correlation between class and probing estimates for different probing streams; (b) IPLR error estimation

Test6 - Exploring probing packet size

Intuitively, small size probing packets do not necessarily experience loss when large packets do. In fact, near queue overflow, a small packet is more likely to be enqueued than a larger one. So, apparently, probing packet size should be similar to the mean packet size of the class it intends to measure.

The present test scenario aims at exploring if the size of probing packets influences IPLR estimation. For the test conditions in [17], Figure 7.7(b) shows the absolute IPLR estimation error ($\epsilon_{IPLR,i} = |IPLR_i^{real} - IPLR_i^{estimated}|$) obtained for SC3 when an equivalent number of red probing packets of 100 and 512 bytes (the same as in the class) is considered. As the results show, the histograms for both packet sizes are mostly overlapped suggesting minor differences in the observed error. Although there is not evident impact of probing packet size on IPLR results, a mixed combination of probing packet sizes is sometimes used [174].

Additional considerations

Depending on the overall purpose of QoS metrics and traffic control mechanisms which may react based on them, increasing the time interval Δt in which measurements are carried out may overcome excessive sensitivity to fluctuations and mis-scaling of metrics' behavior. A wider Δt is likely to allow more stable measurements facing traffic variability and more probing packets are taken into account in a single measure. However, according to [199], to reach accurate measurements the number of probes considered is more relevant than extending the measurement interval and when the number of probes is increased accuracy is achieved earlier. Exploring the impact of Δt on multipurpose measures' accuracy was left for further study. Nevertheless, as regards the edge-to-edge monitoring-based AC mechanism in use, obtaining measurement inputs each 5s revealed to be a good compromise for having an updated vision of network dynamics in order to guide AC decisions efficiently.

In the context of active measurement, although the use of Poisson probing in real environments is recommended [22] (see also Section 4.3.1), it may constrain the Δt in use. In fact, for small Δt values and low probing rates (e.g., $\Delta t = 5s$; 2 pps), there might be intervals where no probe packets are generated due to the unbounded nature of exponential interarrivals [22]. The use of a probing on-off source (such as $B2B_P$) with a deterministic on period and a bounded random off period will allow to take advantage of pre-defined probing bursts while preventing possible synchronization effects.

Finally, a remark is made regarding distinct test scenarios oriented exclusively to UDP traffic. The evaluation of the active measurement methodology considering three classes of UDP traffic, i.e., SC3 carrying out UDP traffic instead of TCP, and SC1 used as concurrent class instead of SC2 is presented in [17]. The tests results, although not covering a wide range of probing rates and schemes, show similar trends as regards the considered IPTD, ipdv and IPLR metrics

(Test1 and Test2). In [17], a detailed table including relevant statistics was provided aiming at comparing, infer and correlate probing and class measurements outcome, for the different service classes. In [12], initial results considering also three classes of UDP traffic and SC3 as concurrent traffic are also available.

7.2.3 Evaluation of the estimation mechanism

In a first instance, the evaluation of an estimation mechanism consists of determining how close an estimate is to the real traffic load. In this way, the rate estimations of each service class using the estimation mechanisms TW, Avg_PS and EA described in Section 6.3 are compared (see Figure 7.8), taking Avg_PS estimates as reference [12]. This is because Avg_PS represents the real aggregate mean rate in a pre-defined interval S. In this experiment, using T=10, S=2 and $\gamma = 0.25$, the traffic sources are $EXPOO$ with mean rate 500kbps, on/off=0.5s, and flow's interarrival and holding times 0.4s and 120s, respectively [12].

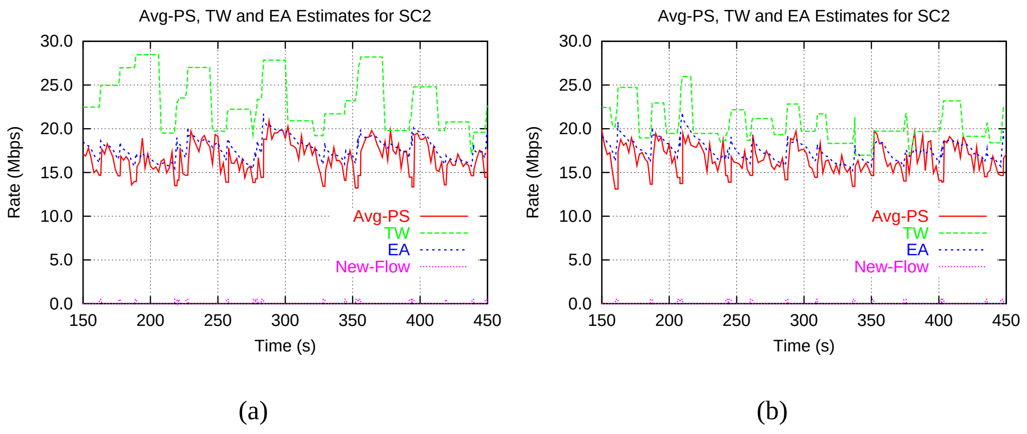


Figure 7.8: Comparison of estimation mechanisms: (a) resetting T; (b) without resetting T on flow admittance

In most of the cases, TW leads clearly to overestimation of the metrics and, in practice, it can be a very conservative method. In special, when the window T is reinitialized upon a new flow admission and for short flow interarrivals, the estimate increases steadily as the departure of flows is not taken into account. The importance of the ratio between flow duration and T is studied in detail in [105]. However, this method allows to consider in advance the weight the new admission might have. This also occurs with EA, where the estimation is artificially increased when a new flow is admitted. This estimation method is controlled by the parameter γ. As shown in Figure 7.8, using $\gamma = 0.25$ a close match is achieved.

As far as AC is concerned, there are other aspects to consider: (i) the estimate is due to be used during a measurement time interval; (ii) the estimate needs to reflect, and somehow foresee, the network behavior trends. Initial tests on AC criteria presented in [12] show that Avg_PS allows to achieve high network utilization without service violations, for CBR traffic. However, for EXP and PAR traffic, all services have suffered degradation. EXP/PAR traffic fluctuations and a particularly low estimate lead to overacceptance. When this happens, in the following estimation period, the AC rate and QoS control rules will refrain new flows from entering the network, however, degradation may still occur during the lifetime of existing flows. This effect can be reduced when using TW and EA as the flow rate is accounted for in advance. In fact, an immediate increase of the estimate, reflecting the impact that the new flow rate will have, allows a more adaptive and conservative AC. This has motivated the implementation of an hybrid Avg_PS (Avg_PS_Alt) mechanism that adjusts, in each I_n, the rate estimate according to the flow rate of new accepted flows (in the same I_n). This mechanism will be used throughout the following experiments.

7.3 Evaluation of the AC criteria

This section intends to provide a proof-of-concept of the proposed AC model regarding its ability to self-adapt and control QoS and SLS parameters in multiclass IP networks, assessing its effectiveness in satisfying service commitments while achieving high network utilization. In this evaluation, a single multiservice domain ruled by AC Eqs. (5.7) and (5.10) is considered. Focusing initially on the intradomain operation circumscribes the subject under study, allowing a clearer identification and understanding of the most influent variables, and an in-depth performance analysis of the AC criteria in controlling the QoS levels in the domain and the utilization of existing SLSs. A multidomain performance analysis, including the end-to-end AC rule (5.12), is left for future study.

Generically, the performance analysis of the AC criteria will consist of assessing each class QoS behavior, reflected by the values obtained for the controlled QoS parameters, and of evaluating and verifying each class and SLS rate shares. This involves:

(i) verifying if QoS parameters are in conformance with the established QoS levels;

(ii) quantifying QoS violations, at class and packet level;

(iii) evaluating each class blocking probabilities;

(iv) measuring the utilization level of each class individually and of the network domain globally, verifying the conformance of each SLS rate share (R^{+}_{i,E_m}).

This evaluation process, involving a simultaneous and progressive tuning of the variables influencing the model behavior, takes into consideration the distinct test conditions described in the following section.

7.3.1 Test scenarios taxonomy

Table 7.3 summarizes the planned test scenarios exploring different aspects which may influence the performance of the AC model. Similarly to the evaluation of the active monitoring process, for each test scenario, aspects of the model such as the type of concurrent or cross traffic (referred as CT-I2), the type of traffic sources considered in each class and other relevant information evaluated in each test, are included in Table 7.3.

Table 7.3: Test scenarios taxonomy - AC evaluation

Test Scen.	Tested Variable	AC model configuration		Other Information
		$CT-I2$	Source models (SC1,SC2,SC3)	
Test1	Generic operation	All	$EXPOO_{SC1/SC2}, FTP_{SC3}$	QoS/Share/Utilization
Test2	Implicit AC	All	$EXPOO_{SC1/SC2}, FTP/Telnet_{SC3}$	$AC\_Status_{\Delta_{t_i}}$
Test3	Cross traffic	All	$EXPOO_{SC1/SC2}, FTP_{SC3}$	Relevance QoS Rule
Test4	β^{+}_{i,E_m}/$T_{i,p}$	$SC2$	$EXPOO_{SC1/SC2}, FTP_{SC3}$	Load/Metrics
Test5	Traffic charact.	$SC1/SC2$	$CBR/PAR_{SC1/SC2}, FTP_{SC3}$	Rate/Fint/Fhold/Fairness
Test6	Δt_i	$SC2$	$EXPOO_{SC1/SC2}, FTP_{SC3}$	Load/Fint/Fhold/χ_{i,E_m}

In more detail, Test1 and Test2 are devoted to an initial assessment and tuning of the explicit and implicit AC criteria. In these tests, the concurrent traffic of each service class, injected into ingress I_2, contends with I_1 traffic, and the aggregate is considered for load estimation at egress E_1. QoS parameter estimation at E_1 follows an (I_n, E_1) perspective. Test3 considers that the traffic injected into ingress I_2 is cross traffic, i.e., it will use the domain resources and share the bottleneck link without being considered in the estimation of SLS utilization performed at egress E_1. Hence, E_1 is not aware of cross-traffic apart from the impact it may have on QoS estimation. This aspect is of major relevance as, due to the internal traffic dynamics and topology characteristics, a given amount of traffic may constitute an additional load just in parts of an edge-to-edge path. Therefore, Test3 will allow to test the impact of cross traffic on the AC model performance and reevaluate the initial model parameterization. Tuning safety margins and exploring new thresholds, identifying the most relevant QoS parameters under control, are aspects explored in Test4. Test5 is devoted to study the effects that traffic characteristics, resulting from different source models, flow interarrival and holding times, have in the AC criteria performance. The influence of the measurement time interval Δt_i is studied in Test6. For each test scenario, the column $Other\ Information$ highlights several aspects that are subject of discussion in the corresponding section.

The service-dependent AC rules are parameterized as specified in Table 7.1. By default, the values of β^{+}_{i,E_m} and $T_{i,p}$ in Table 7.1 are applied, with exception of Test4 where several values of those variables are tested. SC1, SC2 and SC3 traffic is generated resorting to the source models specified and parameterized according to Table 6.5. Although Table 6.5 includes flow interarrival times ranging from 300ms to 2s, most of the presented results correspond to tests performed either under high demanding conditions, with a flow interarrival of 300ms for SC1 and 500ms for SC2 and SC3 (referred as Fint1), or moderate conditions where the previous values are doubled (referred as Fint2)[7]. The measurement time interval Δt_i is set to $5s$, with exception of Test6 where $\Delta t_i = 5;\ 30;\ 60s$ are used. Once again, the QoS and utilization measures report to mean values in Δt_i. For explicit AC, the Avg_PS_Alt mechanism is used to estimate the average rate within a measurement time interval ($S = \Delta t_i$), considering rate adjustments carried out at each I_n.

As a final remark, for each (I_n, E_m) pair, a single probing source is embedded in each service class for active measurement purposes. However, while the active monitoring process is being tuned, the estimation of relevant parameters for the AC criteria is based on passive measurements. This avoids misleading the AC model evaluation with eventual inaccurate estimates.

The following sections will concentrate on the results obtained for each of these test scenarios. Despite the sequence of the test scenarios presented in Table 7.3, situations such as the initial study of the AC criteria operation and performance involved the simultaneous evaluation of distinct variables.

[7]Note that, as shown in Test1 (see Section 7.3.2), the values of Fint1 and Fint2 induce a network load that allows triggering the AC criteria. Apart from Test1 and Test2 where both situations are deeply evaluated, unless otherwise stated, the remaining tests use Fint2. Similarly, unless otherwise is stated, SC3 consists of traffic from FTP sources.

7.3.2 Test1 - Generic model operation

In this test scenario, the generic model operation is assessed in terms of its capability of assuring each service class QoS commitments and, simultaneously, verifying the utilization levels obtained per class and globally. Considering the network topology illustrated in Figure 6.2, traffic flows belonging to service classes SC1, SC2 and SC3 are generated dynamically, undergoing AC at domain entrance[8]. Whereas SC1, SC2 and SC3 flows arrive and leave the domain through I_1 and E_1, respectively, concurrent flows (CT-I2) arrive and leave through I_2 and E_1, respectively. The potential overacceptance problem deriving from concurrency and traffic fluctuations is, at this point, reduced through the definition of safety margins.

Generically, for the defined test conditions, the results of Test1 show that the self-adaptive behavior inherent to on-line monitoring combined with the established AC rules is effective in controlling each class QoS and SLS commitments. More specifically, when concurrent traffic (CT-I2) is either SC1 or SC2, as illustrated in Figure 7.9[9], the obtained IPTD, ipdv and IPLR of the service classes SC1, SC2 and SC3, exhibit a very stable behavior regarding the pre-defined QoS levels, in special, for delay related parameters. Although IPLR is more difficult to keep tightly controlled, its deviations stay well-bounded. Note that, these results are particularly encouraging attending to the high overall network utilization obtained (see Figure 7.10), considering the bottleneck of 34Mbps. This figure also illustrates that the share configured for each class is well accomplished, with SC2 and CT-I2 obtaining a similar behavior and share and with SC3 exceeding its share slightly. This occurs due to the adaptive nature of traffic within SC3, the more relaxed implicit AC criterion (discussed in Test2, Section 7.3.3) and the work conserving nature of the scheduling algorithm in use, which allows SC3 to take advantage of unused resources. When the concurrent traffic belongs to SC3, the total utilization reaches its maximum level ($\sim 100\%$) with a noticeable increase of IPTD in SC3, which may reach 80ms. Despite that, SC3 IPLR is kept within the same range of variation exhibited in Figure 7.9 and the remaining classes maintain a similar behavior as before.

[8]A set of initial tests performed without including the AC proposal, i.e., where all generated flows are accepted, have resulted in a obvious degradation of the QoS behavior of all service classes and a full utilization of the available bandwidth. Considering concurrent traffic from SC2, $EXPOO$ source models and Fint1, the IPTD and IPLR behavior for all service classes are as follows: (i) SC1, having its maximum rate controlled by the PQ scheduler, exhibits the worst behavior ($\overline{IPTD}$=82ms, $IPTD^{max}$=346ms, $Total\ IPLR$=0.68); (ii) SC2 traffic obtains values around $\overline{IPTD}$=52ms, $IPTD^{max}$=93ms, $Total\ IPLR$=0.69; (iii) SC3 traffic due to its adaptive nature achieves the best results ($\overline{IPTD}$=46ms, $IPTD^{max}$=99ms, $Total\ IPLR$=0.20). Generically, without AC, the obtained QoS values are far away from the defined service thresholds. When the PQ EF rate is enlarged (for SC1), the QoS degradation of the remaining service classes, and particularly of SC2, is even worst.

[9]All figures included in Test1 report to experiments carried out with CT-I2=SC2 and Fint1.

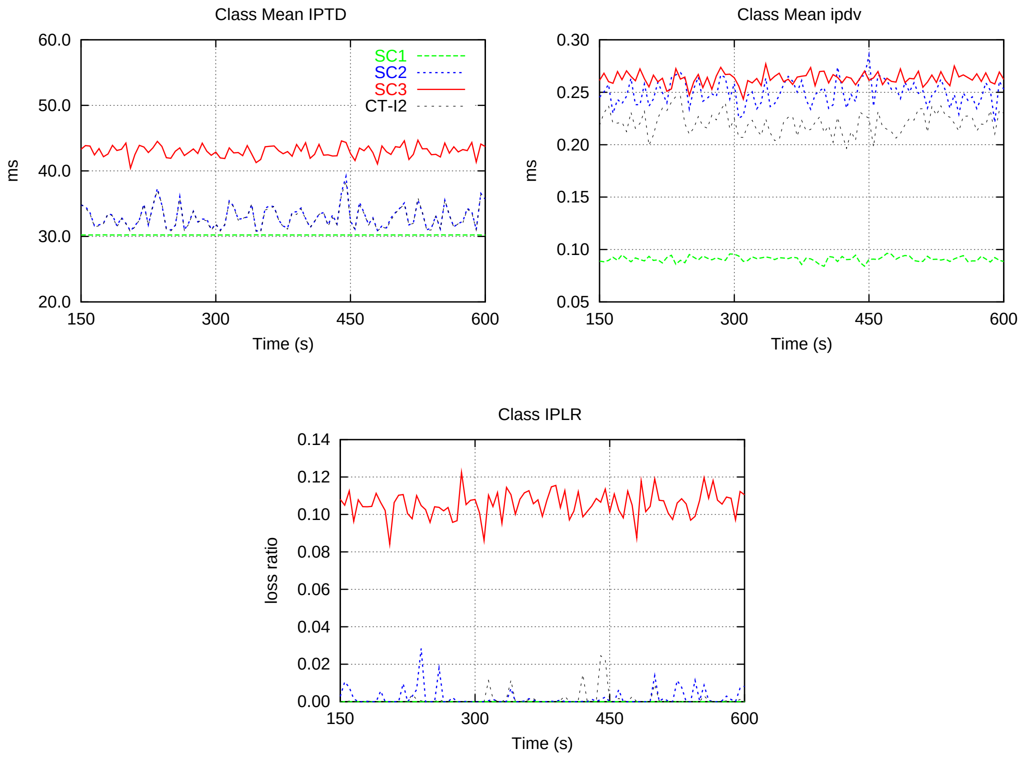


Figure 7.9: Class mean IPTD, ipdv and IPLR

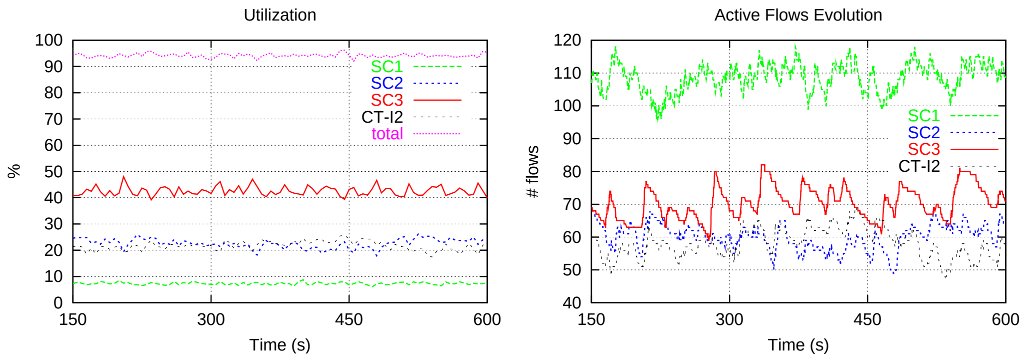
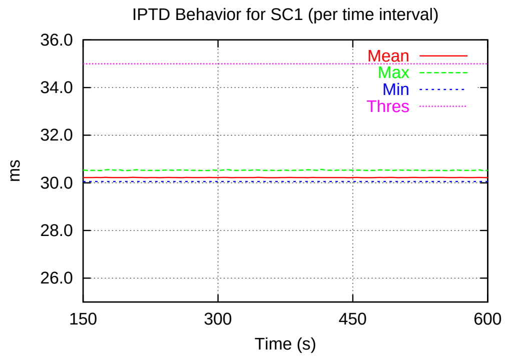


Figure 7.10: Utilization and number of active flows



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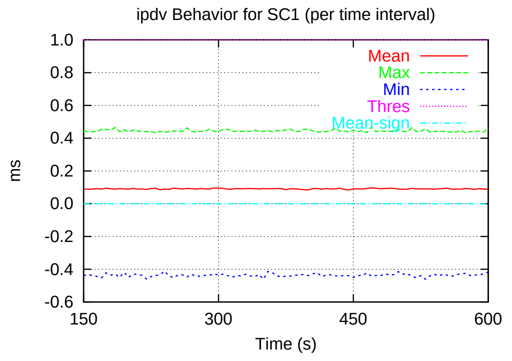

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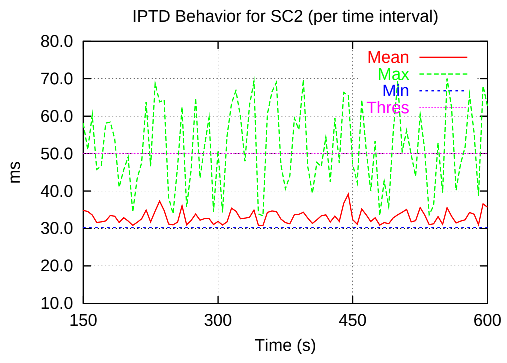

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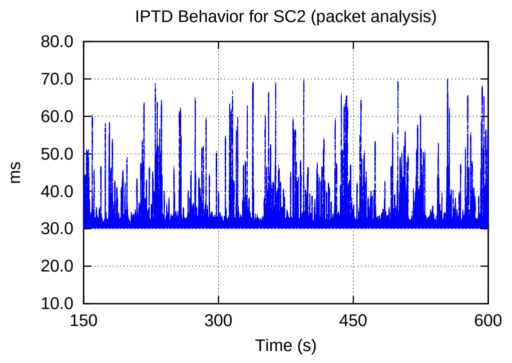

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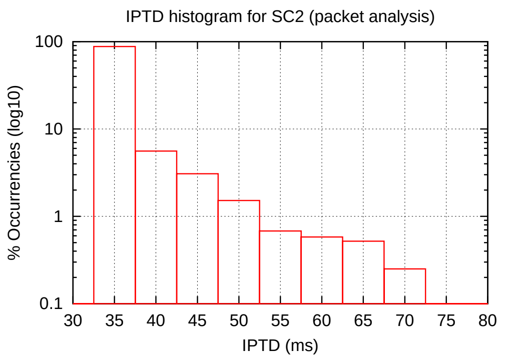

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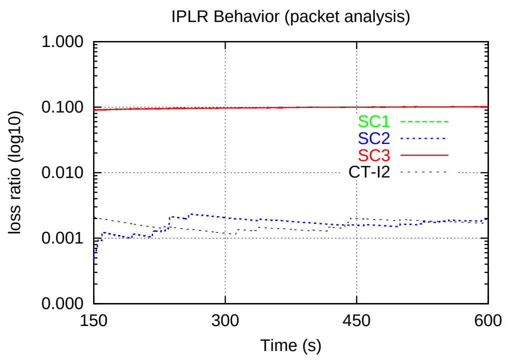


(f)

Figure 7.11: Results in Δt_i: (a) (b) IPTD and ipdv for SC1; (c) IPTD for SC2. Results at packet level: (d) IPTD for SC2 ; (e) IPTD histogram for SC2; (f) IPLR evolution for all classes

Detailing AC results

Going further on the QoS analysis in the domain, a more detailed view of some of the controlled metrics for each class is shown in Figure 7.11. This figure represents the evolution of IPTD and ipdv in Δt_i, including their mean, minimum, maximum and threshold values in each interval. Some of the most interesting metrics are further detailed, plotting their evolution at packet level and corresponding histogram. The evolution of IPLR along the time is also presented. From the graphs in this figure, it is visible that:

(i) SC1 is very well controlled presenting a stable QoS behavior. As shown, IPTD is kept almost constant throughout the simulation period. The mean ipdv assumes a low value as a result of small variations, bounded by a well-defined maximum and minimum value. When the mean ipdv is not evaluated as an absolute value, i.e., $\overline{ipdv^s}$ (mean-sign) is taken instead of $\overline{ipdv}$, the positive and negative ipdv variations tend to cancel each other in each Δt_i;

(ii) for SC2, although the mean IPTD is well-bounded, in some time intervals, the maximum IPTD exceeds the defined thresholds. From the analysis of the plots at packet level and corresponding histograms, it is clear that the number of packets exceeding the QoS thresholds is very small. This is sustained by the statistical analysis of the involved time series, included in Table 7.4;

(iii) SC3 IPLR evolution tends to the defined IPLR threshold of 10^{-1}. For SC2 traffic, IPLR has a less continuous behavior as it results from occasional loss events, converging to the defined threshold of 10^{-3}.

Table 7.4[10] summarizes statistical results obtained for each service class SC_i as regards: the average number of active flows; the corresponding utilization; the percentage of packets exceeding the pre-defined IPTD and ipdv bounds[11]; and the total loss ratio. The results, which consider two distinct flow interarrival times - Fint1 and Fint2, show that:

[10]The measurements reported in Table 7.4 refer to average values from experiments with SC2 as concurrent traffic (CT-I2). The standard deviation and variance considering the distinct sets of results is very low. As an example, following the sequence SC1, SC2, SC3, CT-I2, for fint-2, the standard deviation for (i) $\#act\_flows$ is 1.04, 1.48, 0.92, 1.79; (ii) $\%util$ is 0.042, 0.60, 0.23, 0.68 (ii) $\%pkts\_viol$ for IPTD is 0, 0.25, n.a., 0.23; (iii) $total\ IPLR$ is 0, 0.0005, 0.0011, 0.0008. Due to the small variation noticed on the results, the following experiments will not detail these statistics. The results of a similar analysis at class and packet level for distinct test scenarios are provided in [13, 11].

[11]An instance of an SLS may specify in the Expected QoS field a percentile or inverse percentile for a QoS parameter under control. The inclusion of the percentage of packets exceeding the parameters' bound, apart from the relevant information about whether the service commitments are met at packet level, can also be used to verify if the service percentile commitments are met.

Table 7.4: Test results and statistics at packet level

Service	#act_flows (avg)		%util. (avg)		%pkts_viol:(IPTD;ipdv)		Total IPLR	
Class	Fint2	Fint1	Fint2	Fint1	Fint2	Fint1	Fint2	Fint1
SC1	105.7	107.5	7.2	7.4	(0.0;0.0)	(0.007;0.0005)	0.0	0.00009
SC2	57.0	59.5	21.6	22.9	(1.62; n.a.)	(2.95; n.a.)	0.0011	0.0027
SC3	65.9	70.2	43.4	42.9	(n.a.; n.a.)	(n.a.; n.a.)	0.102	0.106
CT-I2	59.6	58.6	22.6	22.3	(1.55; n.a.)	(2.82; n.a.)	0.0018	0.0022

- in both cases, the global utilization is kept high, and each class rate share is well accomplished. Note that, considering the safety margins and the SLSs rate share defined in Table 7.1, the utilization target for SC1, SC2 and SC3 is 8.5%, 45% (SC2+CT-I2) and 40%, respectively. As explained later, the rate control is disabled for SC3. For SC1, considering the obtained results with CT-I2 from SC1 type, the achieved share is slightly increased to $\sim$ 8%;

- the percentage of QoS violations at packet level is very small, in special for SC1[12], and the total IPLR is within the pre-defined thresholds. Note that, a QoS threshold violation does not necessarily imply a service QoS violation, as the defined concept of threshold comprises a safety margin to the QoS parameter target value (see Eq. 5.11).

AC rules effectiveness

When examining in detail which AC rules determine the generic behavior of the model discussed above, the following is identified:

(i) SC1 flows are controlled essentially by the SLS rate control rule (Eq. 5.7) as a result of a stable QoS behavior associated with this high priority class;

(ii) AC for SC2 flows is triggered by SLS and/or QoS control rules (Eq. 5.7 and Eq. 5.10);

(iii) SC3 flows are mostly controlled by the QoS control rule (in fact, as explained in Test2 discussion on Section 7.3.3, the rate control rule is disabled);

[12]This is also true when the concurrent traffic is from SC1. For instance, for Fint2, there are no QoS violations at packet level in class SC1. Graphically, the results are similar to those in Figure 7.9.

(iv) according to the results, IPLR violations assume a predominant role in setting the variable $AC\_status_{\Delta t_i}$ to a rejection mode in the QoS control rule.

Although the AC rules are effective in blocking new flows when QoS degradation or an excessive rate is sensed, the effect of previously accepted flows may persist over more than one measurement time interval, depending on these flows' characteristics and duration. Nonetheless, the system tends to recover fast. The eventual overacceptance is mainly caused by traffic fluctuations reflecting a low activity period of the admitted flows. In fact, low estimation in Δt_{i-1} may lead to false acceptance during Δt_i. This effect, likely to be stressed by concurrency and traffic characteristics[13], is particularly evident when observing the behavior of the SLS rate control rule for SC2 and the resulting AC decision, as shown in Figure 7.12. To minimize this, more conservative estimates, larger safety margins and/or specific approaches to control concurrency, as discussed in Section 5.8.1, may be required.

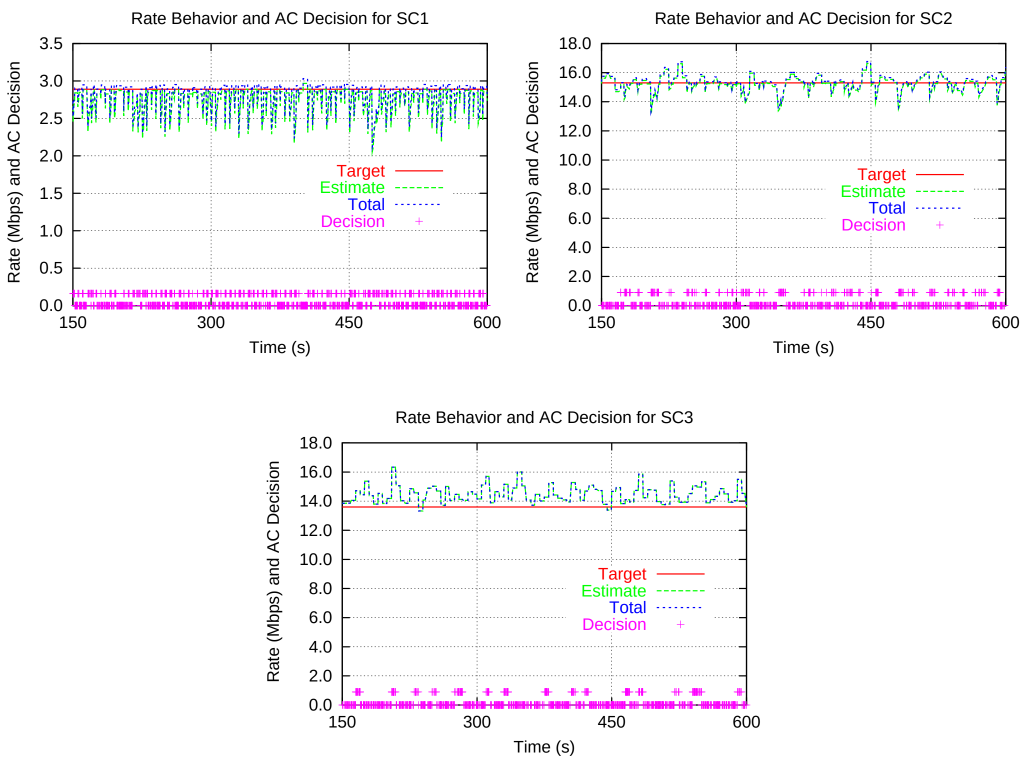


Figure 7.12: Rate estimate evolution and AC decision for SC1, SC2 and SC3

[13]The described effect is more visible when the involved flows are more demanding in terms of rate and duration (see Test5 discussion in Section 7.3.6 and [13]).

In Figure 7.12, *Target* line represents the value $\beta^{+}_{i,E_m} R^{+}_{i,E_m}$ above which AC rejection occurs, *Estimate* line represents the estimated rate or load of SLS^{+}_{i,E_m}, i.e., $\tilde{R}^{+}_{i,(*,E_m)}$, and *Total* line reports to the previous estimate by adding the new flow rate r_j. *Decision* dots represent a positive (dots above the x-axis) or negative (dots overlapping the x-axis) AC decision, considering also the QoS control rule evaluation. The almost constant overrate situation exhibited in Figure 7.12 for SC3, as mentioned before, results from the adaptive nature of TCP traffic combined with the traffic fluctuations of the remaining classes, the more relaxed SC3 AC criterion and the inherent properties of the scheduler in use.

In addition, the results with smaller safety margins for SC1 show that this class can be particularly affected by the scheduling mechanism. While PQ is suitable and commonly recommended to handle in-profile high priority aggregates (EF traffic), if the aggregate rate exceeds the maximum rate allowed by the scheduler, the class is severely punished. This is evident through an increase of IPTD and IPLR (see Figure 7.13 [13] and SC1 results in Section 7.3.4) resulting from the head-of-line blocking effect which persists until the scheduling cycle is completed. This stresses the need to have a tighter control on this class and a wider safety margin.

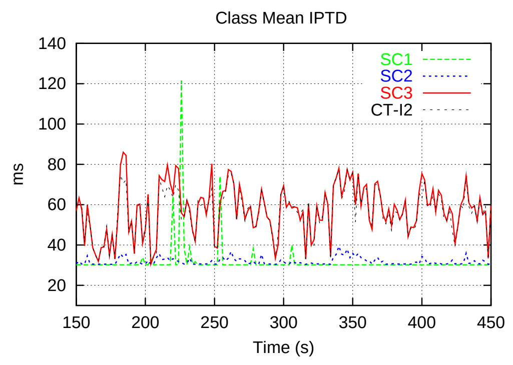


Figure 7.13: PQ effect on SC1 IPTD

7.3.3 Test2 - Redefining the implicit AC criterion

In the AC evaluation process, it was noticed that for implicit AC, controlling the rate variables included in Table 5.2 brings negative effects to SC3 stability and should be avoided. In fact, a criterion resorting to a rate-based $AC\_status_{\Delta t_i}$ and to $Adm\_flows_{\Delta t_i}$, which limits the number of active flows, leads to long AC blocking periods and to a resource taking over effect caused by long-lived flows. Conversely, considering an $AC\_status_{\Delta t_i}$ determined by QoS control has proved to be mandatory in order to keep a "lively" number of active flows (see Figure 7.10(b)), while satisfying the classes' QoS requirements. In more detail, the experiments carried out to assess the impact of these variables on the implicit AC criteria effectiveness show that:

(i) when the rate control determines the $AC\_status_{\Delta t_i}$ admittance value, this AC rule is clearly dominant, causing long rejection periods cyclically. In these periods, whose length depends on $Adm\_flows_{\Delta t_i}$, Δt_i, and on the flow interarrival and holding time distributions, long-lived TCP flows progressively take over spare resources freed by departing flows. As a consequence, the rate estimate remains high and $AC\_status_{\Delta t_i}$ is kept in rejection mode until few flows are left. When this stage is reached, the $AC\_status_{\Delta t_i}$ enters in an acceptance mode and a new cycle begins (see Figure 7.14);

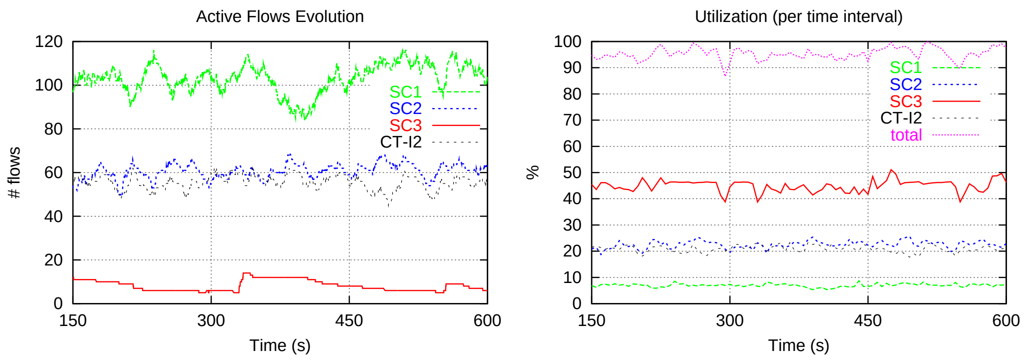


Figure 7.14: SC3 behavior with SLS rate control active: (a) active flows evolution; (b) achieved utilization (CT-I2=SC2 ; Fint1)

(ii) considering $AC\_status_{\Delta t_i}$ only determined by the QoS control rule has proved to be effective in maintaining the QoS parameter IPLR bounded. However, as in (i), SC3 may exceed slightly its defined rate share, taking advantage of SC1/SC2 unused bandwidth resources (e.g., due to their traffic fluctuations or safety margins), increasing the global utilization achieved by the system without an evident QoS degradation of SC1 and SC2;

(iii) controlling $Adm\_flows_{\Delta t_i}$ may also be relevant to assure that the accepted flows receive an adequate service, therefore, this variable should be dimensioned considering the class share and, on average, an acceptable throughput for the admitted flows[14]. Controlling SC3

[14]Choosing the value of one hundred for $Adm\_flows_{\Delta t_i}$ has proved not to be restrictive for flow admission in SC3 (as exhibited in Figure 7.10(b)), allowing the QoS control rule to be applied according to the defined IPLR threshold. For low rate interactive TCP traffic (e.g., Telnet using tcplib-telnet.cc default parameterization) the number of $Adm\_flows_{\Delta t_i}$ needs to be increased or disabled to make the QoS control rule effective.

based on a new AC rule that compares the throughput achieved by a probing TCP stream with a reference target value may be an alternative approach for implicit AC that will be explored in future.

The configuration of the implicit AC criteria in the experiments defined in Table 7.3, including Test1, has already followed the findings and suggestions expressed above.

7.3.4 Test3 - Impact of cross traffic

In this set of experiments, the traffic injected at I_2 traverses the multiclass domain in the same way as traffic injected at I_1 but, conversely to this one, it is not considered at egress E_1. In this way, I_2 traffic is seen as cross traffic in the link L_{C1-E1} having an impact on domain's QoS and load, without being explicitly measured at E_1. This means that E_1 does not consider that traffic when performing load estimations (more precisely, the estimation of SLS^+_{i,E_1} utilization ($\tilde{R}^+_{i,E_m}$)), but it senses its potential negative impact on $(I_{1,}E_1)$ QoS measurements (see Figure 7.15).

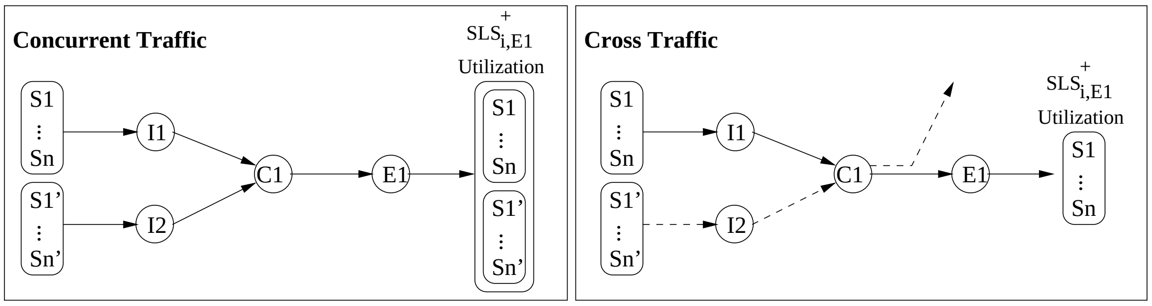


Figure 7.15: Concurrent vs. cross traffic for SCi

Test3 experiments allow to: (i) separate the dimensioning of R^+_{i,E_1} and the rate-based control rule from the bottleneck link capacity; (ii) further assess the effectiveness and relevance of the QoS control rule; (iii) redefine safety margins and thresholds and, above all; (iv) evaluate the AC criteria in scenarios likely to occur in real network environments. The impact that the unmeasured cross traffic has on the AC criteria effectiveness is evaluated analyzing the behavior and performance achieved by the service classes in the path $(I_{1,}E_1)$. At I_2, cross traffic from the three defined classes is considered separately, using an $EXPOO$ source with an on/off period of 250/250 ms. Table 7.5 illustrates the percentage of cross traffic submitted to the network in terms of per class and global share. This latter percentage indicator is used throughout the experiments.

Table 7.5: Percentage of cross traffic

CT-I2	% Class Share		% Global Share	
SC1	25%	50%	2.5%	5%
SC2	20%	40%	10%	20%
SC3	25%	50%	10%	20%

The obtained results vary substantially according to the service class considered as cross-traffic. The more interesting and meaningful results are obtained when SC2 cross traffic is considered, hence, it is covered first.

SC2 cross traffic

In the presence of cross traffic from SC2, the main rule determining the AC decisions in this class is the QoS control rule, with an $AC\_status_{\Delta t_i} = reject$ activated by IPLR violations. This rule by itself maintains the QoS levels, in particular IPLR, controlled with a behavior similar to the one showed in Figure 7.9. The SLS rate control rule and the corresponding safety margins are now less relevant and restrictive. In fact, maintaining their values, a rate limit to I_1 traffic is more unlikely to occur due to the tight IPLR threshold and the influence of cross traffic on the loss at C_1 and, consequently, on the measured IPLR for the pair (I_1, E_1).

For the default QoS thresholds, the global utilization of SC2 (I_1+ CrossTraffic) decreases comparing to the concurrent case, with the amount of traffic accepted at I_1 being adjusted according to the amount of cross traffic. For instance, to maintain the QoS compromise at the same levels when the volume of cross traffic is increased from 10% to 20% , i.e., up to 40% of the SC2 class share, AC decreases the number of accepted flows at I_1 approximately to half of its initial value. Consequently, the utilization drops from 44% (concurrent case) to 36% and 32% respectively. This interesting effect can be explained attending to the distinct traffic characteristics of concurrent and cross traffic. In fact, concurrent traffic results from the aggregation of multiple flows, and cross traffic is induced resorting to a single high rate bursty flow. As a consequence, its effect on $C1$ queue occupancy increases loss events triggering the QoS control rule more frequently. Figures 7.10 and 7.16 allow to compare the utilization and burstiness of SC2 and CT-I2 traffic for the three referred conditions.

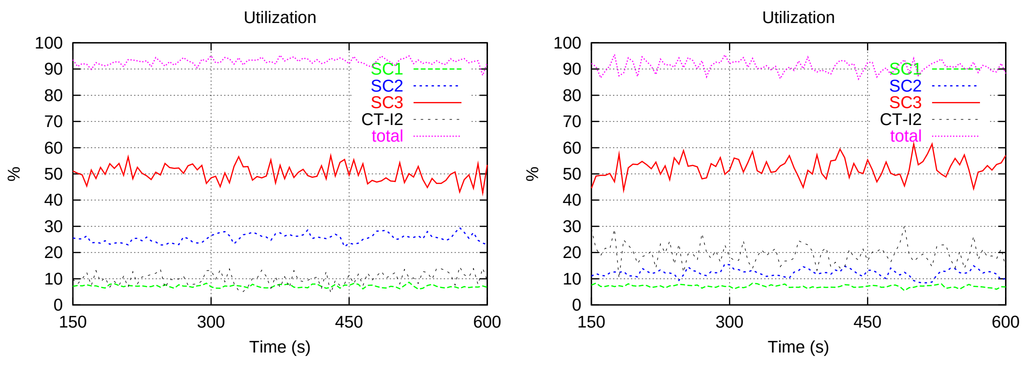


Figure 7.16: Utilization for: 10% of SC2 cross traffic (left); 20% of green SC2 cross traffic (right)

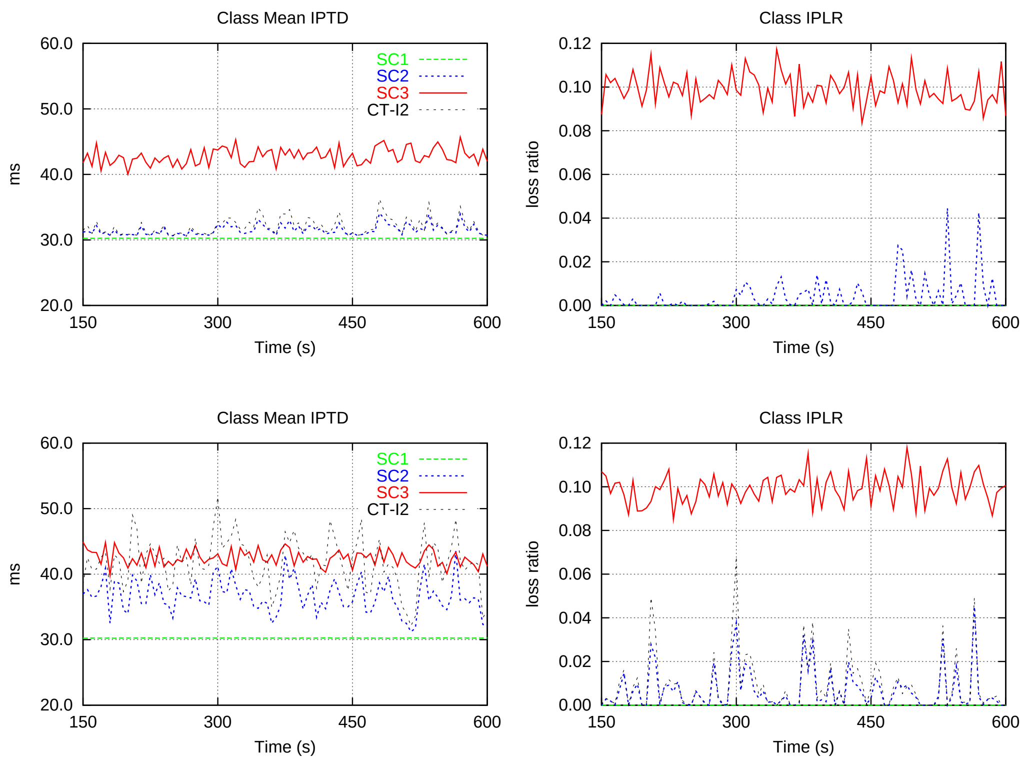


Figure 7.17: Class mean IPTD and IPLR for 10% of SC2 cross traffic (above); 20% of green SC2 cross traffic (below)

Another aspect influencing SC2 IPLR regards the effect of policing/marking at ingress nodes and RIO-C queue management at $C1$. The different characteristics between SC2 traffic from I_1

and SC2 cross traffic from I_2 result in distinct packet marking and, consequently, distinct packet discarding at $C1$. In particular, while for 10% of cross traffic RIO-C impact on loss affects SC2 traffic coming from I_1, for 20% of cross traffic that impact falls essentially on cross traffic due to the large number of colored (yellow and red) packets. When cross traffic is forced to green marking at I_2, IPLR behaves similarly for SC2 and CT-I2. Figure 7.17 shows both test conditions. From that figure, it is also notorious that IPTD increases for 20% of cross traffic. IPTD behavior for both conditions (10% and 20%) is detailed in Figure 7.18. The packet level analysis reveals that $\%pkt\_violations$ on IPTD is 0.05 and 12.8, respectively, and $Total\ IPLR$ is 0.005 and 0.008.

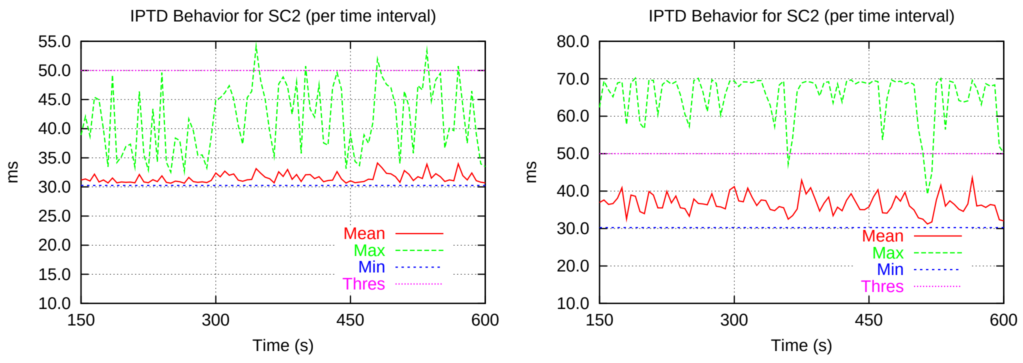


Figure 7.18: Detailed analysis of IPTD for 10% of SC2 cross traffic (left); 20% of green SC2 cross traffic (right)

SC1 and SC3 maintain a similar behavior to the one exhibited in Test1. As usual, the service class SC3 takes over unused bandwidth resources increasing its utilization slightly. This behavior can be observed in Figure 7.16.

SC1 cross traffic

In the experiments with cross traffic from class SC1, the results show that the QoS of this class is significantly affected by cross traffic and, under the default safety margins and thresholds, numerous QoS violations in IPTD, ipdv and IPLR become evident and difficult to control despite the rejection indication provided by the QoS control rule. This is due to high traffic fluctuations and to the nature of the scheduling mechanism, which has defined a Max-EF-Rate for PQ treatment. In the presence of an excessive rate at C_1, unmeasured and uncontrolled by E_1, several blocking events may occur at the scheduler affecting SC1 traffic.

As shown in Figure 7.19, for 2.5% of SC1 cross traffic (i.e., 25% of the class share), this leads to several episodes of QoS threshold degradation, particularly for IPLR[15]. The QoS control rule, detecting these violations, sets $AC\_Status_{\Delta t_i}$ to rejection mode. However, the effect of flows already accepted within the previous acceptance period (bounded by the rate control rule with $\beta^+_{i,E_m} = 0.85$), along with the cross traffic load, leads to QoS degradation that may span more than one Δt_i. Consequently, defining larger safety margins becomes essential to accommodate and reduce the effects of unmeasured cross traffic. These safety margins will essentially limit I_1 traffic through the rate control rule, and should be defined in order to guarantee that I_1 traffic in addition to the amount of cross traffic (and corresponding high fluctuations) do not exceed the class share and the corresponding Max-EF-Rate value. As an example, for 2.5% of SC1 cross traffic, $\beta^+_{i,E_m} = 0.5$ allows an SC1 behavior similar to the one achieved in Test1 with $\beta^+_{i,E_m} = 0.85$ (without loss). Figure 7.20 compares the rate behavior of SC1 and the acceptance decisions at I_1, for $\beta^+_{i,E_m} = 0.85$ and $\beta^+_{i,E_m} = 0.50$. As shown, $\beta^+_{i,E_m} = 0.50$ leads to a more stable AC behavior; the global SC1 utilization decreases from 8.5% to 6.8% (this value should increase for less bursty CT-I2). In both conditions, the remaining classes SC2 and SC3, maintain the expected behavior with a slight QoS improvement for SC2.

From the above tests with SC1 cross traffic, it is clear that the conservativeness and degree of overprovisioning of SC1 are fundamental. According to [6], a simple ISPs design rule for tight delay, jitter and loss control is provisioning twice the capacity of the expected aggregate peak load. Additional tests on SC1 performance are advisable, mainly considering distinct scheduling mechanisms and large-scale environments. This is also stressed by the findings in [46].

SC3 cross traffic

When cross traffic is from class SC3, the model behaves similarly to the concurrent traffic case. In fact, as AC for this class is not based on the rate control rule, the presence of cross and concurrent traffic is only reflected in the measured QoS. This means that SC3 IPLR is kept controlled by the QoS control rule, preserving the QoS behavior. The same occurs for the remaining service classes.

[15]The packet level analysis reveals that the $\%pkt\_violations$ for IPTD is 3.3, for ipdv is 0.36 and $Total\ IPLR$ is 0.012 (two orders of magnitude above the defined IPLR threshold). Although not visible in the figure, SC1 mean ipdv ranges from 0.10 to 0.30ms.

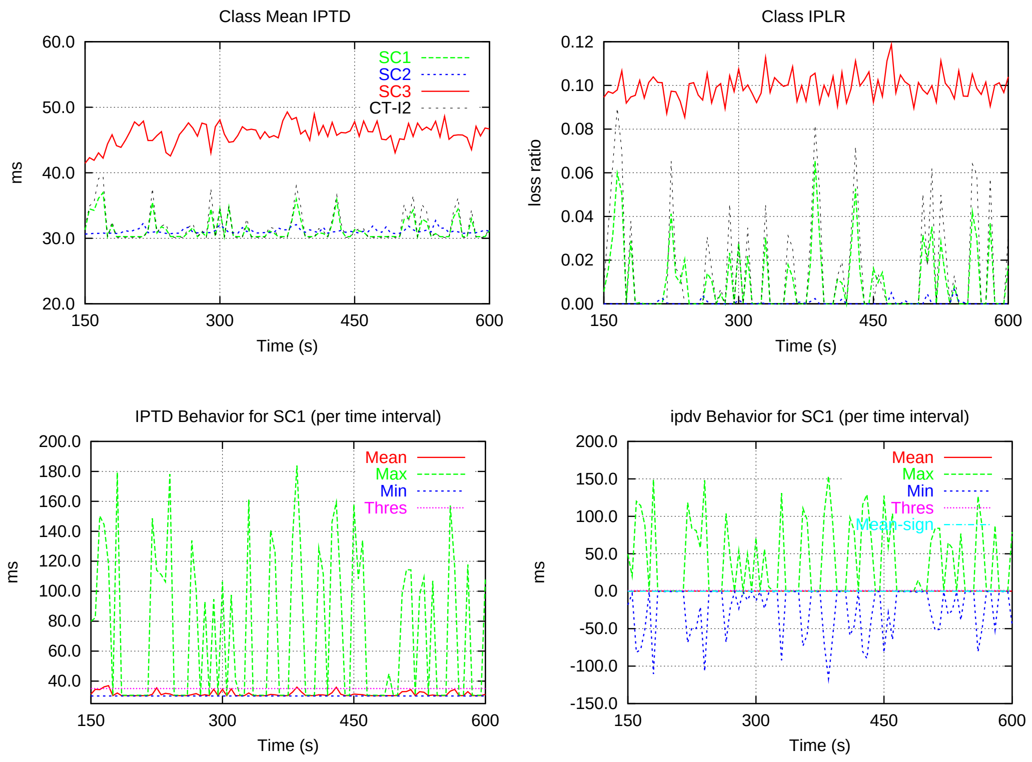


Figure 7.19: Class Mean IPTD and IPLR for 2.5% of SC1 cross traffic (above); detailed analysis of IPTD and ipdv (below)

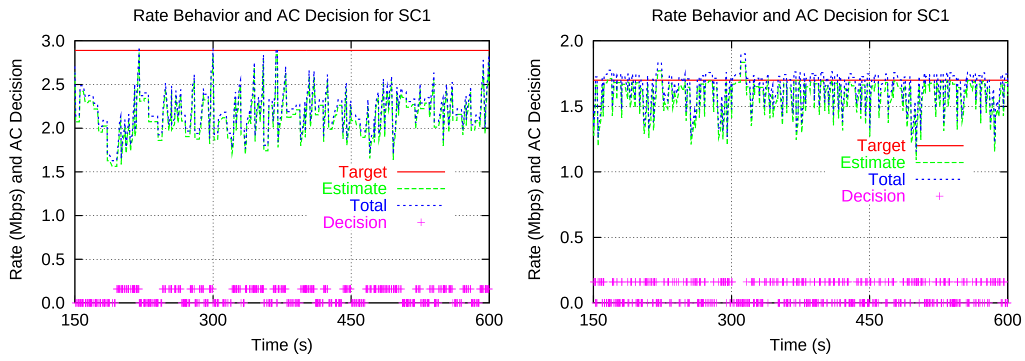


Figure 7.20: Rate estimation evolution and AC decision for SC1 at I_1 with $\beta^+_{i,E_m} = 0.85$ (left) and $\beta^+_{i,E_m} = 0.50$ (right)

Test3 concluding remarks

From these set of experiments, the relevance of the defined AC rules becomes evident in assuring service commitments in the domain. While the rate control rule assumes a preponderant role for service classes SC1 and SC2 to control the traffic load and indirectly QoS, particularly in situations involving concurrent traffic, the QoS control rule is decisive to assure the domain QoS levels in presence of unmeasured cross traffic[16]. In real environments, where the two type of situations are likely to occur simultaneously, the two AC rules will complement each other to increase the domain capabilities to guarantee service commitments. Although being encouraging on this aspect, the obtained results might be even more satisfactory when considering that a significant amount of the involved cross traffic will be sensed and controlled by other egress nodes.

From the above reasoning, it is important to remark that, knowing which AC rule is more influent on the AC decision process can also bring relevant information and directions for improving service configuration and provisioning both intra and interdomain.

7.3.5 Test4 - Redefining safety margins and thresholds

New safety margins

The results of Test1 and Test3 suggest that achieving a service level without QoS threshold violations requires more conservative estimates or larger safety margins (β^{+}_{i,E_m}). In Test4, this latter option is explored by establishing new safety margins aiming at a service provision without QoS violations. Additionally, varying the safety margins allows to induce and test different load conditions. In particular, assessing the AC performance under low to moderate loads is also important as it represents a realistic operating scenario, for instance, for many ISP network cores [6, 41].

Under these test conditions, the emphasis of the analysis is given to the behavior of the service classes, essentially SC1 and SC2, disregarding the values achieved for the global utilization. In fact, as explained before, due to the adaptive nature of SC3 traffic and to the work-conserving nature of the scheduling process, SC3 might use available resources and, therefore, the global utilization tends to remain at the same level.

[16]Once again, IPLR metric is the most relevant in setting $AC\_status_{\Delta t_i}$ to rejection mode.

In this way, for test conditions similar to Test1 and using SC2 as concurrent traffic (CT-I2), Test4 extends the results obtained initially for each service class SC_i, presented in Table 7.4, exploring how the blocking probabilities, the average number of active flows and the utilization evolve with the variation of the safety margins.

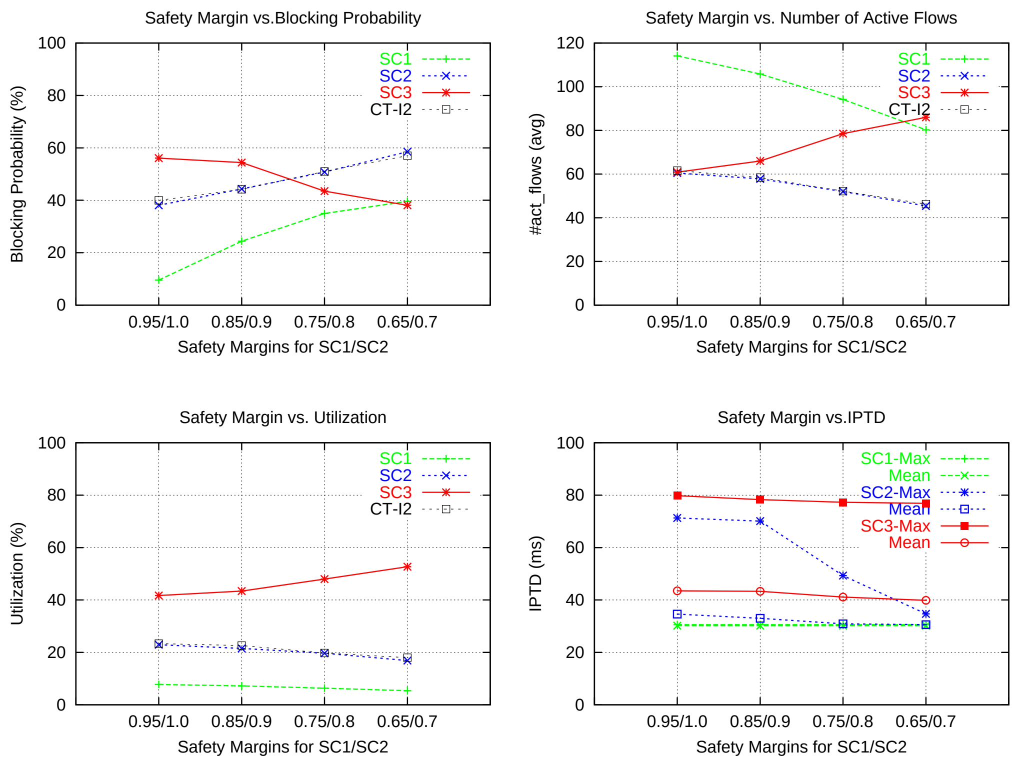


Figure 7.21: Influence of varying the safety margins on the blocking probabilities, average number of active flows, mean utilization and IPTD

Figure 7.21 shows four different sets of safety margins reflecting from less to more conservative AC scenarios. Once again, no safety margin was defined for SC3 as the rate control rule is disabled. The results in Figure 7.21 show an evident relation between the variables under analysis. Under more conservative conditions, the blocking probability increases for SC1 and SC2, and consequently, there is a consistent decrease in the number of active flows. In the same way, the utilization levels follow a descending trend. More precisely, SC1 illustrates an almost exact proportionality of 30% among the three variables studied when the safety margins vary from 0.95 to 0.65. SC2 also exhibits a clear proportionality among those variables but with a slight variation of 5% between the blocking probability and the other two variables. Reporting again to Figure 7.21, a clear inverted behavior is exhibited for SC3 resulting from the reasons explained above. In practical terms, the global utilization varies from 95.8% to 92.9%, which means that under the defined safety margins, the AC criteria, despite being more conservative on SC1 and SC2, achieves high network utilization. As regards IPTD, Figure 7.21 also illustrates that while SC1 and SC3 maintain a similar behavior on IPTD (mean and maximum) for all test conditions, SC2 tends to converge to SC1 behavior when the utilization decreases.

A packet level analysis similar to the one provided in Table 7.4 reveals that the percentage of packet violations for the established QoS thresholds decreases progressively. For SC1, no QoS violations were noticed for safety margins below 0.95. However, for more demanding traffic sources, a larger safety margin may need to be configured, as stressed in [13][11][17]. For SC2, the $\%pkts\_violations$ of IPTD and $Total\ IPLR$ decrease from 5.62% to 1.62% and from 0.0046 to 0.0011, respectively, when the corresponding safety margin goes from 1.0 to 0.9. For the remaining safety margins considered, no QoS violations occur. For all test situations, $Total\ IPLR$ for SC3 remains very stable around 10^{-1}, varying from 0.105 to 0.099.

New thresholds

A different set of experiments performed in Test4 aims at testing the AC model performance when distinct QoS thresholds are established. In particular, these new thresholds are defined in order to assess the adaptability of the model to other QoS constraints than IPLR. In this context, more relaxed IPLR and/or tighter IPTD thresholds are used. As SC1 behavior is mainly influenced by rate control, these experiments focus essentially on SC2 and SC3, with either concurrent or cross traffic (referred as 10% of SC2 cross traffic). Within the presented results, the emphasis is given to scenarios with similar characteristics to Test3 (cross-traffic) and CT-I2=SC2, as they are more challengeable for the AC evaluation with respect to the QoS levels achieved by each class. For SC3, tighter IPLR thresholds were also tested. In this context, the new test conditions are as follows:

Test4.1 - Thresholds: IPLR=0.05 for SC2 and SC3; IPTD = 50ms for SC2;

Test4.2 - Thresholds: No IPLR constraints in SC2 and SC3; IPTD = 50ms for SC2;

Test4.3 - Thresholds: No IPLR constraints in SC2 and SC3; IPTD = 35ms for SC2.

[17]As an example, in [13], using $EXPOO,\ \ r = 200kbps,\ on/off = 500ms;\ Fint = 0.4s;\ Fhold = 60s$ as SC1 traffic sources, the safety margin proposed was 0.55. In [13] all service classes carried UDP traffic, SC2/SC3 used higher rate sources and $\Delta t = 2s$. In [11], with test conditions similar to the ones used in Test4, for Fint1, the proposed service margin for SC1 was 0.8.

Similar to the safety margin tests, the results express the blocking probability, the number of active flows and the mean utilization (see Figure 7.22), including as well, a packet level analysis and graphical behavior of the QoS metrics under control.

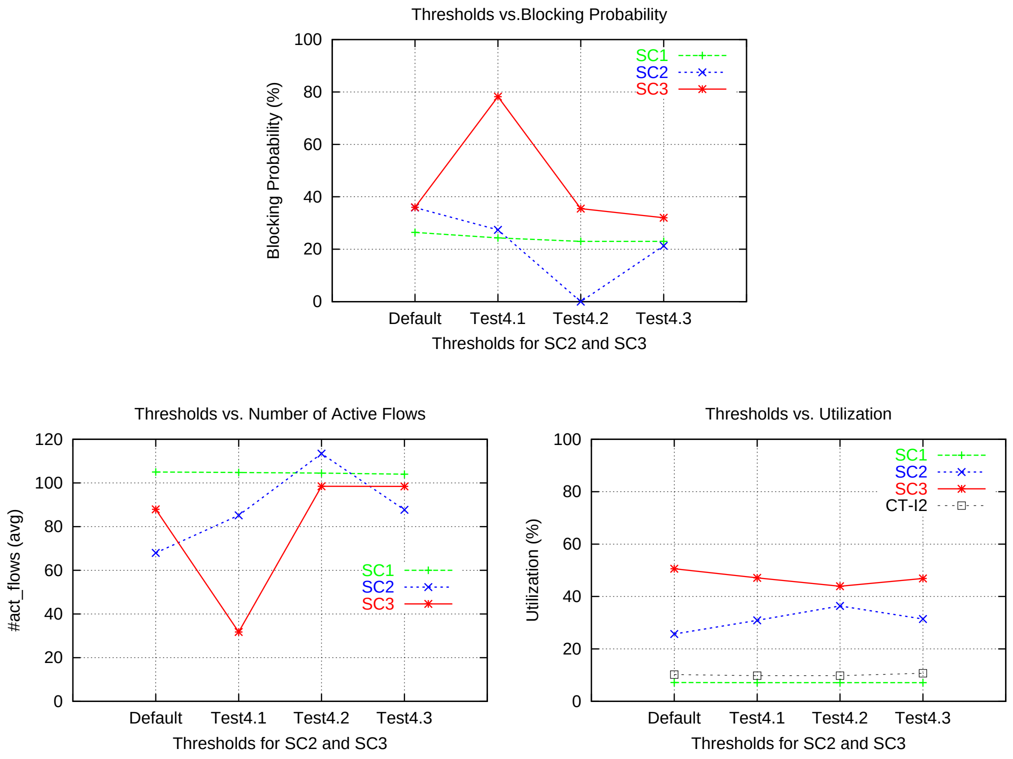


Figure 7.22: Influence of varying the QoS thresholds on the blocking probabilities, average number of active flows and mean utilization (10% of SC2 cross traffic)

Test4.1 results

According to Figures 7.22 and 7.23, the results of Test4.1 show that, under a more relaxed IPLR threshold, SC2 acceptance levels increase. As a consequence, the class utilization is higher and closer to the defined share. IPTD also increases but is kept behind the defined threshold. In this case, the AC decisions are determined by the QoS control rule according to the value of IPLR, and although IPLR oscillates around the defined threshold, the magnitude of oscillations may reach occasionally one order the magnitude above (see Figure 7.23 (right)). However, $Total\ IPLR$ for SC2 is kept controlled ($Total\ IPLR \sim 0.04$). With concurrent traffic, in presence of a more relaxed IPLR threshold, AC decisions are mainly determined by the SLS rate control rule with

IPLR being considerably lower than with cross traffic (one order of magnitude below).

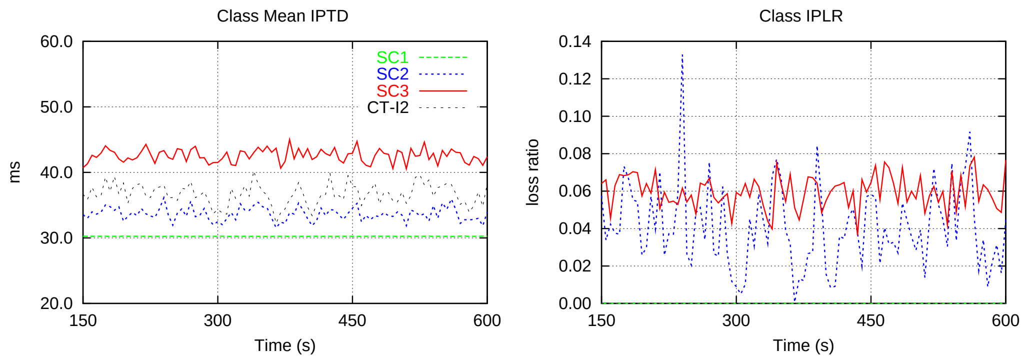


Figure 7.23: Test4.1: Class mean IPTD and IPLR for 10% of SC2 cross traffic

For SC3, the new IPLR threshold is tighter than the considered by default (10^{-1}). As a consequence, the acceptance levels and the class utilization decrease. Under the adaptive nature of SC3 flows, the QoS control rule is more effective in maintaining the IPLR of this class well delimited around the defined threshold (see Figure 7.23 (right)), with $Total\ IPLR = 0.059$.

Test4.2 and Test4.3 results

When no IPLR constraints are present an increase in IPTD and, specially, in IPLR is noticeable for class SC2. However, the mean values of these metrics tend to stabilize around 41ms (IPTD) and 0.36 (IPLR), for 10% of SC2 cross traffic. As IPTD threshold is 50ms, the QoS control rule is not decisive for the AC decision, which is made just based on the SLS rate control rule. As a consequence, SC2 utilization reaches its maximum share. In this way, to test the model's ability to control delay bounds, Test4.3 scenario is defined where a tighter IPTD threshold of 35ms is set, in complement to the case without IPLR constraints. Under these new test conditions, it is visible and measurable the AC model's effectiveness in maintaining IPTD of SC2 controlled around 35ms. As a side effect, IPLR clearly decreases to new values around 0.10. Figure 7.24 illustrates this behavior comparing Test4.2 and Test4.3 results.

For SC3, when no IPLR constraints are set, AC decisions depend on the value of the variable $Adm\_flows_{\Delta t_i}$. The QoS behavior of this class is not very distinct from the one achieved with the default thresholds, with $Adm_flows_{\Delta t_i}$set either to 100 or 200 flows. In fact, the throughput of each individual flow may change, but the overall class utilization remains at the same levels, justifying the similar QoS behavior achieved.

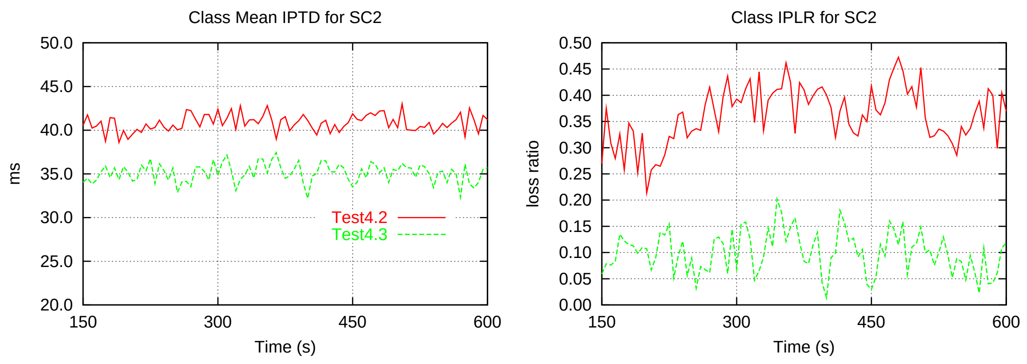


Figure 7.24: Test4.2 vs Test4.3: IPTD and IPLR behavior for 10% of SC2 cross traffic (Fint1)

For the three defined threshold conditions, the packet level analysis reveals that:

(i) SC1 maintains a behavior without QoS violations;

(ii) the percentage of packets exceeding the IPTD QoS (threshold) violations for SC2 is kept low for Test4.1 and Test4.2, varying from 0.7% (Test4.1) to 6.2% (Test4.2). For Test4.3 conditions, where a tighter IPTD threshold of 35ms is set for class SC2, the percentage of QoS violations at packet level reaches 30.5% (Fint2) and 33.6% (Fint1). For this test, only 1.1% (Fint2) and 3.1% (Fint1) of packets exceed the initial 50ms delay threshold;

(iii) although not being a variable under control in Test4.2 and Test4.3, $Total\ IPLR$ for SC2 decreases from 0.36 (Test4.2) to 0.10 (Test4.3).

7.3.6 Test5 - Impact of traffic characteristics

From the analysis carried out so far, it is clear that controlling QoS and SLS utilization in a multiservice domain involves configuring and handling multiple and interrelated variables. The difficulty and complexity of such control cannot be dissociated from the statistical properties of traffic entering the network domain. From the experiments above, several traffic aspects have shown particular influence on the AC evaluation results, namely:

(i) the parameterization of the traffic source models ruling the generation of packets belonging to individual or aggregate flows;

(ii) the flows' arrival and departure process, namely the flow interarrival and holding time distributions.

On the one hand, the choice and parameterization of a source model determine the intrinsic characteristics of each traffic flow, reflecting the way it behaves during its lifetime. On the other hand, at aggregate level, i.e., when considering multiple flows, they also determine the statistical properties of the traffic within each service class, and consequently, the challenges posed to traffic control mechanisms. For instance, low or high load estimates resulting from short-term traffic fluctuations may mislead AC decisions, while long-term properties such as LRD have proved to impact on the nature of congestion and on some AC algorithms [95]. The flows' peak and mean rates also have a noticeable effect in the QoS achieved by a service class and in its eventual QoS degradation. Flows with higher peak and mean rates tend to produce higher fluctuations on the load estimations and therefore, the number of positive AC decisions due to low estimates tend to increase QoS degradation. The safety margins required in the presence of high flow rates need to be large enough to accommodate traffic variability. This behavior is noticeable in simulations with different flow rates on SC1 [13], being also visible when comparing the admission decision results of SC1 and SC2, represented in Figure 7.12.

The flow arrival and departure process (flow interarrival time - fint; flow holding time - fhold) is another aspect of traffic characterization that impacts on several issues regarding the performance evaluation of the AC model. First of all, such process determines the flows' dynamics and load submitted to the network. More specifically, the average values of the flow interarrival time, flow holding time and flow rate interfere with:

(i) global and service class utilization - in fact, fint, fhold, flow rate and each class allocated bandwidth are closely interrelated and their values determine the way the network (and the simulation model) is loaded. The mean class utilization, the mean number of active flows, the maximum number of supported flows and the time required to reach a steady state in the simulation depend on these variables. When considering a measurement time interval Δt_i, in which the flow arrival is taken into consideration but the flow departure is not considered, long lasting flows (larger fhold) lead to more stable operation and higher utilization (see Test6 discussion in Section 7.3.7);

(ii) blocking probabilities - attending to each class allocated capacity and each flow rate, it is possible to predict the maximum number of supported flows. On average, when the number of potentially active flows, determined by the relation between fhold and fhint, falls behind this maximum number the blocking probability tends to be zero. In this way, for the same fhold, a shorter fint leads to higher blocking probabilities. Therefore, when an AC proposal is evaluated resorting to a blocking probabilities analysis, the marginal variation of the blocking probabilities due to the change on AC parameters under evaluation should be considered rather than taking the corresponding absolute values;

(iii) network dynamics - fint and fhold may also induce some nasty synchronization effects according to their values. This may occur, for instance, when the fhold distribution leads to synchronized flow departure and the fint distribution is very demanding to flow admission. This may generate load cycles influencing the acceptance/rejection AC decisions accordingly;

(iv) the rate estimation mechanisms such as TW (see Section 7.2.3).

All the aspects discussed above stress the need to take into account the traffic characteristics when configuring the monitoring and AC modules[18]. In the present context, maintaining an AC parameterization similar to Test1 (i.e., the safety margins and thresholds), several experiments were carried out to evaluate the impact of different types of sources on the performance of the AC proposal. In this way, in addition to $EXPOO$ sources, CBR and $PAROO$ sources were included in the tests, as illustrated in Table 7.6. Pareto sources with a shape parameter $1 < \alpha < 2$ under aggregation allow to generate traffic exhibiting LRD.

Table 7.6: AC results for distinct source models

Src Type	#act_flows	%util.	IPTD: mean;	max;	%pkts_viol	Total IPLR
CBR_{SC1}	107.3	7.3	30.2	30.6	0.0	0.0
CBR_{SC2}	116.3	44.0	31.2	38.0	0.0	0.0
FTP_{SC3}	61.6	43.0	42.7	74.9	n.a.	0.102
$EXPOO_{SC1}$	105.9	7.2	30.2	30.6	0.0	0.0
$EXPOO_{SC2}$	116.6	44.2	32.4	69.9	1.58	0.0015
FTP_{SC3}	65.9	43.4	41.7	77.2	n.a.	0.102
$PAROO_{SC1}$	104.3	7.2	30.2	30.6	0.0	0.0
$PAROO_{SC2}$	115.5	44.1	32.3	70.3	1.62	0.002
FTP_{SC3}	66.9	43.3	42.8	79.0	n.a.	0.103

The results obtained with these new source models similarly parameterized (in terms of rate, fint, fhold and on/off periods when applicable) show that the utilization levels achieved for the

[18]Finding formal relations and guidelines between the considered variables and the system's configuration was left for future study.

distinct service classes are maintained. However, $IPTD^{max}$, *% pkt_ violations* on IPTD threshold and $Total\ IPLR$ tend to increase with traffic variability[19]. While for CBR sources there are no packets exceeding the IPTD threshold and there is no packet loss, for $EXPOO$ and $PAROO$ sources the delay and loss behavior mentioned above is verified, in particular for SC2. Nevertheless, each class QoS commitments are generically met.

In this context, the obtained results indicate that the proposed AC model exhibits good performance in handling traffic burstiness and, eventually, long time scale fluctuations, stressing the argument that LRD provides additional motivation to the use of measurement-based AC [99]. In addition, following [121], from these results there is no reason to conclude that LRD will pose particular challenges to the proposed AC approach. The only remark to hold is that the degree of LRD is related to the number of aggregated sources, and the simulation time considered is also relevant to the evaluation of long-term statistical properties. Although longer simulations did not show significant changes in the results, additional tests using specific traffic aggregates exhibiting LRD (e.g., for SLS AC) may be relevant to do in the future. Additional results on testing the impact of traffic characteristics under different parameterization of AC and traffic flows can be found in [13].

AC fairness on concurrent flows

Although a complete fairness study of AC decisions is suggested as topic of future research, several preliminary tests were carried out in order to analyze the model behavior in the presence of concurrent traffic with distinct flow characteristics within the same service class. Initial results show that the model is able to adapt consistently to different conditions in the concurrent classes, adjusting the number of admitted flows according to the flows' defined rate and maintaining the global and per-class utilization levels similar to the ones obtained previously.

The results in Table 7.7 illustrate this fair behavior when the concurrent service class is SC1 with more demanding flow peak rates, burstiness and flow arrival/holding times[20]. Under the new traffic conditions, the QoS behavior of SC1 shows a slight degradation. However, the %

[19]According to [95, 20], IPTD and IPLR are the parameters mostly influenced by LRD.

[20]The initial configuration of SC1 sources is referred as $EXPOO^1_{SC1}$ (rate = 64kbps; On = 0.96 /Off = 1.69ms (mean rate = 23kbps); Fint = 0.3s; Fhold = 120s). $EXPOO^2_{SC1}$ (rate = 256kbps; On/Off = 500ms (mean rate = 128kbps); Fint = 0.3s; Fhold = 90s) corresponds to a more demanding traffic source and $EXPOO^3_{SC1}$ is equivalent to $EXPOO^2_{SC1}$ varying the flow arrival and departure processes, i.e., ($EXPOO^2_{SC1}$; Fint = 0.6s; Fhold = 120s). As mentioned, to test more demanding traffic conditions and unbalanced loads, $EXPOO^2_{SC1}$ and $EXPOO^3_{SC1}$ peak rates are around five times $EXPOO^1_{SC1}$ peak rate.

Table 7.7: AC results on fairness

Class	Src Type	#act_flows	%util.	%pkts_viol (IPTD ; ipdv)	Total IPLR
SC1	$EXPOO^1_{SC1}$	56.9	3.9	(0 ; 0)	0.0
	$EXPOO^1_{SC1}$	58.4	4.0	(0.16 ; 0.035)	0.0010
	$EXPOO^1_{SC1}$	52.4	3.6	(0.21 ; 0.052)	0.0012
CT-I2	$EXPOO^1_{SC1}$	58.2	3.9	(0 ; 0)	0.0
	$EXPOO^2_{SC1}$	10.4	3.9	(0.17 ; 0.026)	0.0011
	$EXPOO^3_{SC1}$	11.5	4.2	(0.24 ; 0.039)	0.0014
SC2	$EXPOO_{SC2}$	111.1	42.1	(0.19 ; n.a.)	0.0043
	$EXPOO_{SC2}$	111.3	42.0	(0.17 ; n.a.)	0.0040
	$EXPOO_{SC2}$	110.7	41.8	(0.09 ; n.a.)	0.0032
SC3	$EXPOO_{SC3}$	99.4	49.3	(n.a. ; n.a.)	0.093
	$EXPOO_{SC3}$	99.4	49.1	(n.a. ; n.a.)	0.094
	$EXPOO_{SC3}$	99.1	49.1	(n.a. ; n.a.)	0.096

pkt_ violations is very low and $Total\ IPLR$ is kept well bounded within one order of magnitude above the established QoS thresholds. IPLR behavior in Δt_i is illustrated in Figure 7.25.

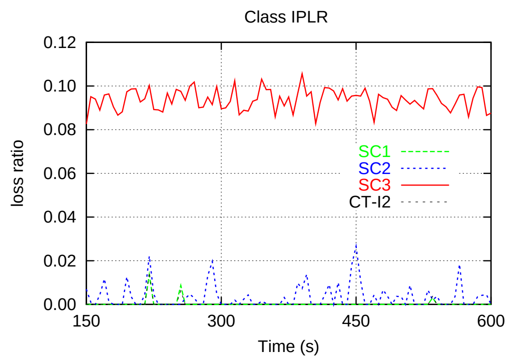


Figure 7.25: IPLR behavior (CT-I2 = $EXPOO^2_{SC1}$)

As mentioned earlier and also noticed in [13], the cause of QoS degradation is the higher fluctuations in the rate estimations when SC1 flows' rate is increased (see Figure 7.26[21]), irrespectively of the concurrent traffic having or not similar characteristics. The QoS degradation noticed can be avoided resorting to a higher safety margin in the SLS rate control rule for SC1. As illustrated in Table 7.7, the remaining service classes are not particularly affected by the new test conditions.

[21]The difference between the green curve (rate Estimate) and the blue curve (Total) corresponds to the peak rate of the flow requiring admission (64kbps and 256kbps for SC1 and CT-I2, respectively). A flow rejection occurs if the blue curve is above the Target line. The green curve (and not the blue one) identifies episodes of rate violations.

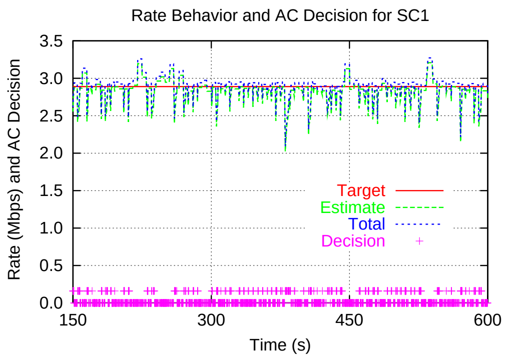


Figure 7.26: Rate estimations for SC1 and CT-I2 (CT-I2 = $EXPOO^2_{SC1}$)

Results on concurrent traffic belonging to SC2 (e.g., with the flow mean rate halving the previous CT-I2 rate configuration) exhibit similar trends regarding $\#act\_flows$ and achieved utilization, and also a stable QoS behavior.

Additional remarks on distinct traffic sources

This section includes results from tests exclusively with UDP classes and using higher rate traffic sources [13]. As SC3 is now a non-adaptive traffic class, the overall utilization tends to suffer larger bounces. When the safety margins β^+_{i,E_m} are increased to avoid QoS degradation, the influence on the utilization levels is also more notorious, however, the overall utilization remains high. Figure 7.27 [13] illustrates this behavior, assuming an initially defined SLS share of 10%, 50% and 40% for SC1, SC2 and SC3, respectively, and having SC3 as concurrent traffic.

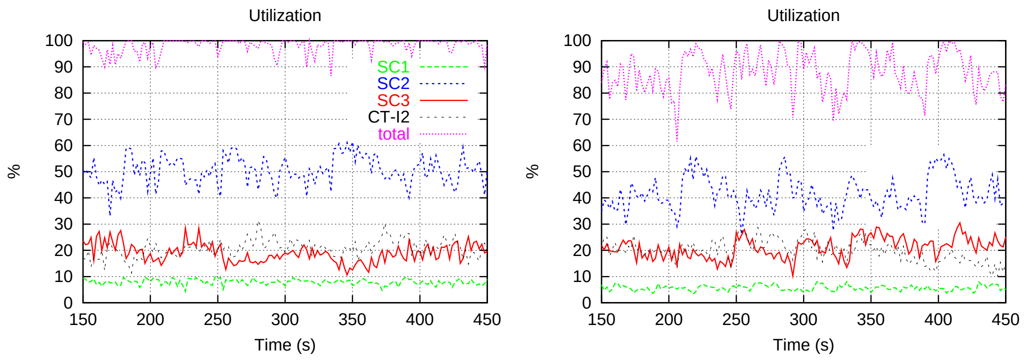


Figure 7.27: Utilization for distinct β^+_{i,E_m}: (left) (0.75; 0.90; 1.0); (right) (0.55; 0.75; 0.8)

7.3.7 Test6 - Impact of the measurement time interval

The measurement time interval Δt_i used in the evaluation of MBAC and EMBAC solutions may vary significantly. For instance, in [157] the measuring time window to perform MBAC at ingress nodes, based on their link capacity, ranges from 0.05s to 2s. While in some edge-to-edge MBAC proposals a Δt_i as small as $1s$ is used for AC performance evaluation [194], in real environments larger time intervals should be used to reduce the overhead of keeping the metrics updated. For instance, a Δt_i of 60s to few minutes is sometimes recommended for one-way measurements [223, 224].

In the context of the present work, the AC evaluation tests performed so far have used $\Delta t_i = 5s$, which has been defined and adjusted in order to maintain an updated view of each class's performance and, simultaneously, to face Δt_i constraints imposed by the probing patterns in use (see Section 7.2.2). Test6 experiments aim at evaluating the impact of larger Δt_i on the AC model's performance. In this way, using the same test conditions of Test1 and SC2 as concurrent traffic, new measurement time intervals of 30s and 60s are under evaluation.

As illustrated in Figure 7.28 (labels 5, 30, 60), on average, the number of active flows and the utilization for SC1 and SC2 decrease, especially for SC1. As a result of this utilization decrease, the QoS behavior of these service classes for $\Delta t_i = 30s$ and $\Delta t_i = 60s$ is better than for $\Delta t_i = 5s$, both from a measurement interval and packet level perspectives[22]. As usual, SC3 benefits from unused resources to increase its share while maintaining IPLR ~ 0.1.

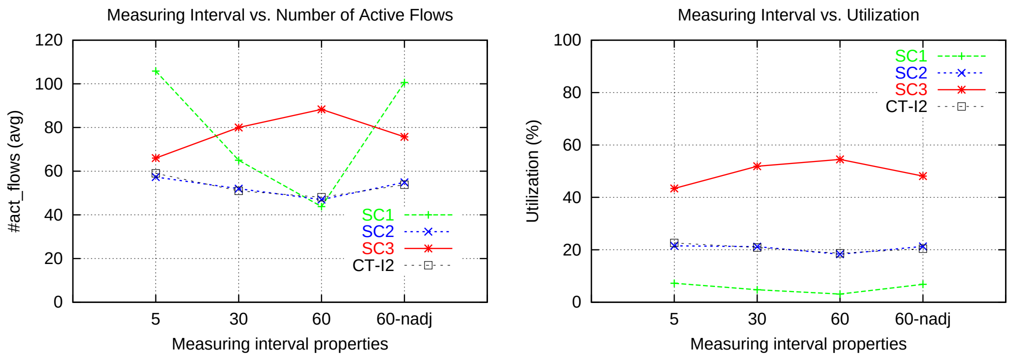
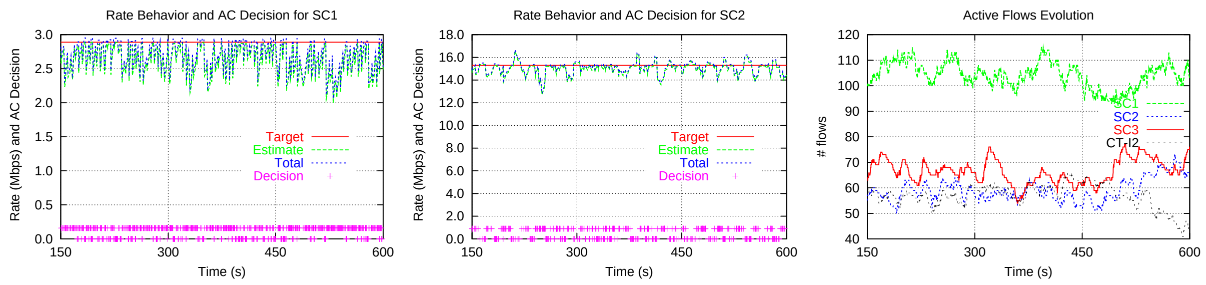
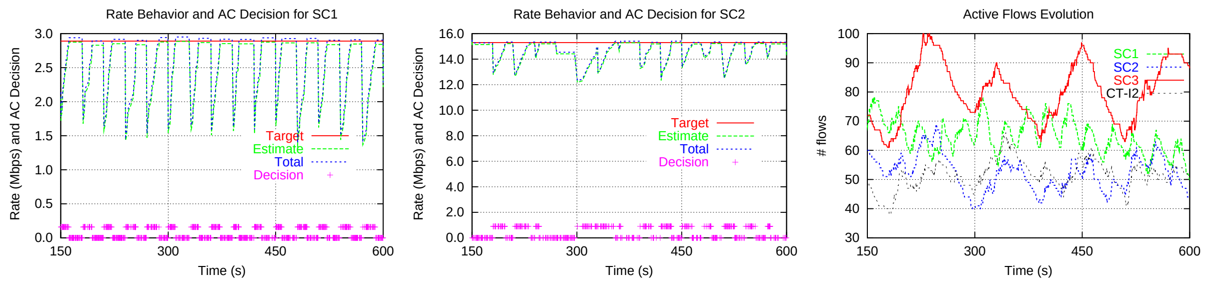


Figure 7.28: Influence of Δt_i on the number of active flows and utilization

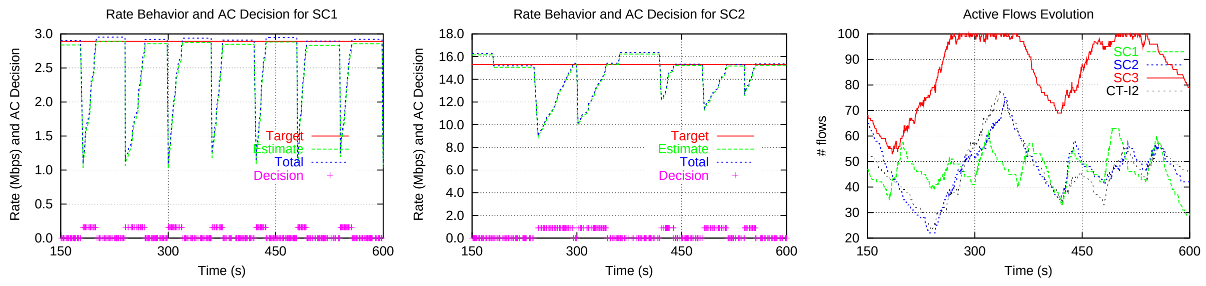
[22]When increasing Δt_i, the initial simulation convergence period and the running time need to be longer to sustain this reasoning. In this way, the forthcoming analysis with $\Delta t_i = 60s$ reports to a simulation window from 240 to 1440s.



(a) $\Delta t_i = 5s$



(b) $\Delta t_i = 30s$



(c) $\Delta t_i = 60s$

Figure 7.29: Influence of Δt_i on the rate and AC behavior for SC1 and SC2, and on the evolution of active flows

In Figure 7.29, taking Δt_i as 5, 30 and 60s, a longer cyclic behavior is noticeable both on the AC decisions and on the number of active flows. In more detail, considering SC1 and $\Delta t_i = 60s$ as an example, it is visible that after each load estimation update, the system enters into a positive AC cycle with a slope that depends on fint. After each flow admission, each I_n will update the load estimate until detecting that the new acceptances lead to the defined utilization target. In that moment, new incoming flows start to be refused and the last estimation is kept until Δt_{i+1}, when a new load is estimated and provided. As flow departures within a time interval are not taken into account, when the new update takes place, the rate estimation at the ingress node tends to decrease abruptly[23]. From the results in Figure 7.29, it is also visible that this rate decrease is more pronounced for a larger Δt_i, as the number of departing flows in the interval tends to increase. SC2 shows a similar behavior but not so precise due to the distinct traffic profile (higher rates, longer fint and fhold), the presence of concurrency and the traffic scheduling discipline. The graphs corresponding to the rate estimation and AC decision of SC3 flows are not included as the rate control rule is disabled.

When exploring the impact of Δt_i, there are, at least, three relevant aspects which may interfere with the system's behavior:

(i) update an estimate upon flow acceptance - update the rate estimates at each I_n according to the mean or peak rate of accepted flows leads to a more conservative AC as new incoming rates are considered without pondering the compensation effect of departing flows. This effect tends to be more notorious when Δt_i increases as the I_n estimation update reflecting the real network conditions, sent by the monitoring module, is provided later. Keeping rate estimates ($\tilde{R}^{+}_{i,E_m}$) unchanged during Δt_i irrespective of flows acceptance, explores this compensation effect but may increase overacceptance and lead to more QoS violations in all the service classes. This was verified through simulation results, where the mean number of active flows and the utilization obtained for Δt_i=60s (labeled 60-nadj in Figure 7.28)[24] and the QoS behavior of the service classes (illustrated in Figure 7.30) confirm this tendency. The evolution of the number of active flows in both cases (illustrated in Figure 7.31) shows a longer cyclic behavior when $\tilde{R}^{+}_{i,E_m}$ is not adjusted. This interesting side effect results from consecutive Δt_i intervals where the acceptance status is kept unchanged. When the rate estimation exceeds its target and/or QoS degradation is sensed, the system

[23]A flow signaling process with explicit "teardown", i.e., where flows' departure is explicitly known, allows to decrement the rate estimate when a flow terminates. This may bring more stability to the mentioned system behavior.

[24]Although the concave tendency of SC1 and SC2 curves is visible, it is important to highlight that the small inflection of SC1 (60-nadj) utilization curve corresponds to a 100% increase.

enters in a consequent longer rejection status. This behavior leads to higher oscillations in the utilization achieved. Intuitively, when no adjustments are made during Δt_i, the control of concurrency becomes more relevant to reduce the likelihood of overacceptance (see Section 5.8.1). Preliminary tests using a concurrency index $\chi_{i,E_m} = 2$ for the concurrent service class (SC2) show that the QoS levels of SC2 can be significantly improved and that SC1 also benefits from the new test conditions[25];

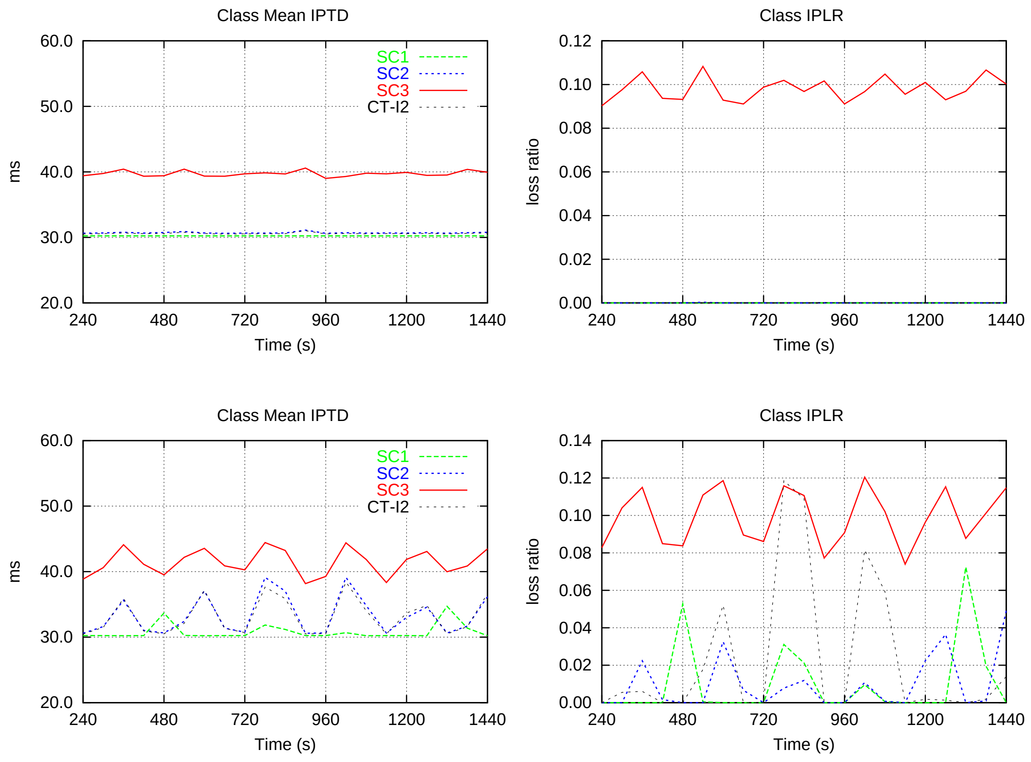


Figure 7.30: QoS results for $\Delta t_i = 60s$ adjusting $\tilde{R}^+_{i,E_m}$ (above); not adjusting $\tilde{R}^+_{i,E_m}$ (below)

(ii) the flow arrival and departure process - in particular the flows' holding time may affect the utilization and QoS obtained for each class. In fact, when the accepted flows have a longer

[25]The graphical behavior of SC2 and SC3 in Δt_i is similar to one shown in Figure 7.30 (above); SC1 still has sparce loss events with IPLR reaching 0.04. In more detail, the number of active flows and the utilization of SC1 are maintained, of SC2 decreased in $\sim$ 30% and of SC3 increased in $\sim$ 20%. The packet level analysis reveals an improvement of one order of magnitude in all the QoS controlled parameters for both SC1 and SC2. For instance, the percentage of $\%pkts\_violations$ on IPTD is reduced from 1.7% to 0.5% for SC1 and from 4% to 0.2% for SC2. $Total\ IPLR$ decreased from 0.02 to 0.005 for SC1, from 0.02 to 0.001 for SC2 and 0.099 to 0.089 for SC3. Thus, generically, all service classes benefit from the new test conditions. Despite the QoS improvement, the only class that did not meet the $Total\_IPLR$ commitments was SC1.

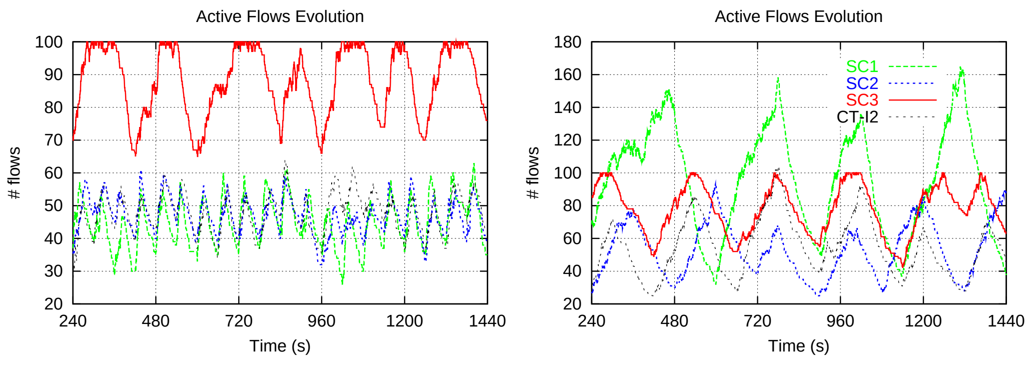


Figure 7.31: Active flows for $\Delta t_i = 60s$ adjusting $\tilde{R}^+_{i,E_m}$ (left); not adjusting $\tilde{R}^+_{i,E_m}$ (right)

duration, the effect of update the rate estimations without considering the flows' departures tends to be less significant as less flow departures are noticed during Δt_i. The impact of the flow interarrival time on each class's utilization can also be significant, influencing the slope of the rate estimation curve when AC enters into an acceptance mode (see Figure 7.29). The cyclic behavior exhibited in Figure 7.31 is also stressed by the demanding characteristics of the flow arrival process; under more moderate flow arrival conditions, that behavior tends to smooth and the evolution of active flows and utilization become more regular, both whether $\tilde{R}^+_{i,E_m}$ is adjusted or not;

(iii) finally, considering the update of rate estimations in Δt_i, reducing the safety margins is also a way to bring SC1 and SC2 into higher utilization levels.

In conclusion, according to the obtained results maintaining the default test conditions, the major impact of increasing Δt_i (creating consequently a longer "blind" period regarding the real network status) is to create a cyclic AC status behavior affecting the number of active flows and utilization of each class. When considering the rate estimates' update, the classes' QoS commitments are easily met for higher Δt_i, as result of an utilization decrease. SC3 follows similar trends to the tests using smaller Δt_i. Despite the good QoS results achieved, for $\Delta t_i = 60s$ the AC rejection period may be excessive in particular when not adjusting $\tilde{R}^+_{i,E_m}$.

Dimensioning Δt_i also involves establishing a trade-off between the overhead of the metrics' update process and the accuracy of capturing the real network status. This trade-off is simplified when AC and QoS monitoring are both performed at egress nodes, as the metrics' dissemination overhead is avoided.

In summary, considering the test scenarios presented previously, a smaller Δt_i may be preferable to take advantage of the good compromise among network utilization, QoS and stability achieved.

7.4 Comparison with other AC approaches

From a conceptual point of view, an extensive comparison of the proposed AC model with current measurement-based AC approaches has been detailed in Section 5.7.3. Carrying out a strict comparison in quantitative terms is rather hard to achieve for several reasons. Although having in common some principles (being measurement-based), the AC approaches are mostly distinct as regards their scope and the network variables that are kept under control. Therefore, reproducing identical test conditions to allow that comparative study would imply to implement those approaches (not always available), which falls outside the scope of this work.

Generically, every AC proposal includes a debate of performance aspects related to the solution. However, the test conditions are usually very specific considering evaluation scenarios difficult to compare to the ones defined in this work. Regarding the test platform and study of cross traffic impact, [147] presents an approximate test topology to the one supporting the present study, but it is mainly focused on single class environments and the control of SLSs is not covered. Other studies are dedicated to survey and compare the performance of MBAC algorithms [99, 105], or the performance of EMBAC solutions [106]. However, these studies have to be well-delimited as regards the comparisons carried out. For instance, their concerns focus on a single node perspective, evaluate few performance parameters (e.g., loss vs. load) or do not study multiclass environments deeply. As far as the control of SLSs or the support of guaranteed services are concerned, the comparison would have to include other type of AC proposals such as BBs or DPS based strategies. The conceptual and practical divergence from these approaches (see Section 3.3) and the lack of documentation reporting operational details make difficult their implementation and comparison under similar test conditions.

In summary, the main objective of the performance evaluation carried out in this chapter was to provide a proof-of-concept of the present AC proposal, identifying the critical aspects of the model behavior and performance, highlighting as well aspects that deserve further research.

7.5 Scalability issues

The scalability of the proposed AC model already debated within the QoS monitoring context (see Section 4.4) is certainly an important topic to discuss and evaluate concerning its deployment in real environments. The network dimension, the number of service classes SC_i and the number of incoming flows and active flows are identified as the main variables to consider when studying the scalability of an AC proposal. These aspects are serious constraints when the network keeps per-flow state information and/or the AC decisions involve all network nodes along the data path [23, 111]. When AC takes an SLS as reference, the number of existing SLSs should also be considered as a variable with impact on scalability [12].

It is important to recall that performing edge-to-edge QoS control, embedding SLSs control within the corresponding service class and keeping the amount of state information and signaling reduced (see Section 5.7) are properties which increase the model's resilience to scalability problems. Despite its potential ability to scale, studying the model's scalability using more complex simulation scenarios is an important issue suggested as topic for future work. As an initial step for that debate, a summary identifying the impact that large-scale environments may have on the proposed AC solution is highlighted in Table 7.8. Future work intends to sustain and extend these initial considerations providing quantitative results on the topic.

Table 7.8: Issues on the AC model scalability

Main variables	Scalability issues
network dimension	Number of edge nodes involved: - impacts on edge state information and monitoring overhead - may increase the need for handling concurrent AC Core complexity: - no impact on model overhead - no significant impact expected on AC criteria efficiency
number of SCi	SCi state information at edge nodes QoS monitoring overhead Probing intrusion (if applicable)
number of SLSs	SLS state information at involved edge nodes SLS utilization monitoring overhead No impact on QoS monitoring overhead
number of flows	Number of AC decisions No impact on domain state information TC at source domain I_n (if applicable)

7.6 Summary

In this chapter, several test scenarios have been devised in order to evaluate two major components of the proposed AC model: the QoS measurement methodology and the AC criteria. This evaluation resorts to the simulation prototype of a multiclass network embedding the proposed AC model, defined and configured in Chapter 6.

In more detail, the test scenarios for monitoring evaluation have been defined to pursue the main objective of assessing the suitability and effectiveness of multipurpose in-band probing patterns in measuring the defined QoS parameters. Several aspects of probing patterns such as distribution, rate, color and packet size have been explored and tunned. In addition, a first incursion in the evaluation of existing estimation mechanisms has been made. The test scenarios for evaluating the AC criteria have been defined considering general and particular aspects likely to influence the model performance, namely: (i) the initial assessment and tuning of the explicit and implicit AC criteria; (ii) the impact of cross traffic on each service class; (iii) the safety margins and thresholds; (iv) the influence of traffic characteristics and the measurement time interval Δt_i. The obtained results have focused, whenever appropriate, on an analysis of the AC model performance at class and packet levels.

Generically, the results show that the proposed AC model, using a two-rule AC criterion defined on a service class basis, has been able to assure service level guarantees and achieve high network utilization, without adding significant complexity to the network elements. The use of systematic edge-to-edge monitoring and a controlled degree of overprovisioning revealed to be essential design aspects contributing for reaching a good compromise between simplicity and performance. A preliminary discussion on the AC model scalability issues has also been launched, motivating further research on this topic.

A concluding analysis summarizing the more relevant results and contributions will be included in the following chapter.

Chapter 8

Conclusions

This chapter provides a concluding review of the present research work. At first, an assessment is carried out regarding to what extent the objectives outlined initially have been fulfilled, then the main contributions of the thesis are presented and debated. Finally, possible future research directions are pointed out.

8.1 Summary

The widespread use of high-speed networks, multimedia capable end-systems and the current Internet popularity have fostered the development of multimedia applications highly demanding in terms of network resources. To face this demand and support the coexistence of heterogeneous applications and services with distinct QoS requirements, the research community has been contributing to enhance the TCP/IP stack with new protocols and service models. From the network perspective, providing QoS brings an additional burden to the IP level. As new policy rules and traffic control mechanisms have to be deployed, a major principle to preserve should be *keep it simple*. The design of service-oriented networks based on CoS paradigm, where traffic is aggregated in a limited number of classes according to its QoS requirements, pursues this principle. To allow an efficient management of each class's resources and fulfill SLS commitments, lightweight AC mechanisms are convenient to keep classes under controlled load and assure the required QoS levels with minor impact on network performance.

Considering the survey of current AC approaches provided in Chapter 3, it became evident that despite the variety of existing proposals, the problematic of handling AC in CoS IP networks, considering the simultaneous control of multiple intradomain QoS levels and interdomain SLSs in a simple and flexible way, is still an open issue. It is within this context that the motivation of this work was raised, being its main objective defined as

> *achieving an encompassing, flexible and lightweight AC model able to control QoS and SLSs in multiclass and multidomain environments.*

Thus, taking simplicity, flexibility and easy deployment as initial goals, and considering the need for on-line service monitoring and for traffic control at the network domain edges, a new service-oriented distributed AC model has been proposed. The model resorts to feedback from edge-to-edge on-line monitoring of relevant per-class service metrics to drive implicit and explicit AC decisions. To improve the trade-off between service guarantees and complexity, the model relies on the use of service-dependent levels of overprovisioning and QoS thresholds embedded in the AC equations.

As stated in Chapter 1, a question that emerges from the model properties is whether the defined AC rules driven by edge-to-edge on-line monitoring, without knowing details of the network core, are able to control distinct service level guarantees and SLSs commitments properly. Therefore, facing the conceptual and operational characteristics of the model,

> *exploring the challenges, effectiveness and efficiency of the distributed AC solution based on on-line edge-to-edge monitoring in satisfying each service class commitments and existing SLSs in a multiclass domain*

has been defined as the proof-of-concept necessary to sustain the feasibility and contribution of the devised AC proposal.

8.2 Reviewing objectives and results

Considering the main objectives of this work and the identification of the relevant interrelated areas involved in the proposed AC model, namely service definition, on-line monitoring, AC algorithms and CoS traffic characterization, a set of objectives was formulated in Chapter 1. These objectives are here revisited and the main results obtained from their fulfillment are highlighted.

(i) To contextualize and clarify the underlying concepts of class-based IP networks

The proposed AC model is oriented to multiservice IP networks based on CoS paradigm. Therefore, the first objective defined was performing a bibliographic review of the main concepts and principles behind this paradigm to be used throughout this dissertation.

This objective was addressed in Chapter 2 where, after grounding the motivation for using class-based QoS solutions, the theoretical background regarding the Diffserv model as a reference CoS model was provided both from a conceptual and practical perspective. The main underlying principles of Diffserv, the model components and operation, the functionality of edge and core nodes were explained.

(ii) To identify and structure the main issues and tasks subjacent to the definition and building of network services both intra and interdomain

As service definition and deployment intra and interdomain is a key area of interest when devising a consistent multiservice AC proposal, the following topic addressed in Chapter 2 discusses how to build services in Diffserv networks. The definitions and standardization efforts regarding PHBs and PDBs were outlined and other main tasks required to support services were identified and layered in the data, control and management network operating planes. The next aspect under study focused on the relevance of establishing standard SLA/SLS for domain QoS provisioning, interdomain negotiation and end-to-end QoS delivery. Considering the outcome of relevant works on this subject, an SLA/SLS template including the main service parameters and their usual contents was proposed and the hierarchical relation between SLSs and the Diffserv service building blocks established. The source and cascade business models for the support of interdomain IP-based services were described, and the way SLSs are settled within these models and their main advantages and disadvantages were also discussed. Finally, a perspective on additional SLSs deployment issues such as SLS control and auditing was presented.

(iii) To survey existing AC proposals, covering their main characteristics, advantages and limitations

This objective concerns to the bibliographic review surveying current AC proposals. Having discussed the motivation to perform AC in multiservice networks, the survey carried out in Chapter 3 starts with an identification of multiple high-level aspects that distinguish existing AC approaches. Then, taking a service-oriented perspective, a detailed description of the main characteristics, advantages and limitations of those AC proposals provided a comprehensive analysis of the current state-of-the-art in AC research area. Although the discussion embraced AC in IP networks following distinct QoS paradigms, the emphasis was given to proposals for class-based IP networks. In more detail, centralized and distributed AC proposals oriented to either flow or hybrid or class-based QoS models, as well as measurement-based AC proposals based on passive and active measurements were discussed. The role of the AC criterion regarding the trade-off between service guarantees and resource usage, and the performance of common measurement-based AC algorithms was also discussed. The analysis carried out under this objective grounded the motivation for the present research study, pointing out the main strategic directions to achieve an encompassing and lightweight AC model for CoS IP networks.

(iv) To identify and study the main issues and recent developments related to the problematic of QoS and SLS monitoring

The proposed AC model resorts to feedback from systematic edge-to-edge on-line monitoring to control QoS and SLSs. Thus, a bibliographic review covering conceptual and practical aspects of the problematic of QoS and SLS monitoring is of major importance. This objective was addressed in Chapter 4, where an in-depth discussion of the recent developments in this research area was carried out. Starting by a high-level presentation of relevant characteristics of today's monitoring systems, the main aspects covered in that discussion include:

- identification of relevant QoS and SLS metrics - both the ITU-T and the IETF IPPM WG have devoted substantial efforts to this topic, trying to define a set of standard metrics providing unbiased quantitative measures of Internet quality, performance and reliability. In this way, the outcome of these works was studied and the proposed metrics identified, classified and described considering the eventual distinct visions ITU-T and IPPM might have;

- identification of adequate measurement methodologies and parameter estimation mechanisms - the measurement methodologies were classified into passive and active and explained pondering their main advantages, disadvantages and suitability for edge-to-edge measurements;

- identification of relevant high and low-level timing issues subjacent to an on-line monitoring process.

Facing the additional challenges that multiclass networks pose to on-line QoS monitoring, special attention was given to devise efficient monitoring solutions to be deployed in multiservice CoS networks. Accomplishing this objective led both to the introduction of the concept - *multipurpose* probing pattern - which characterizes the ability of a single probing stream in capturing simultaneously multiple QoS metrics of a service class, and to the design of a new probing source and policer/marker scheme to improve multipurpose QoS estimation. The evaluation of the adequacy and effectiveness of a multiclass and multipurpose active measurement methodology in sensing each class's behavior was carried out in Chapter 7.

The discussion on monitoring issues ends with a debate on eventual scalability problems of an edge-to-edge monitoring process, pointing out principles for improving monitoring scalability.

(v) To understand and characterize statistically the properties of Internet traffic under the CoS paradigm

The relevance of this objective lays on the need to understand the characteristics of network traffic, both at flow and aggregate level, in order to help devising and parameterizing service-oriented AC algorithms and configuring network services consistently. In addition, modeling traffic sources properly is a crucial step to achieve simulation models that express the dynamics and realistic behavior of networks and communication systems. This research topic has been covered in [20], where the impact of fractal properties on network traffic is emphasized. In this thesis, that work was further developed within the context of multiclass networks [19]. Although a brief theoretical review of this research was addressed in Chapter 2 and several tests evaluating the impact of traffic characteristics carried out in Chapter 7, finding formal relations and guidelines among the variables describing the traffic behavior and the parameterization of AC rules was left for future study. At present, the safety margins and thresholds of AC rules were used to accommodate the effects of more demanding traffic properties such as LRD.

(vi) To conceive and specify the proposed AC model for the control of QoS and SLSs in multiservice CoS networks

The achievement of this main objective, addressed in Chapter 5, resulted in the definition and specification of a service-oriented distributed AC model for managing QoS and SLSs in multiclass and multidomain environments, based on feedback of edge-to-edge on-line monitoring. In more detail, this main objective was tackled as follows:

- the strategic issues considered of major relevance for devising the AC model were identified. These issues include the model's ability to be multiservice, multidomain, simple, flexible, efficient, scalable and easy to deploy in real environments. Their fulfillment was discussed after describing the model conceptually;
- the model's underlying ideas were presented. Mainly, one idea was to take advantage of the need for on-line QoS and SLS monitoring in today's networks and use the resulting monitoring information to drive distributed AC. The use of service-dependent overprovisioning levels to simplify AC, widening the range of service guarantees supported by monitoring-based AC, was other relevant idea behind the model design;
- the initial assumptions were stated in order to clarify the positioning and operation of the AC model;
- the model architecture, interrelating research outcome from service definition, monitoring, traffic characterization and AC, was presented;
- a generic description of the model operation both intradomain and end-to-end was provided to clarify its more detailed specification;
- the main components of the model were specified using an expressive notation introduced for that purpose. For a multiclass domain, the ingress and egress nodes, the supported service classes and controlled QoS parameters, the negotiated upstream and downstream SLSs and the corresponding fields, the flows and its requirements were considered as key entities;
- the AC criteria were defined and specified in order to cover both explicit and implicit AC. In more detail, rate-based SLS control rules and QoS control rules for intradomain operation, and cumulative QoS control rules for interdomain operation were defined. These rules incorporate service-dependent overprovisioning levels, safety margins and thresholds;
- the state information and signaling required for the model operation were debated and alternative AC scenarios to reduce the overhead of both aspects were suggested. In particular, a debate on the advantages and disadvantages of decoupling AC between ingress and egress nodes was carried out;
- the major conceptual virtues and hurdles inherent to the proposed AC model were identified and discussed. Conceptually, the model was compared to other existing AC proposals

to further highlight its characteristics. Considering the difficulties pointed out, in particular for the problematic of handling concurrency in distributed AC models, several approaches to minimize the eventual occurrence of over or false acceptance were suggested. While the main virtues of the model are evinced in the section describing the main contributions, the difficulties deserving further study are discussed as part of future research topics.

(vii) To implement a simulation prototype of the proposed AC model covering a single multiclass domain

This objective is a natural step that precedes the validation of the AC model. The use of a simulation prototype allows a flexible evaluation and improvement of the AC model functionality. Accomplishing this objective, addressed in Chapter 6, led to the identification and discussion of the main implementation aspects concerning the evaluation of the AC criteria and the monitoring process. These aspects involve the definition of the service classes' characteristics and control policies, the identification of the QoS and SLS metrics to control, the corresponding measurement methodologies and the parameterization of the AC criteria. The conceptual and practical decisions made took as input the research outcome deriving from the achievement of the objectives discussed above.

Regarding the development of a simulation prototype of a multiclass domain embedding the proposed AC model, the choice of NS-2 as a simulation platform was justified and the main characteristics of the developed simulation model presented. These include the model's internal structure, the simulation topology, the source models, the services' configuration and AC configuration. The steps toward the validation of the simulation model were also discussed. The new functions required to support particular aspects of the AC model under evaluation were defined and added to the NS-2 libraries.

(viii) To provide a proof-of-concept of the proposed AC model

The proof-of-concept of the proposed AC model has as main target the performance evaluation of the AC model, assessing its ability to self-adapt to network dynamics and to assure QoS and SLS commitments in a multiclass domain efficiently. A second objective consists of assessing the suitability and effectiveness of multipurpose in-band probing patterns in measuring the QoS parameters of the defined service classes, while reducing network overhead and intrusion side effects. These objectives, covered in Chapter 7, involved planning relevant test scenarios intending to explore different aspects which may influence the performance of the AC model and of the QoS monitoring process, demonstrating their behavior under distinct test conditions.

Starting by the evaluation of the multipurpose active measurement methodology, the devised test scenarios explored multiple aspects of probing patterns such as probing distribution, rate, precedence (color) and packet size when estimating simultaneously one-way delay, jitter and loss related metrics. The main results on the measurements' accuracy, when comparing the probing and real traffic measurement outcome, are the following:

- common probing patterns for systematic measurement (e.g., Poisson traffic with light probing rates of 2 or 4 UDP pps) capture closely both the shape and scale of IPTD metric, however, they fail to sense and measure ipdv and IPLR properly. In particular ipdv, being a consecutive packet measure sensitive to probing gaps, is clearly overestimated and most of IPLR events are missed unless heavy loss occurs. These results suggest the use of alternative probing patterns with, for instance, higher rates and/or distinct drop precedence marks;

- generically, a probing rate increase leads to an improvement in the accuracy of QoS metrics estimation. This improvement is, however, rather dependent on each class characteristics and on the metrics being estimated. Furthermore, the trade-off between the estimation accuracy and probing overhead may be prohibitive, and even high probing rates were unable to match both the scale and shape of metrics such as IPLR. This has motivated exploring alternative or complementary probing features capable of increasing multipurpose active monitoring efficiency. From the tested probing characteristics, the results have shown that the dropping action of active queue management mechanisms on colored probes can influence the probing measurement outcome significantly. Red probing packets strongly improve the detection of loss events worsening IPTD estimation slightly. Interleaved color schemes have exhibited a better compromise, which has proved to be particularly relevant in service classes oriented to elastic traffic, where simultaneous estimation of IPTD and IPLR has only been achieved with an interleaved colored probing stream. As regards the probing packet distribution, a new hybrid on-off source, which allows to generate more flexible probing streams with more controlled number of probing events and probing gaps, has been proposed. The resulting probing streams, especially conceived to improve ipdv estimation, when complemented by a proper coloring scheme can also improve the estimation of the other metrics;

- the coloring scheme of probes is even more relevant when TCP probing is used, as the TCP probing stream might be rather bandwidth consuming when green probes are used. The coloring scheme is relevant to control both the accuracy of the estimate and the probing overhead. The results have shown that an interleaved color TCP probing pattern leads to a good compromise between accuracy and overhead.

Regarding the evaluation of the AC criteria, the devised test scenarios explored general and particular aspects likely to influence the model's performance. In more detail, the tests covered: (i) an initial assessment and tuning of the explicit and implicit AC criteria; (ii) studying the impact of cross traffic on each service class; (iii) adjusting the safety margins and thresholds of the service-dependent AC equations; (iv) studying the influence of flows' traffic characteristics and of the measurement interval Δt_i on the results. The obtained results contemplating, whenever appropriate, an analysis of the AC criteria performance at class and packet level, are the following:

- the initial assessment of the model's performance has demonstrated that the self-adaptive behavior inherent to on-line measurements combined with the proposed AC rules is effective in controlling QoS and SLS commitments of each service class. The obtained measures of IPTD, ipdv and IPLR for the defined service classes exhibited a very stable behavior regarding the pre-defined QoS thresholds. IPLR was the most difficult metric to keep tightly controlled in each Δt_i, triggering the QoS control rule more frequently. The total IPLR achieved is in-line with the defined threshold and the percentage of QoS violations at packet level was very small for all classes and in special for the most demanding one. The bandwidth share configured for each class was well accomplished, and the overall utilization obtained was very high. The implicit AC criteria on adaptive traffic was redefined, being proposed the use of the QoS control rule neglecting the control on SLS rate;

- the presence of cross traffic, i.e., traffic impacting on the domain's load and QoS without being explicitly measured, represents a bigger challenge for the AC criteria making evident the relevance of the two defined AC rules. In fact, for explicit AC, the SLS rate control rule assumes a preponderant role in controlling the traffic load and indirectly QoS in situations involving concurrent traffic. In the presence of unmeasured cross traffic, the QoS control rule is decisive to assure the domain QoS levels. As in real environments the two situations are likely to occur simultaneously, the two complementary rules increase the domain capabilities to guarantee service commitments. In addition, knowing which AC rule has been more influent brings relevant inputs for improving service configuration and provisioning both intra and interdomain. The importance of using a conservative degree of overprovisioning for more demanding classes became also evident in the presence of cross traffic;

- increasing the safety margins to avoid QoS violations at packet level has resulted in a consistent decrease of each class utilization and number of accepted flows, and an increase of blocking probabilities. The class with adaptive traffic takes clear advantage of unused resources, showing an opposite behavior, i.e., increasing its utilization levels. Generically, the tests with different QoS thresholds have revealed the capacity of the AC criteria in bringing the QoS levels of each class to the established thresholds. Relaxing the IPLR threshold and tightening the IPTD one has resulted, however, in more QoS threshold violations at packet level;

- regarding the impact of traffic characteristics on the performance of AC criteria, the flow rate, the flow interarrival and holding times revealed to be the most influent variables, affecting the global and each service class utilization, the flow blocking probabilities, the network model dynamics and the rate estimation mechanisms. According to preliminary results regarding the AC fairness on concurrent flows with distinct characteristics, the system exhibited a consistent and fair behavior;

- the measurement time interval Δt_i has a visible and measurable effect on the AC model behavior. Increasing Δt_i creates a longer "blind" period regarding the real network status, causing a cyclic behavior on the model operation and a decrease on each class utilization. When exploring the impact of increasing Δt_i in more detail, two aspects have been identified as interfering significantly with this behavior which are: (i) update or not the rate estimates at each ingress upon a new flow acceptance; (ii) the characteristics of the flow's arrival and departure process. In particular, when rate estimates are not updated, the impact of enlarging Δt_i on the utilization increase is notorious; nevertheless, acceptance/rejection cycles are longer. Regarding the QoS behavior, the service commitments are met for higher Δt_i with exception of the cases where rate estimates are not updated and overacceptance occurs;

- generically, the proposed multiservice AC model has been able to establish a good compromise between simplicity, service level guarantee and network resource usage, even for services with strict QoS requirements. Through the proposed service-dependent AC rules and safety margins, service requirements and commitments have been efficiently satisfied or bounded, proving that the simplicity and flexibility of the model can be explored to control successfully the quality of multiple Internet services.

(ix) To perform an analysis of the proposed AC model, reflecting on future research steps

The achievement of this objective corresponds to the topics addressed along this chapter.

8.3 Main contributions

Taking into account the initial objectives and obtained results, the main contributions of this work are summarized below.

- *Design and definition of a new AC model for multiservice class-based IP networks* - A new encompassing and lightweight AC model for the control of QoS and SLSs in multiservice networks based on the CoS paradigm has been devised [11, 12, 13, 10, 14] having as major properties: (i) distributed control of domain QoS levels and negotiated SLSs between domains; (ii) self-adaptive behavior resorting to feedback from edge-to-edge on-line monitoring; (iii) abstraction from network core heterogeneity and complexity through an edge-to-edge QoS vision, i.e., involving only edge nodes; (iv) support of distinct service assurance levels and applications requiring either implicit or explicit AC; (v) ability to operate both intradomain and end-to-end with reduced state information, signaling, latency and intrusion; (vi) flexibility to accommodate the evolution of applications, services and technologies, and possible enhancements of AC algorithms and monitoring strategies. The conceptual and operational properties characterizing the proposed AC model, which constitutes a novel approach to the problematic of AC in class-based IP networks, corroborated by performance evaluation results, are the principal contributions of this work.

- *Definition of service-dependent AC criteria* - The proposed AC criteria are based on two complementary rules - QoS control rule and SLS rate control rule - for intradomain operation and on an end-to-end control rule. These rules are parameterized according to the service type to be provided. In this way, the concepts of service-dependent overprovisioning levels, safety margins and thresholds have been introduced and concretized in the rules in order to allow a flexible and efficient, yet simple, operation of the AC model. For instance, larger safety margins and tighter thresholds can be applied for more demanding classes. The AC rule defined for end-to-end operation considers AC as a repetitive and cumulative process of available service computation. As regards rate control and QoS estimation, the applicability of algorithms and mechanisms usually used within a single node context have here been extended to edge-to-edge multiclass environments.

- *Notation to specify AC model entities, rules and operation* - An intuitive and expressive notation based on the set theory has been introduced in order to specify the main network domain entities concerning multiservice AC, SLSs and QoS management [11]. This notation includes indexes reflecting the involved service classes, ingress and egress nodes. As the model is class and edge-to-edge based, this approach enriches the notation semantically while keeping it intuitive. In particular, considering a generic domain comprising multiple ingress and egress nodes, the following entities have been considered and specified: (i) service classes; (ii) upstream SLSs; (iii) downstream SLSs; (iv) traffic flows. The network resources have been implicitly considered and controlled by the edge-to-edge monitoring process. Resorting to the proposed notation, the service-dependent AC criteria and the model operation both intra and interdomain have been specified. As a final remark, a matricial definition of accepted SLSs based on their scope has been introduced and its potential in identifying the expected ingress-to-egress traffic load and downstream SLSs utilization, useful for intra and inter domain service provisioning, has been highlighted.

- *Proposals for handling concurrent AC* - Distributed AC models may involve multiple nodes making concurrent AC decisions. In order to tackle the eventual over or false acceptance deriving from concurrent AC, several alternative or complementary solutions have been suggested. These proposals include (i) the definition of a per-class concurrency index; (ii) a token-based system; (iii) a rate-based credit system controlled by egress nodes [15].

- *Introduction of multipurpose active monitoring concept* - This concept, proposed in the context of multiclass on-line monitoring, reflects the ability of a single probing pattern to capture multiple QoS metrics of a service class simultaneously. In fact, multiclass IP networks open new dimensions and demands on active monitoring as efficient strategies of in-band probing are required to sense each class's performance without causing noticeable side effects on real traffic. Hence, achieving light and multipurpose probing patterns is an important step to reduce overhead and interference of on-line active monitoring. The work reported in [16, 17] focuses on finding and tuning per-class multipurpose probing patterns so that each class behavior is correctly captured, even if more than one QoS metric is under control.

- *Design and development of a new multipurpose colored probing scheme* - This novel proposal aims at improving the effectiveness of multipurpose active monitoring. In this way, a flexible on-off probing source regulating both the occurrence of probing events and the time gap between consecutive probes within an event has been devised to improve the estimation of delay-based metrics. Moreover, an approach of coloring probes using a single color or interleaved color scheme has also been explored in this thesis to improve loss estimation. For this purpose, a new policer/marker able to mark packets with an interleaved color scheme has also been developed [16].

- *Proposal of an SLA/SLS template and additional insights on corresponding management tasks* - Considering previous work on SLS definition (see Section 2.2), an integrated SLA/SLS template including its relevant parameters and typical contents has been defined. Additional SLS deployment issues such as SLS control and auditing have also been debated [14]. In this context, as further highlighted and developed in [11], two relevant aspects of the proposed AC model regarding SLSs management are: (i) the suitability of ingress-to-egress QoS monitoring for SLS auditing purposes; (ii) the QoS control of accepted SLSs (and respective flows) for a service class embedded within the corresponding class QoS control performed at egress nodes. This simplifies the monitoring process and improves scalability as QoS control is performed per-class and not per-SLS. New ongoing work respects to SLS processing and validation [18].

- *Definition of a traffic classification criteria and first results on CoS traffic characterization* - following the work initially carried out in [20], in [19] the problematic of traffic classification into distinct service classes has been introduced, a traffic classification criterion has been proposed and the statistical properties of each service class traffic aggregate have been analyzed following the concepts of fractal theory. This characterization work has resorted to real traffic traces collected at an University of Minho's major backbone router, during distinct periods of network activity.

- *Comprehensive survey encompassing both conceptual and practical issues on major areas supporting the proposed AC model* - In this survey the following contributions in each area are highlighted: (i) *multiservice class-based networks* - their principles, components and operation mode have been discussed and the relevant tasks involved in building up services identified and layered into distinct network operating planes; (ii) *AC in multiservice networks* - the high-level characteristics which distinguish AC proposals have been identified and a service-oriented debate appraising the most relevant AC proposals has been provided. The main characteristics subjacent to these proposals have been summarized in a table to facilitate their comparison; (iii) *QoS monitoring* - the main characteristics and challenges of today's monitoring systems have been identified and discussed. Considering the vision of distinct working groups on the topic, relevant metrics of Internet quality, performance and reliability have been identified, classified and described, providing a clearer understanding of their meaning and purpose. The most relevant measurement methodologies and parameter estimation mechanisms have been presented and discussed, debating also timing related issues; (iv) *traffic characterization* - the motivation for new research on traffic characterization and modeling under the new paradigm of CoS aggregation has been presented and relevant aspects to characterize traffic both at flow and aggregated level identified.

The main contributions regarding model implementation and performance evaluation are highlighted next.

- *Development of an AC model prototype* - A simulation prototype comprising a multiclass domain controlled by the proposed AC model has been developed. The configuration of all entities involved such as the service classes and traffic sources, the monitoring decisions and the AC rules has been carefully established considering and interrelating realistic inputs and guidelines from the related research areas. In addition, to support the model implementation, new functions have been added, or extended, to NS-2 libraries, such as the simultaneous support of multiple TCP flows, multimetric QoS egress monitors, specific probing sources and an interleaved color policer/marker.

- *Expertise deriving from the AC model evaluation* – The ability to perform an effective distributed control of QoS and SLSs using feedback from edge-to-edge on-line monitoring has been proved. The results have shown that the proposed multiservice management scheme establishes a good compromise between simplicity and efficiency, allowing to satisfy effectively distinct service level commitments, while achieving high network utilization. Furthermore, the usefulness and the context of applicability of the two complementary AC rules defined have revealed to bring relevant information and directions for improving service configuration and provisioning both intra and interdomain. Establishing service-dependent overprovisioning levels, especially for more demanding service classes, has also proved to be crucial to allow using monitoring-based AC systems in multiservice networks. Finally, regarding the monitoring process itself, the challenges and the viability of multiclass and multipurpose active monitoring approaches have been explored.

8.4 Topics of future work

From the analysis carried out along this work, several topics have been identified as deserving further research. A first set of topics derives directly from the assumptions, decisions and procedures followed in the definition of the present AC proposal. Covering these topics may improve particular aspects of the proposed solution or extend them. Thus, in addition to the discussion in Section 5.8, interesting issues are:

- *further develop the process of metrics computation and dissemination* - the choice of a light, effective and reliable process for computing and disseminating QoS metrics in real environments is an aspect requiring further study. Although active measurements are particularly suitable for edge-to-edge metrics' computation, alternative or complementary schemes to compute and provide measurements to edge nodes can be explored (e.g., the use of passive measurements, the combination of hop-by-hop measures, the use of QoS metrics provided by routing protocols). For the dissemination of metrics, evaluating the performance of solutions based on, for instance, ICMP, routing updates or SNMP may be useful. The use of multicast IP, where edge nodes can be member of specific network monitoring groups, may also be considered to achieve an efficient metrics' distribution;

- *scalability analysis and end-to-end performance* - future work intends to sustain and extend the obtained results of model evaluation to more complex network topologies and test scenarios, involving also multiple domains and SLSs. Considering the preliminary analysis of the main variables influencing the scalability of an AC proposal, summarized in Table 7.8, quantitative results should also be provided. Although the model's end-to-end behavior has been conceptually debated, evaluating the end-to-end performance across multiple domains and the effectiveness of the AC decision rule given by Eq. 5.12, deserves further investigation;

- *handling concurrent AC* - although the problem of concurrent AC has been here subject of study, an in-depth analysis of the proposed solutions' performance reflecting on their implementation costs vs. service benefits is relevant;

- *fairness of AC decisions* - usually, MBAC and EMBAC have implicit a single decision policy that tends to privilege small flows, flows with more relaxed QoS objectives and flows that traverse smaller path lengths [99, 106]. Although not all of these cases apply to the proposed AC model, studying the fairness of AC decisions involves defining a clear and unambiguous criterion of fairness, and performing an analysis at flow level and/or at SLS level to verify if fairness is accomplished. Improving the AC rules with additional policies defined according to an established fairness criterion may be done in the future. In particular, a progressive and proportional AC criteria (RIO-like AC), which would reduce the privilege to small flows and the cyclic admission behavior in Δt_i, could be explored. AC algorithms alternative to the Measure Sum, including a more precise forecast of the impact of accepting a new flow and/or formal relations between traffic characteristics and AC equations' parameters, could also be explored.

The following list comprises a set of more demanding and broader topics, pointing out future research directions:

- *policy-based management and security issues* - in Chapter 1, several research areas have been pointed out, and further developed in the following chapters, as relevant to devise a realistic and consistent AC solution. The use of policy-based management and the inclusion of security issues in the model have been left for future study. Examples of policy-based management concepts applied to both AC and SLS contexts are proposed in [87, 225, 226]. In particular, specifying AC requests, SLS dynamic negotiation, definition and enforcement of AC policies and systems' configuration could benefit from policy-based management. Thus, exploring the advantages and disadvantages of its use in the management of the entities and decisions involved in the proposed AC solution and to support the configuration and operation of the model is a topic to be covered[1]. The inclusion of functions and state information related to security aspects regarding service usage, such as authentica-

[1]As an example, the paradigm and protocols behind policy-based management, such as COPS and COPS-PR, has the advantage of allowing a level of abstraction between the policy rules to apply and the devices configuration details, creating a normalized interface between the management decision entities and the managed entities. The amount of signaling involved is a possible disadvantage.

tion, authorization and accounting [227] and denial of service attacks, is also an important research topic related to AC;

- *dynamic negotiation of SLSs and SLS AC* - having tackled the problem of flow AC, the proposed model may be extended to cover dynamic SLS negotiation and SLS AC. In fact, as stated in Section 5.1.1, flow and SLS AC involve considering similar variables, such as traffic profile and QoS objectives, being this last one bounded by the service class QoS levels. However, the time and space granularity upon which the decision is made, the domain state information that sustain the decision, the new state information to keep and the need to (re)configure the network elements involved are distinct. As an example, SLS AC should not be sustained only by on-line monitoring information but also by less transient information such as load forecasting based on the matrix of accepted SLSs for the validity period of the new SLS. The challenges and changes required to support this topic may be explored in the future;

- *bi-directional AC* - the present study covers unidirectional AC, which is in-line with, for instance, the definition of PHBs and PDBs. This should not be viewed as a conceptual limitation of the model as bi-directionality can be decoupled in unidirectional AC instances. In fact, a bi-directional SLS can be defined as two unidirectional SLSs [69]. For the proposed AC model, attending that an ingress node I_n maintains monitoring data for the pair (I_n, E_m) and assuming that each edge node may be either an ingress or egress depending on the flow's direction, covering bi-directional AC may explore and take advantage of bi-directional monitoring data located at each edge. The use of interdomain symmetric paths clearly simplifies bi-directional AC;

- *handling multicast and composite applications* - multicast represents a challenge for AC as traffic is replicated dynamically inside the network and it is difficult to know beforehand how the multicast trees will expand. This behavior is a further motivation for the use of a monitoring-based AC approach relying on systematic on-line monitoring, able to capture intrinsically the network dynamics and load changes. Using more elaborate control strategies and/or defining specific service classes and AC rules to handle multicast traffic flows is also a future research topic. Extending flow AC to the application level should also deserve attention giving that an application may encompass multiple interrelated flows requiring admission. Leaving to composite applications the final AC decision following an application dependent criterion based on flows' admittance or extending AC model functionality is an aspect that needs to be pondered as the semantics' enrichment in the AC model may bring additional complexity and state information;

- *handling route changes* - the connectionless packet forwarding nature of IP clearly makes difficult traffic control tasks and resource management as, in general, the entire route that packets will follow is not known in advance, and the route may change during flows' lifetime. As stated in Section 3.2, this is an aspect that increases the complexity and scalability problems of strict AC proposals with state information closely tied to network topology, routes and resource reservation, favoring measurement-based approaches. Especially in the proposed AC model, intradomain route changes or route balancing are not particularly troublesome due to the black box vision of the network core and adaptive nature of the model. Handling interdomain path changes, which falls within the end-to-end AC perspective of the model operation, is particularly challengeable as the crossed domains and the flow's available service computation may change substantially. Despite the change of interdomain routes may affect already accepted flows, and degradation may occur, this problem is reduced by the fact that transit domains' ingress nodes do not maintain per-flow state information and ISPs' neighboring tends to be rather stable. These considerations do not avoid the need of more in-depth reasoning on this topic. Peering and AS-path information collected by BGP and feedback mechanisms may be helpful for fast interdomain service (re)negotiation and end-to-end service re-establishment;

- *handling multipath options at domain boundaries* - in the proposed model, unless AC is decoupled between ingress and egress nodes, the topological, routing and service information in the domain should allow to determine at network entrance the egress node which will be used to leave the domain. Choosing the egress node (E_m) and downstream SLS (SLS^+_{i,E_m}) to use when more than one possibility is available should be based on domain policies to explore. In addition, assuring that all packets from a flow will use the same E_m and SLS^+_{i,E_m} selection, independently of following or not distinct intradomain paths, may involve additional state information and registration of involved boundaries nodes. Note that, this assurance may be provided at a higher level than the flow's one, for instance, at SLS_{i,I_n} level. The use of other techniques, such as flooding of AC requests in distinct boundaries (E_m) for subsequent assessment and selection of the most favorable end-to-end path, may also be explored in the future.

- *extending the proposed AC model to mobile environments* - attending to a clear trend toward mobility of users and devices, studying the viability, performance and migration issues of the AC model to mobile environments, such as mobile IP and ad-hoc networks, is definitely a research direction for the present work. Mobile environments increase the changes in topology and load conditions; thus, an important concern is to minimize convergence time (e.g., efficient handoff and fast recovery from route instability, particularly in ad-hoc networks). Several properties of the AC model such as its self-adaptive distributed nature, the reduced control and state information required are likely to favor the model's adequacy to the dynamics inherent to mobility. Nonetheless, this issue needs further research.

8.5 Final considerations

This research work focused on multiple issues regarding the provision of QoS in IP networks. In particular, the problematic of AC in multiservice class-based IP networks was the main subject of research. As initially mentioned in this dissertation, there are no ubiquitous and perfect solutions for a multidimensional problem as the one being addressed. Despite that, there was the intention to endow the proposed AC solution with properties believed relevant for its feasibility in real environments, balancing its underlying virtues and limitations. The topics pointed out as future work, aiming at enhancing or extending the present AC proposal, reveal interesting research directions remaining ahead.

Appendix A

Summary of the Proposed Notation

Table A.1 summarizes the main components specified in Chapter 5, providing the definition and a brief description of the notation proposed. This summary includes notation concerning:

- generic network domain entities;
- supported service classes and controlled parameters;
- negotiated upstream and downstream SLSs;
- traffic flows;
- matrices defined to aggregate data regarding
  - accepted and active SLSs;
  - QoS and SLS monitoring.

Table A.1: Model notation summary

Notation	Definition	Description
Domain Notation		
D_x		Current domain
D_x^-		Upstream domain
D_x^+		Downstream domain
I^{D_x}	$\{I_1, I_2, ..., I_N\}$	Set of ingress nodes in domain D_x
I_n	$1 < n < N$	Ingress node n
E^{D_x}	$\{E_1, E_2, ..., E_M\}$	Set of egress nodes in domain D_x
E_m	$1 < m < M$	Egress node m
Service Class Notation		
SC^{D_x}	$\{SC_1, SC_2, ..., SC_Y\}$	Set of service classes supported in D_x
SC_i or i	$1 < i < Y$	Service Class i
P_{SC_i}	$\{(P_{i,1}, \beta_{i,1}), ..., (P_{i,P}, \beta_{i,P})\}$	Set of controlled QoS parameter for SC_i
$P_{i,p}$	$1 < p < P$	Target value of QoS parameter p for SC_i
$\beta_{i,p}$		Safety margin of QoS parameter p for SC_i
$T_{i,p}$	$\beta_{i,p} * P_{i,p}$	Threshold of QoS parameter p for SC_i used in AC equations
$SLS_{SC_i}^{D_x^-}$	$\{SLS_{i,I_n} \| I_n \in I^{D_x}\}$	Set of accepted SLSs in D_x from upstream domains for SC_i
SLS_{i,I_n}		Accepted upstream SLS for SC_i connecting D_x through I_n
$SLS_{i,(I_n,E_m)}$		Accepted upstream SLS_{i,I_n}, considering $E_m \in$ Scope
R_{i,I_n} or $R_{i,(I_n,*)}$		Negotiated rate for SLS_{i,I_n}, independently of the domain E_m
$R_{i,(I_n,E_m)}$		Negotiated rate for SLS_{i,I_n}, considering egress node E_m
$\tilde{R}_{i,I_n}$		Measured rate for SLS_{i,I_n} (estimated load)
β_{i,I_n}		Safety margin for R_{i,I_n} used in AC equations
$P_{SLS_{i,I_n}}$	$\{P_{i,I_n,1}, ..., P_{i,I_n,P'}\}$	Set of expected QoS parameters for SLS_{i,I_n}
$P_{i,I_n,p'}$	$1 < p' < P'$	Target value of QoS parameter p'
$SLS_{SC_i}^{D_x^+}$	$\{SLS_{i,E_m}^+ \| E_m \in E^{D_x}\}$	Set of SLSs negotiated in D_x with downstream domains for SC_i
SLS_{i,E_m}^+		Negotiated downstream SLS for SC_i leaving D_x through E_m
R_{i,E_m}^+ or $R_{i,(*,E_m)}^+$		Negotiated rate for SLS_{i,E_m}^+, independently of the domain I_n
$\tilde{R}_{i,E_m}^+$		Measured rate for SLS_{i,E_m}^+ (estimated load)
β_{i,E_m}^+		Safety margin for R_{i,E_m}^+ used in AC equations
P_{SLS_{i,E_m}^+}	$\{P_{i,E_m,1}^+, ..., P_{i,E_m,P+}^+\}$	Set of expected QoS parameters for SLS_{i,E_m}^+
$\notin SLS$		Traffic not supported by an SLS
$R_{i,I_n}^{\notin SLS}$ or $R_{i,E_m}^{\notin SLS}$		Rate limiting traffic not sustained by an SLS at I_n or E_m for SC_i
$\tilde{R}_{i,I_n}^{\notin SLS}$		Measured rate for traffic not sustained by an SLS at I_n for SC_i
$\beta_{i,I_n}^{\notin}$		Safety margin for $R_{i,I_n}^{\notin SLS}$ used in AC equations
Flow Notation		
F_j or $F_j \in SLS_{i,I_n}$		Flow j belonging to an upstream SLS requiring AC
$F_j \notin SLS_{i,I_n}$		Flow j without a pre-defined upstream SLS requiring AC
r_j		Rate of flow F_j (peak or mean)
$\tilde{r}_{i,(I_n,E_m)}$		Measured aggregated rate of flows between I_n and E_m for SC_i
P_{F_j}	$\{(P_{j,1}, \gamma_{j,1}), ..., (P_{j,P''}, \gamma_{j,P''})\}$	Set of QoS parameter requirements for F_j
$P_{j,p''}$	$1 < p'' < P''$	Target value to QoS parameter p''
$\gamma_{j,p''}$		Tolerance to parameter $P_{j,p''}$ degradation
$P_{j,p''}^{acc^-}$		Cumulative value for $P_{j,p''}$ when entering D_x
$P_{j,p''}^{acc}$		Cumulative value for $P_{j,p''}$, including $P_{i,p}$ of D_x

Table A.2: Model notation summary (cont.)

Notation	Definition	Description
SLS and QoS Matrix Notation		
$\Phi_{SC_i}^{SLS}$	$(\phi_{i,n})$ or $(\phi_{i,(n,m)})$	Matrix of accepted and active upstream SLSs for SC_i
$\phi_{i,n}$	SLS_{i,I_n}	Specific SLS matrix entry
$\phi_{i,(n,m)}$	$SLS_{i,(I_n,E_m)}$	Specific SLS matrix entry, considering $E_m \in SLS_{i,I_n}$ scope
$\Phi_{SC_i}^{SLS^+}$	$(\phi_{i,m}^+)$	Matrix of accepted and active downstream SLSs for SC_i
$\phi_{i,m}^+$	SLS_{i,E_m}^+	Specific SLS matrix entry
Δt_i		measurement time interval for SC_i
$\Psi_{SC_i}^{QoS}$	$(\psi_{i,(n,m)})$	QoS monitoring matrix for SC_i in Δt_i for (I_n, E_m) pairs
$\psi_{i,(n,m)}$		Specific matrix entry corresponding to (I_n, E_m) pair
$\psi_{i,n}$		Specific matrix entry not dependent of E_m
$\psi_{i,m}$		Specific matrix entry not dependent of I_n
$\psi_{i,(n,m)} \rightarrow P_p$	$\tilde{P}_{i,(I_n,E_m),p}$	Measured QoS parameter p of P_{SC_i} for (I_n, E_m) pair
$\psi_{i,(n,m)} \rightarrow AC\_Status_{\Delta t_i}$	$AC\_Status_{\Delta t_i}$	AC status for Δt_i considering all QoS parameters in P_{SC_i}
$Adm\_flows_{\Delta t_i}$		Number of admissible flows in Δt_i for SC_i with implicit AC

Appendix B

AC Algorithms

This Appendix includes the description of several algorithms that support the explicit or implicit AC decision process both intra and interdomain. This description, using pseudocode, considers that:

- AC is carried out at ingress nodes I_n based on the complete set of equations defined in Section 5.5;
- internal SLS_{i,I_n} and SLS^+_{i,E_m} have been defined in the source and destination domains. Covering this aspect simplifies the algorithms as they can be applied to source, destination or transit domains, irrespectively;
- measured rate variables $\tilde{R}_{i,I_n}$, $\tilde{R}^{\notin SLS}_{i,I_n}$ and $\tilde{R}^+_{i,E_m}$ included in the monitoring matrix $\Psi^{QoS}_{SC_i}$ are updated during Δt_i;
- all flows without a pre-defined upstream SLS requiring AC, i.e., $F_j \notin SLS_{i,I_n}$, are aggregated within a specific SLS_{i,I_n}.

For implicit AC, new incoming flows need to be implicitly detected so that AC can take place. Implicit AC algorithms are simpler as no verifications regarding the new flows' traffic profile and QoS requirements need to be performed. For implicit AC, oriented to elastic TCP traffic, it is assumed that:

- the QoS and the optional rate control rules are complemented by an $Adm\_Flows_{\Delta t_i}$ variable controlling the number of admitted flows within Δt_i;

- new flows are identified and controlled based on the detection and forwarding/discarding of packets that initialize a TCP connection (SYN and SYN ACK).

The presented algorithms are possible proposals to implement and verify the set of QoS and rate control rules defined in Section 5.5.

Algorithm 1

This algorithm handles flows requiring explicit admission. Each new flow F_j AC request is processed at ingress node I_n, after being classified and validated facing the requested service. When valid, if D_x is the source domain then the corresponding ingress node identifier I_{src} may be kept for eventual TC configuration.

The variable $ACDecision$ is updated bitwise $(\leftharpoonup)$ according to the acceptance conditions or rejection causes reported by AC rules. Based on its value, a flow F_j is accepted and forward, or rejected, being an AC request reply sent to source (and eventually processed at I_{src}). When the destination is reached, the receiver accepts or rejects the AC request after verifying the flow's $TProfile$, $ReqQoS$, $QoSTolerance$, $AccQoS$ fields. It may also propose to the source new QoS parameter values within the flow's acceptable tolerance range, updating F_j QoS specification accordingly.

Algorithm 1: Explicit AC Decision

```
$ACRequest(I_n, F_j)$
        /* Ingress nodes process the incoming AC requests */
        (...)
        $SC_i \longleftarrow Classify(F_j)$
        $SLS_{i,I_n} \longleftarrow IdentifySLS(SC_i, I_n, F_j)$              /* Considering
        $E_m \longleftarrow GetEgress(SC_i, F_j \rightarrow Dst_{id})$              $(F_j, \Phi^{SLS}_{SC_i}, \Phi^{SLS^+}_{SC_i})$
        $SLS^+_{i,E_m} \longleftarrow IdentifySLS^+(SC_i, E_m, F_j)$              identify $\phi_{i,n}$ and $\phi^+_{i,m}$ */
        $[CheckPermission(SC_i, SLS_{i,I_n}, SLS^+_{i,E_m}, F_j)]$
        $if(F_j \rightarrow Src_{id} \in D_x)\ then$
                $(F_j \rightarrow I_{src}) \longleftarrow I_n$

        /* At beginning of $\Delta t_i$ update $\psi_{i,(n,m)} \rightarrow AC\_Status$ through
                $CheckQoSStatus(\psi_{i,(n,m)})$ ) */

        $ACDecision \leftharpoondown (\psi_{i,(n,m)} \rightarrow AC\_Status)$
        $ACDecision \leftharpoondown CheckSLSStatus(\phi_{i,n}, \phi^+_{i,m}, \psi_{i,n,m}, F_j \rightarrow TProfile)$
        $ACDecision \leftharpoondown CheckAccQoS(SC_i, F_j \rightarrow ReqQoS, F_j \rightarrow QoSTolerance,$
                                                        $F_j \rightarrow AccQoS)$
        $if(ACDecision = \texttt{Accept})\ then$
                $UpdateRateUsage(\psi_{i,n,m}, F_j \rightarrow TProfile)$
                $UpdateAccQoS(SC_i, F_j \rightarrow AccQoS)$
                $if\ (Scope = \texttt{External})\ then$
                        /* optional information for downstream usage */
                        $[(F_j \rightarrow SLS_{id}) \longleftarrow SLS^+_{i,E_m}]$
                        $[(F_j \rightarrow D_{id}) \longleftarrow D_x]$
                $ForwardRequest(F_j)$
        $if(ACDecision = \texttt{Reject})\ then$
                $ACReply(F_j, ACDecision)$       /* to $F_j \rightarrow Src_{id}, F_j \rightarrow I_{src}$ */
        (...)
        /* When the destination is reached */
        $if(F_j \rightarrow Dst_{id} \in LocalNode)\ then$
                $ACDecision \longleftarrow ReceiverAcceptanceAlgorithm(F_j)$
                $F'_j \longleftarrow ReceiverNewQoSProposal(F_j)$
                $ACReply(F'_j, ACStatus)$
        (...)
```

Algorithm 2

This algorithm determines how a source and ingress node I_{src} process an AC reply to a previous flow AC request. Note that, only these nodes process an AC reply, i.e., the reply is transparent to transit ingress nodes. At I_{src}, acceptance/rejection tables may be updated accordingly. These tables can be used to control and avoid misbehaved sources, performing systematic AC requests upon each rejection notification. In case of acceptance, TC configuration at I_{src} may occur using $F_j \to TProfile$.

Algorithm 2: AC Decision Notification Reception

```
$ACReply(F_j, ACStatus)$
    (...)
    $if(F_j \to I_{src} \in LocalNode)\ then$
        $if(ACStatus = \texttt{Accept})\ then$
            $ConfigureTC(F_j \to TProfile)$
            $[UpdateAcceptanceTable(F_j, timestamp)]$
        $if(ACStatus = \texttt{Reject})\ then$
            $[UpdateRejectionTable(F_j, timestamp)]$
        (...)
        $ForwardReply(F_j, ACStatus)$

    $if(F_j \to Src_{id} \in LocalNode)\ then$
        $SenderAcceptanceAlgorithm(F_j, ACStatus)$

    $if((F_j \to I_{src} \notin LocalNode)\ or\ (F_j \to Src_{id} \notin LocalNode))\ then$
        $IgnoreACReply()$
        $ForwardReply(F_j, ACStatus)$
    (...)
```

Algorithm 3

This algorithm is responsible for performing the verification of SLS_{i,I_n} and SLS^{+}_{i,E_m} rate control rules (Eqs. (5.5) or (5.6), and (5.7)). When I_n and SC_i are used by $F_j \notin SLS_{i,I_n}$, the rate of traffic $\notin SLS_{i,I_n}$ can also be controlled. However, Eq. (5.9) is considered a special case of Eq. (5.5).

Algorithm 3: SLS Rate Usage Verification

```
$CheckSLSStatus(\phi_{i,n}, \phi^{+}_{i,m}, \psi_{i,n,m}, F_j \rightarrow TProfile)$
    (...)
    $SLSRateRule \leftarrow (\psi_{i,n} \rightarrow R + F_j \rightarrow TProfile) \leq (\phi_{i,n} \rightarrow \beta * \phi_{i,n} \rightarrow R)$
    /* When $\vec{R}_{i,I_n}$,
    $SLSRateRule \leftarrow (\psi_{i,(n,m)} \rightarrow R + F_j \rightarrow TProfile) \leq$
                                        $(\phi_{i,(n,m)} \rightarrow \beta * \phi_{i,(n,m)} \rightarrow R)$ */

    $SLS^{+}RateRule \longleftarrow (\psi_{i,m} \rightarrow R^{+} + F_j \rightarrow TProfile) \leq (\phi^{+}_{i,m} \rightarrow \beta * \phi^{+}_{i,m} \rightarrow R^{+})$
    $ReturnACCode(SLSRateRule, SLS^{+}RateRule)$
```

Algorithm 4

For a domain D_x, service class SC_i and (I_n, E_m) pair, this algorithm determines the QoS acceptance status for Δt_i according to the QoS measures provided by egress node E_m (Eq. (5.10)). This acceptance status is updated once each Δt_i interval, but other scenarios can be devised.

Algorithm 4: Domain QoS Verification

```
$CheckQoSStatus(\psi_{i,(n,m)})$
    (...)
    $\forall_{(P_{i,p}, T_{i,p}, \beta_{i,p})} \in P_{SC_i}$
        $T_{i,p} \longleftarrow \beta_{i,p} P_{i,p}$
        $if\ ((\psi_{i,(n,m)} \rightarrow P_p) \leq T_{i,p})\ then$
            $(\psi_{i,(n,m)} \rightarrow AC\_Status) \longleftarrow AcceptCode$
        $else$
            $(\psi_{i,(n,m)} \rightarrow AC\_Status) \longleftarrow RejectCode$
            $Return()$
    (...)
```

Algorithm 5

This algorithm performs the cumulative evaluation of QoS in D_x, checking the fulfillment of flows' requirements and end-to-end service availability (Eq. (5.12)). Performing this test in all the involved domains allows to test if $F_j \rightarrow ReqQoS$ and $F_j \rightarrow QoSTolerance$ is met considering both the domain's metrics and $F_j \rightarrow AccQoS$. Testing if flow requirements fit within the corresponding SLS_{i,I_n} QoS specification is not necessary as SLS_{i,I_n} acceptance has already been conditioned by SC_i QoS.

Algorithm 5: End-to-End QoS Verification

```
$CheckAccQoS(SC_i, F_j \rightarrow ReqQoS, F_j \rightarrow QoSTol, F_j \rightarrow AccQoS)$
    (...)
    $\forall(P_{j,p}, \gamma_{j,p}, P_{j,p}^{acc^-}) \in (F_j \rightarrow ReqQoS, F_j \rightarrow QoSTol, F_j \rightarrow AccQoS)$
        $P_{i,p} \in P_{SC_i}$
        $if\ not((\mathtt{op}_1\ (P_{j,p}^{acc^-}, P_{i,p}))\ \mathtt{op}_2\ (\gamma_{j,p} P_{j,p}))\ then$
            $ReturnACCode(e2eRejectCode)$
    $ReturnACCode(e2eAcceptCode)$
```

Algorithm 6

This algorithm updates the rate estimates $\tilde{R}_{i,(I_n,*)}$, $\tilde{R}^+_{i,(*,E_m)}$ or $\tilde{R}^{\notin SLS}_{i,(I_n,*)}$ in the monitoring matrix located at ingress node I_n. This update is only visible at the corresponding I_n and remains active until the next Δt_i information update from E_m to I_n takes place. This allows to count in advance with the new flow rate until it can be sensed by the monitoring process in the following Δt_i. If a flow F_j is rejected in D_x^+, the next Δt_i update brings the system to the real state.

Algorithm 6: SLS Rate Usage Update

```
$UpdateRateUsage(\psi_{i,n,m}, F_j \rightarrow TProfile)$
    /* Updates $\tilde{R}_{i,(I_n,*)}$ and $\tilde{R}^+_{i,(*,E_m)}$ at $I_n$ monitoring matrix.
    (...)
    $(\psi_{i,n} \rightarrow R) \longleftarrow (\psi_{i,n} \rightarrow R) - (F_j \rightarrow TProfile)$
     /* When $\vec{R}_{i,I_n}$,
     $(\psi_{i,(n,m)} \rightarrow R) \longleftarrow (\psi_{i,(n,m)} \rightarrow R) - (F_j \rightarrow TProfile)$ */

    $(\psi_{i,m} \rightarrow R^+) \longleftarrow (\psi_{i,m} \rightarrow R^+) - (F_j \rightarrow TProfile)$
    (...)
```

Algorithm 7

If a flow F_j is accepted in domain D_x, $F_j \rightarrow AccQoS$ is updated according to the QoS parameters of SC_i within D_x (Eq.5.13).

Algorithm 7: End2End Cumulative QoS Update

```
$UpdateAccQos(SC_i, F_j \rightarrow AccQoS)$
    (...)
    $\forall P_{j,p}^{acc^-} \in F_j \rightarrow AccQoS$
        $P_{i,p} \in P_{SC_i}$
        $P_{j,p}^{\prime acc^-} \longleftarrow \texttt{op}_1(P_{j,p}^{acc^-}, P_{i,p})$
    (...)
```

Algorithm 8

This algorithm handles implicit AC of TCP flows. After detecting implicitly a new flow F_j, an AC decision is made at ingress node I_n.

Algorithm 9

This algorithm exemplifies a verification of the implicit SLS rate usage. The function $f()$, which takes the defined rate and the estimated rate, may determine how many flows will be allowed in the interval.

Algorithm 8: Implicit AC Decision

```
    (...)
$F_j \longleftarrow NewFlowDetection()$
    (...)
$ImplicitAC(I_n, F_j)$
    (...)
    $SC_i \longleftarrow Classify(F_j)$
    $SLS_{i,I_n} \longleftarrow IdentifySLS(SC_i, I_n, F_j)$            /* Considering
    $E_m \longleftarrow GetEgress(SC_i, F_j \rightarrow Dst_{id})$            $(F_j, \Phi^{SLS}_{SC_i}, \Phi^{SLS^+}_{SC_i})$
    $SLS^+_{i,E_m} \longleftarrow IdentifySLS^+(SC_i, E_m, F_j)$            identify $\phi_{i,n}$ and $\phi^+_{i,m}$ */
    $[CheckPermission(SC_i, SLS_{i,I_n}, SLS^+_{i,E_m}, F_j)]$

    /* At beginning of $\Delta t_i$ perform $CheckQoSStatus(\psi_{i,(n,m)})$
                [and $CheckSLSStatusImp(\phi_{i,n}, \psi_{i,n})$
                and/or $CheckSLSStatusImp(\phi^+_{i,m}, \psi_{i,m})$] */

    $ACDecision \longleftarrow (\psi_{i,(n,m)} \rightarrow AC\_Status)$
    $[ACDecision \longleftarrow (\psi_{i,n} \rightarrow AC\_Status\_R)\ and/or\ (\psi_{i,m} \rightarrow AC\_Status\_R)]$

    $if\ (ACDecision = \texttt{Accept})\ and\ (\psi_{i,n} \rightarrow Adm\_Flows > 0)$ then
        $(\psi_{i,n} \rightarrow Adm\_Flows) \longleftarrow (\psi_{i,n} \rightarrow Adm\_Flows - 1)$
        $ForwardSyn()$
    $else$
        $DiscardSyn()$
    (...)
```

Algorithm 9: Implicit SLS Rate Usage Verification

```
$CheckSLSStatusImp(\phi_{i,n}, \psi_{i,n})$
    (...)
    $if\ (\psi_{i,n} \rightarrow R) \leq (\phi_{i,n} \rightarrow \beta) * (\phi_{i,n} \rightarrow R)\ then$
        $(\psi_{i,n} \rightarrow AC\_Status\_R) \longleftarrow AcceptCode$
    $else$
        $(\psi_{i,n} \rightarrow AC\_Status\_R) \longleftarrow RejectCode$
    $(\psi_{i,n} \rightarrow Adm\_Flows) \longleftarrow f((\phi_{i,n} \rightarrow R) - (\psi_{i,n} \rightarrow R))$
    (...)
```

Appendix C

Performance Discussion of MBAC Algorithms

Conceptually, two goals drive the design of MBAC algorithms [99]: (i) to provide a parameter that estimates a priori the level of service failures accurately; (ii) to achieve the highest possible utilization for a given service failure level. According to [121, 99], MBAC algorithms comprise two key components: a method for estimating the performance parameter under control (e.g., rate or utilization) and a decision algorithm that uses this estimation to make AC decisions. Generically, the MBAC algorithms proposed in the literature differ in the following aspects [99]: (i) some are based on solid mathematical formulations while others are more intuitive or ad-hoc; (ii) the concrete equation used to make the AC decision; (iii) the calibration of the parameter that influences the achieved performance; (iv) the measurement method used to produce the parameter estimation (see examples in Section 6.3).

In [107], the AC algorithms are categorized as rate-based or delay-based. As rate-based algorithms, the authors consider and evaluate Rate or Simple Sum, Measure Sum, Equivalent Bandwidth, Acceptance Region. As delay-based algorithms, they focuses on the measurement-based scheme with delay and bandwidth constraints proposed in [121]. According to the authors, all these schemes can be applied as parameter-based or measurement-based, where in the latter case the parameters are substituted by measured values. Their preliminary results show that the Measure Sum and Acceptance Region achieve the highest utilization (but under similar conditions Acceptance Region has higher loss), the Equivalent Bandwidth algorithm is more conservative (no loss) and Rate Sum, being parameter-based, achieves the lowest utilization results. In [105], the same four admission control algorithms are also compared using single hop and multihop simulation scenarios.

In [109], a broad set of algorithms proposed in the literature to provide statistical QoS guarantees in multiservice networks is considered, compared and divided into the following categories: (i) algorithms based on average/peak rate; (ii) algorithms based on additive effective bandwidths; (iii) algorithms based on engineering the *Loss Curve*; (iv) algorithms based on maximum variance approaches; (v) algorithms based on refinements to effective bandwidths using large deviation theory. A complete description of the principles of each category and their evaluation results are presented in [109]. In addition to the mentioned categories, the authors point out measurement-based algorithms based on aggregate traffic measurements (traffic envelopes), strategy refined by the authors in later publications [122, 123].

A comparison of algorithms to measure the aggregated traffic load and perform per-flow admission based on flow traffic descriptors, namely Measure Sum, Hoeffding Bounds, Tangent at Peak, Tangent at Origin, Measure CAC and Aggregate Traffic Envelopes is available in [99]. Their results for a single node test scenario reveal that, despite the mathematical foundations complexity, those algorithms produce similar performance results when considering the trade-off between utilization and loss, however, when considering a performance target, namely the target loss rate, their tuning parameters are unable or fail to predict the loss target consistently.

According to the authors, regarding the performance of the algorithms, the way the new flows arrival and departure is treated and the equations sensitivity to traffic fluctuations, controlled by the measurement time interval, are more relevant than the foundations of the AC equations in use. In [99], two distinct causes for variations in the number of admitted flows that may lead to performance degradation of MBAC algorithms are identified. The first is related to how the algorithms deal with the arrival and departure of flows. The second is related to how they respond to load fluctuations. MBAC algorithms based on aggregate measurements do not know how much a departing flow has contributed for the previous load estimate. For that, they must wait for the new measurements to reflect the flow departure (if known) before admitting a new flow. During this waiting time, additional departures may lead to a decrease on the number of flows within the system. Similarly, when a new flow is admitted, the MBAC algorithm must assume the flow worst-case behavior until its presence is reflected by new measurements. About the second cause, as MBAC relies on measurements of current traffic load, it responds to significant load fluctuations even when the number of flows has not changed. MBAC cannot distinguish whether a load increase is due to an excessive number of accepted flows or due to a high-level traffic fluctuation of a fixed number of flows. When the latter occurs, flows may be rejected even if there are few flows in the system and, similarly, during a low-level traffic fluctuation new flows can be accepted even if too many flows are present. Longer measurement intervals avoid adjusting to short-term traffic fluctuations, however, lead to less reactive AC algorithms upon the departure and arrival of flows. Trying to keep the number of flows constant is not the better performance solution for all cases, for instance, with LRD traffic, the MBAC ability to adjust the number of admitted flows in response to long-term variations increases performance.

Following the panoply of existing AC equations and their evaluation results, in [209] the authors consider that more research in developing better AC equations may be fruitless, being more relevant to discuss and, eventually, develop mechanisms that enable MBAC supporting a range of policies beyond the usual single policy that tends to privilege small flows and flows that traverse smaller path lengths.

Appendix D

Monitoring Applications and Tools

A QoS monitoring system can be build based on common open-source or freeware software management tools (SMTs) or on commercial products. These solutions differ in terms of complexity, scalability, installation and operation cost, security and availability [190].

Open-source SMTs, such as CAIDA tools, RUDE/CRUDE, netperf, usually following a sender/receiver (client/server) model, are particularly suitable for the deployment of distributed monitoring infrastructures. They can be used to build a low cost monitoring infrastructure easily extended to other domains or end-users, and adjusted to specific or new measuring requirements. The provided APIs for collecting measuring data allow an easy manipulation of that data and corresponding on-line or off-line analysis for continuous or sparse network performance evaluation. The security vulnerabilities, the lack of tools for presenting monitoring results in an integrated and consistent way, and the knowledge required to define appropriate measurement scenarios are usually pointed out as disadvantages of SMTs.

Commercial products such as RIPE TTM, Brix Networker, Matrix, SAA, Ipanema, IxChariot follow typically a centralized model, which facilitates to have an integrated view of the network performance, commonly supported by graphical facilities. Scalability problems may, however, occur when monitoring large-scale measurement infrastructures. Commercial monitoring systems, having technical vendor support, are easy to deploy and maintain in production scenarios, however, being based on a closed architecture, more limited scenarios and monitored parameters are imposed, and the support of new features has generally to wait for new software versions at additional costs. The usually required GPS receivers for synchronization purposes make these systems accurate but with high installation costs [190].

Common and widely spread ad-hoc management tools (classical tools) such as ping, traceroute and netstat are sometimes used to assist network monitoring, such as in RIPE TTM. In RIPE TTM traceroute is more sparsely used than other measures (for instance, each six minutes) to register a vector of routes the traffic is following. Changes in the routing vectors can often explain why the mean delay has suddenly changed. These vectors are also of interest to verify the stability of routes and path conformance with a routing policy [92]. Reporting the path traversed by the test packets along with the metric results, whenever possible, is also recommended [168, 167].

An overview describing and evaluating existing tools for measuring QoS parameters defined in Section 4.2.1, covering aspects such as the tool measurement purpose, its measurement underlying principles and obtained accuracy is provided in [81, 104, 176, 179, 228].

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