LRIC cost approaches for differentiated QoS in broadband networks

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Contents

List of Figures

IV

List of Tables

Glossary

AAA	Authentication, Authorization and Accounting
ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
CAC	Call Admission Control
CBC	Capacity Based Charging
CPE	Customer Premises Equipment
DiffServ	Differentiated Services
DoS	Denial of Service
DSCP	Differentiated Services Code Point
DSLAM	Digital Subscriber Line Access Multiplexer
DWDM	Dense Wavelength Division Multiplexing
FRR	Fast Rerouting
FTTB	Fiber to the Building
FTTC	Fiber to the Curb
FTTH	Fiber to the Home
GPON	Gigabit Passive Optical Network
IntServ	Integrated Services
IRG	Interior Gateway Protocol
ITU	International Telecommunications Union
LRIC	Long-Run Incremental Cost
LSR	Label Switch Router
MDF	Main Distribution Frame
MOS	Mean Opinion Score
MPLS	Multi-Protocol Label Switching
MPoP	Metropolitan Point of Presence
MSAN	Multi-Service Access Node
NGN	Next Generation Network
NRA	National Regulatory Agency
O&M	Operations & Maintenance
OSI	Open System Interconnection

Over-eng	Over-engineering
P2P	Point-to-Point
PHB	Per-Hop Behaviour
PQ	Priority Queuing
PSTN	Public Switched Telephone Network
QoE	Quality of Experience
QoS	Quality of Service
RACS	Resource and Admission Control Subsystem
RED	Random Early Detection
RSVP	Resource Reservation Protocol
SDH	Synchronous Digital Hierarchy
Segg	Separated virtual tunnels
SLA	Service Level Agreement
TCP	Transmission Control Protocol
TELRIC	Total Element based Long Run Incremental Cost
TOS	Type of Service
VBC	Volume Based Charging
VC	Virtual Circuit
VDSL2	Very High Speed Digital Subscriber Line 2
VLAN	Virtual Local Area Network
VoIP	Voice over IP
WDM	Wavelength Division Multiplexing
WFQ	Weighted Fair Queuing
WRED	Weighted Random Early Detection

Zusammenfassung

Das Ziel dieses Forschungsprojektes ist es, zu erörtern, wie die Nutzung von Quality of Service (QoS) Techniken in einem LRIC-Kostenmodell berücksichtigt werden sollte. Netzbetreiber setzen heute verschiedene QoS-Techniken ein, um die qualifizierte Bereitstellung von Diensten zu verbessern, was sich auf die Kosten des Dienstes auswirken kann. Einer der wichtigsten Punkte, der bei der Ausarbeitung eines LRIC-Kostenmodells behandelt werden sollte, ist die Definition eines effizienten Netzes. Außerdem muss erörtert werden, wie QoS-Konzepte in ein LRIC-Kostenmodell integriert werden sollten. Um diese Fragen zu beantworten wurde der Bericht in drei Abschnitte unterteilt.

Die Grundsätze für das Design eines effizienten Netzes werden im ersten Teil des Berichts beschrieben. Netzwerk-Design, Netzwerk Engineering und Traffic-Engineering sind die Werkzeuge, die für die Planung eines Netzwerks mit QoS-Funktionen verwendet werden können. Die wichtigsten QoS-Lösungen, die in dieser Studie beschrieben werden, sind PSTN-QoS-, Layer-2-QoS-, IP-Layer-QoS-, sowie Transport-Layer-QoS- und Application-Layer-QoS-Lösungen. Diese Techniken können auch gleichzeitig eingesetzt werden. Der Bericht unterscheidet weiterhin Soft- und Hard-Assurance Modelle der QoS-Bereitstellung. Beide QoS-Modelle unterscheiden sich durch die Dienste, die während des normalen Netzbetriebs und in Belastungssituationen bereitgestellt werden können. Es wird erwartet, dass sich die differenzierten Kosten für die Bereitstellung von QoS-Mechanismen zwischen den Modellen unterscheiden.

Im zweiten Teil des Berichts wird ein effizientes Netz mit QoS-Funktionen geplant. Zuerst werden die zurzeit relevantesten und am häufigsten verwendeten QoS-Mechanismen in Zugangs-, Aggregations- und Kernnetzen identifiziert. Im Folgenden wird erklärt, warum FTTC/VDSL2 und FTTH/P2P als Beispiele für effiziente NGN-Netze gewählt wurden. Der letzte Abschnitt dieses Teils beschreibt, welche Netzelemente QoS-Funktionen in FTTC/VDSL2 und FTTH/P2P Netzen unterstützen müssen, um Dienste mit QoS zu erstellen.

Schließlich erörtert der letzte Teil des Berichts die folgenden Komponenten eines Kostenmodells, die sich durch die Berücksichtigung von QoS ändern könnten: Kostentreiber, Kosten der Netzkomponenten, Verkehr und die Routing-Faktoren der Netzkomponenten. Es wird erklärt, warum die Kapazität des Netzes der wichtigste Kostentreiber werden könnte. Ein weiterer Kostentreiber, der im Fall von Priorisierung oder Reservierung von Kapazitäten in Knoten gebraucht wird, ist die Rechenleistung. Der Einsatz von Netzelementen, die QoS-Techniken verwenden, wird einen Einfluss auf die Kosten haben, und der von QoS-Anwendungen generierte Verkehr wird sich in Abhängigkeit von den eingesetzten QoS-Mechanismen ändern. Der Routing-Pfad von QoS-Verkehr kann auch die Nutzungsfaktoren der Netzelemente verändern. Abschließend wird am Beispiel von FTTC/VDSLS und FTTH/P2P Netzen das Design einer Routing-Matrix mit Nutzungsfaktoren für Dienste mit QoS illustriert.

Summary

The goal of this research project is to discuss how the utilization of Quality of Service (QoS) techniques should be included in an LRIC cost model. Several operators are deploying or have deployed QoS techniques that help improve qualified service production and that can have an impact on the cost of the service. On the one hand, one of the key points that should be addressed in the elaboration of an LRIC cost model is the definition of an efficient network. On the other hand, a question that should be studied is how QoS concepts should be incorporated into an LRIC cost model. To answer these questions the report has been divided into three sections

The principles used for the design of an efficient network are described in the first part of the report. Network design, network engineering and traffic engineering tools can be used for the design of a network with QoS capabilities. The main QoS solutions described are PSTN QoS solutions, Layer-2 QoS solutions, IP QoS solutions, and transport-layer and application-layer solutions. Network operators implement several solutions concurrently. The report discusses also the soft-assurance and hard-assurance models for QoS provisioning. Both QoS models are differentiated by the service that can be provided during normal and abnormal network conditions and it is expected that the cost of deploying QoS mechanisms in both models will differ.

In the second part of the report an efficient network with QoS capabilities is designed. To start with, the state-of-the-art or most used QoS mechanisms in the access, aggregation and core networks are identified. Next, it is argued why FTTC/VDSL2 and FTTH/P2P are taken as examples of NGN efficient networks. The last section of this part describes which main network elements must support QoS capabilities in FTTC/VDSL2 and FTTH/P2P networks in order to provide services with QoS.

Finally, the last part of the report discusses the following components of a cost model which could change when applying the cost model to a network that provides QoS: definition of cost drivers, cost of network elements, traffic carried out by network elements and routing factors. It is explained why the capacity of the network, measured in Kbps, Mbps or Gbps, could be the main cost driver. Another cost driver to take into account in nodes when using prioritization or capacity reservation is processing power. The deployment of network elements that support QoS will have an impact on the cost, and the traffic generated by QoS applications will change according to the QoS mechanisms employed. The routing path of traffic provided with QoS will also affect the usage factor of the network elements. Finally, the report includes examples of FTTC/VDSL2 and FTTH/P2P networks that illustrate the design of a routing matrix with usage factors for services provided with QoS.

1 Introduction

1.1 Motivation of the study

Over the years telecommunications operators have been deploying networks that provide higher and higher broadband capacity. An increase of broadband capacity enables the provision of a better access to data networks such as the Internet, a good Voice over IP (VoIP) service, the provision of IPTV services, etc. Some of the services that are provisioned through broadband networks are regulated and, as a consequence, are subject to price regulations. For example, a number of national telecommunications regulators in the European Union have defined wholesale termination charges for voice services and wholesale charges for the access to the fixed broadband infrastructure.

Operators are competing to provide users with services through a platform that offers more bandwidth, less packet transmission delay, and less –or almost no- interruptions of network operations. In this sense, they need a proper network infrastructure for the delivery of delay-sensitive services such as voice or video. One of the tools operators have to improve the utilization of the resources deployed is Quality of Service (QoS) techniques. Current and future services could then be provisioned through networks where QoS mechanisms are deployed.

Operators use different technologies and access network architectures such as FTTx, cable, and wireless. Furthermore, operators have different ways of deploying QoS mechanisms according to the specific network architecture they have adopted. QoS techniques can be deployed at several layers of the Open System Interconnection (OSI) model; the most well-known QoS techniques at the network layer are Integrated Services, Differentiated Services, and over-provisioning.

The determination of the cost for delivering the services inside a network is necessary for the calculation of termination rates. With the provisioning of new services and the deployment of new telecommunications networks, it will be necessary to update the calculation of costs. In IP networks, operators have the chance of deploying QoS mechanisms to use network resources more efficiently and to increase network performance.

Long-Run Incremental Cost (LRIC) is a cost model method used not only in the European Union for the definition of costs of regulated services. Forward-Looking LRIC models anticipate costs of networks structures; the values over the next years are calculated by working with current values and extrapolating them into the future. An LRIC cost model based on an efficient network can be used, for example, to determine the call termination cost in a PSTN network which provides voice services by establishing fixed capacity channels and stable QoS. So far, the network architecture of an efficient Public Switched Telephone Network (PSTN) was determined, and the cost elements and cost drivers were also specified in order to define an appropriate cost

model. But now we live in a period of network migration, where new networks that combine all types of services on one single network are being deployed, and new services will be provided. Therefore, one of the questions that arise is what will be the impact of the provisioning of QoS on the cost of some services. The provisioning of QoS could have an impact on the cost of the network that is deployed or upgraded. An LRIC cost model of regulated services must therefore consider the impact of implementing QoS in IP-based networks.

In terms of cost definition, the implementation of QoS in IP networks has a few implications. On the one hand, the new LRIC cost model should consider an efficient network that has QoS techniques. The definition of an efficient network with QoS for cost modelling purposes is still an open issue. On the other hand, in comparison with a network architecture without QoS, a network architecture with QoS could probably have different cost elements and cost drivers. This study addresses these issues.

1.2   LRIC cost models and Quality of Service

For the definition of mobile and fixed termination rates in the European Union, the European Commission has encouraged National Regulatory Agencies (NRAs) to assess whether a Forward-Looking LRIC cost model should be used for the calculation of termination rates (European Commission, 2009). For the calculation of the cost of wholesale broadband access services, several NRAs are also using LRIC cost models.

LRIC cost models take into account additional increments, which could be "defined narrowly as a small change in the volume of a particular service, or broadly, as the addition of a whole group of services" ((European Commission, 2009), p. 14). Network operators can use QoS techniques to provide different types of services, such as Gold, Silver and best-effort (Bronze) services. In fixed and mobile networks there are a number of possibilities for the provision of QoS, and network operators have been deploying QoS techniques for some time. As far as the authors know, there are no in-depth studies available in the literature that address how the use of Quality of Service mechanisms deployed by operators should be included in LRIC cost models.

1.3   Goal of the project

As network operators have been deploying QoS techniques in the networks, and as the LRIC cost model will in several cases be used for the determination of the price of services that use QoS techniques, it is then necessary to analyze the impact of QoS on LRIC cost models. In this sense, the goals of this research project are the following:

- *Identification of the state-of-the-art/most implemented QoS techniques in broadband networks*: there are several possibilities to deploy QoS and the

objective is to find out the relevant QoS mechanisms that are being implemented by operators nowadays.

- *Based on existing QoS approaches, design of an efficient network architecture with QoS*: LRIC cost models are based on cost-efficient networks. The objective is to define an efficient network architecture with QoS techniques.

- *Impact of QoS techniques on existing LRIC cost models*: it will be defined what should be modified in an LRIC cost model in order to calculate the cost of services provided with QoS.

- *Evaluation of cost elements and cost drivers of a network with QoS*: it will be determined whether the cost drivers and elements of a network that provides QoS capabilities will remain the same or will change. A point that will be addressed is whether the cost allocation procedures will change or not.

- *Cost allocation concepts in a QoS environment*: an open issue is to know how much of a network element will be used for services with QoS requirements. For example, how much of a node or a link is used for a specific service. This value will help to determine the routing factors[1].

1.4   Outline of the report

The report is organized as follows. Chapter 2 describes the principles that should be taken into consideration at the moment of designing a network with QoS. This chapter includes the basic network design principles and a description of the main QoS techniques.

The objective of Chapter 3 is to illustrate how an efficient network with QoS can be designed. First of all, the state-of-the-art/most used QoS mechanisms are explained. Then, the chapter includes a description of two network architectures that incorporate QoS: Fiber to the Curb/Very High Speed Digital Subscriber Line 2 (FTTC/VDSL2) and Fiber to the Home/Point-to-Point (FTTH/P2P).

Chapter 4 discusses the changes in an LRIC cost model necessary to include services provided with QoS. This chapter includes a description about the cost elements and cost drivers of a network with QoS. Next, there is a discussion about how the cost of QoS can be allocated in the nodes and links of a network. Moreover, two examples based on FTTC/VDSL2 and FTTH/P2P networks that shed light on the procedure used to implement QoS in a cost model were provided.

Finally, chapter 5 addresses the conclusions of the report.

2   Principles for the design of a network with QoS

As one of the objectives of the study is to design a network with QoS mechanisms, it is important to review the basic concepts that are applied when designing a network. Network design, network engineering and traffic engineering techniques can be used for the provision of QoS. Operators are deploying techniques that help increase Quality of Experience (QoE); this chapter explains, therefore, the main factors that affect end users' QoS perception: delay, delay variation, packet loss ratio, and bandwidth. A description of the QoS solutions deployed at different of the OSI model is included. The last point addressed in the chapter is the difference between soft-assurance and hard-assurance models for QoS provisioning.

2.1   Network Design Principles

In the competitive environment of telecommunications markets, network operators strive to provide existing and potential customers with the most attractive services. To this end, they are interested in managing a platform that is technically capable of delivering services that could satisfy the requirements of end users. There are a myriad of techniques that can be used to reach this goal, and only a few of them belong to the specific category of QoS techniques. This section provides an overview of the main network design principles used to improve the Quality of Experience of the end user. The information described in this section helps to put into perspective the QoS techniques that are mentioned later in Chapters 3 and 4.

2.1.1   Network design, network engineering and traffic engineering

Network design: Network design corresponds to the definition of a network topology. Network design covers three activities: Node placement, link placement, and capacity assignment (see Figure 2-1). Node placement consists in locating the nodes of the topology in specific places, whereas link placement is required to connect the nodes. The capacity assignment problem deals with the allocation of capacity to nodes and links (bandwidth, buffer, access lines, etc.) (Heckmann, 2006).

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1 The routing factor quantifies how much of a network element is used by a specific service. The routing factor is also named the usage factor.

Figure 2-1:   Network Design
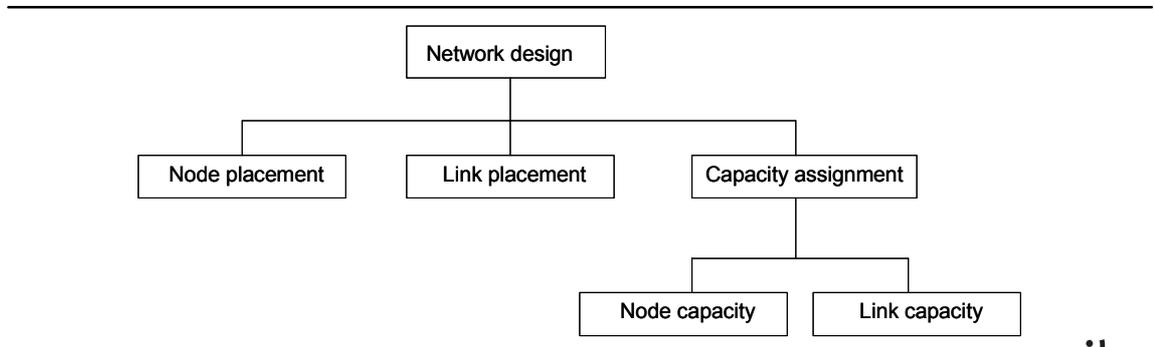
Source: (Heckmann, 2006), p. 238

Network engineering: Whereas network design issues are related to the definition of a (new) network topology, network engineering consists in improving an existing network topology (Heckmann, 2006). This can be done by using capacity expansion and/or structural engineering techniques. Capacity expansion entails boosting the capacity of an existing network; structural engineering consists in changing the nodes and/or links of an existing topology (see Figure 2-2). Network Engineering consists of long-term measures because changes in the current topology or an expansion of the capacity of links or nodes can not be done frequently.

Figure 2-2:   Network Engineering
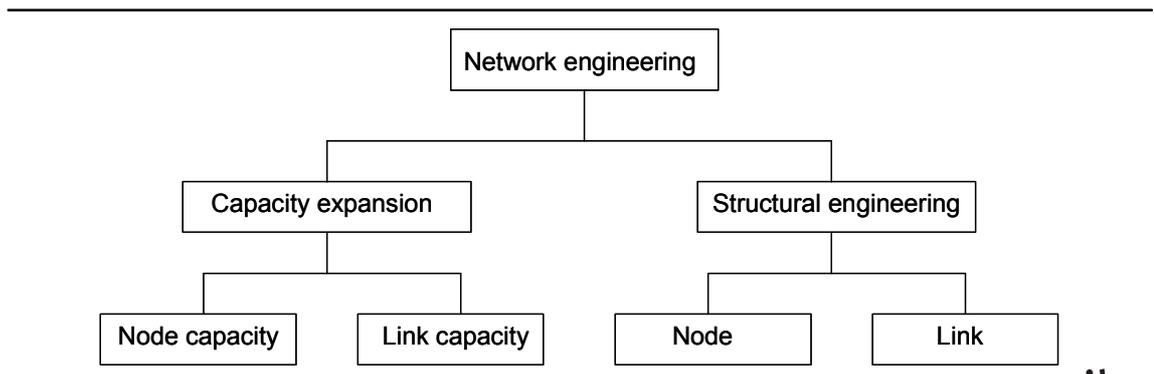
Source: (Heckmann, 2006), p. 240

Traffic engineering: Traffic engineering is concerned with the possibility of re-routing traffic flows by minimizing the over-utilisation of a link capacity when other under-utilised links are available in the network. An example would be the re-routing of traffic from nodes and links where the over-utilisation of capacity causes a bottleneck to alternative paths in the network that have capacity available. Traffic engineering is basically an

optimization problem. Traffic engineering entails medium-term engineering measures because the topology of the network is fixed (Heckmann, 2006).

The two basic tools used by operators to manage their existing networks are traffic engineering and network engineering. For the design of an LRIC cost model for a new network with QoS capabilities, network design, network engineering and traffic engineering techniques can be used.

2.1.2   Network Design procedure

There are a few specific steps that can be followed when designing a network. These steps are also valid for the design of a network with QoS capabilities. Network planning involves the following aspects (Xiao, 2008):

1. Understanding current traffic demand

2. Predicting traffic growth trend

3. Dimensioning one's network to meet current and future demands

4. Planning for failure scenarios.

These activities are explained in more detail below:

- Derive Traffic Demand: In this step it is necessary to determine the traffic that is generated by users. A table that contains the traffic generated by every type of user will be constructed. Table 2-1 shows an example of traffic demand in a case where residential and business users generate different types of traffic. The values represent the percentage of traffic generated by every type of user and sum up to a value of 1 per user type.

Table 2-1:   Example of Traffic demand

Type of user	Data User to Server	Data User to User	Real-Time & Streaming User to Server	Real-time & Streaming User to Server	Virtual Private Network
Standard – Residential	0,4	0,3	0,2	0,1	0
Premium – Residential	0,1	0,5	0,2	0,2	0
Standard – Business	0,3	0,4	0	0,1	0,2
Premium - Business	0,2	0	0,1	0,1	0,6

Source: WIK

- Plan Network Capacity: Capacity planning is about monitoring link utilization and adding capacity to the highly loaded links. It is necessary to identify the future traffic demand in order to determine the links that will be more utilized. In this step it is useful to construct a two-dimensional matrix that represents all the traffic carried out between the source and destination nodes of the network. Table 2-2 shows an example of a traffic matrix of three nodes. To obtain traffic trends, information about historic traffic statistics and traffic forecasts can be used.

Table 2-2:   Example of traffic matrix

Traffic		Destination		
		Node A	Node B	Node C
Source	Node A	8 Mbps	32 Mbps	19 Mbps
	Node B	26 Mbps	14 Mbps	21 Mbps
	Node C	12 Mbps	8 Mbps	5 Mbps

Source: WIK

- Plan Routing Policies: The definition of routing policies involves picking the best route for forwarding a packet. The Interior Gateway Protocols (IGPs) and the Border Gateway Protocols (BGPs) are examples of routing protocols that implement the routing policies.

- Plan for the Most Catastrophic Events: Network designers can use network design tools to simulate failures in the different nodes and links. This will help them define ahead of time the countermeasures that can be taken. A catastrophic event happens when for example a link or a site that contains network equipment is destroyed. Section 3.1.4 describes a few QoS techniques used in failure scenarios.

- Security Considerations: Security involves issues related to the Authentication, Authorization and Accounting (AAA), the coding and the encryption, security policies, and the access rights to the internal network elements (Weyerstraß, 2006).

2.2   QoS techniques

2.2.1   QoS requirements for end user's applications

QoS can be defined as a set of technical mechanisms necessary for the improvement of end user's QoS perspective. This is a user-centric perspective and it is usually named Quality of Experience (QoE). The end user rarely cares about the QoS mechanisms deployed by network engineers such as traffic management, reliability, security, routing, traffic engineering, etc. However, every end user has an idea of the performance of the applications in the network and, as a consequence, the end user can determine how effective is the network he/she is working with.

The first step towards the determination of the effectiveness of a network is the objective quantification of the subjective factors involved in the perception of a network's performance. There are several techniques used to measure the perception of the voice quality. One of the most well-known techniques is the Mean Opinion Score (MOS), which has been used widely for the assessment of voice codecs performance in fixed and mobile networks. VoIP codecs can also be evaluated by means of the MOS.

For the case of applications that run over IP-based networks, the three main factors that affect end users' perception are delay, delay variation, and packet loss ratio, which are explained next.

2.2.1.1   Factors that affect end users' QoS Perception

Delay: The end-to-end delay represents the necessary time to send a packet from the source application to the destination application. Technically speaking, the end-to-end delay is composed of two types of delays: the end-point application delay and the network delay (Xiao, 2008).

The end-point application delay is generated by the end-point application in the end user's device. Examples of application delays are the buffering delay caused by the jitter buffer, which is used to reduce the jitter, and the time needed for the packetization of voice or video samples (packetization delay).

The network delay has basically two components: the transmission delay and the propagation delay. The transmission delay is the time needed to push a packet into the

wire or fibre. This delay is caused by the transmission capacity of the link, which is measured in Kbps, Mbps, Gbps, etc. The propagation delay is the time it takes for the packet to be transferred over a medium to the destination point. The propagation delay depends on the propagation speed of the electromagnetic signal. The presence of several hops along the end-to-end path increases the total delay because at each hop the packet is queued and forwarded to the next hop.

Delay Variation (Jitter): The packet delay variation, known as jitter, is the difference between the delay of a packet and the delay of a reference packet. The different packet delays – and therefore the different packet delay variations - are caused by the following factors: the queuing delay of each packet at the same networking device (router, switch, hub, etc.) can be different; the processing delay of each packet at the same networking device (table lookup, physical switching, etc.) can also be different; and packets can travel through different routes to reach the destination point.

Packet Loss Ratio: This is the rate of packets' lost in a transmission from the source to the destination point. It is caused by the following factors: the congestion of the links generates a packet buffer overflow; network devices such as routers or switches can fail and packets can thus be dropped; packets can also be affected during failures in the transmission on wirelines; or when the routing protocol re-converges some destinations can be named unreachable and, therefore, packets to these destination could be dropped.

Bandwidth: If delay, jitter and packet loss rate are the parameters used to define the end users' QoS perception, then it is not necessary to use bandwidth as an additional factor of QoS. Nevertheless, users associate many times the term "bandwidth" with the performance of the application (the throughput) and, hence, bandwidth is a QoS parameter that can also be used.

2.2.1.2   QoS Requirements for Voice, Video and Data applications

Different applications have different requirements of QoS. Table 2-3 presents end-to-end requirements of voice, interactive video, non-interactive video, and interactive and non-interactive data services. As there is not a definitive answer to the question of which values of QoS metrics are the most convenient, the table is a comparison of the value of QoS parameters proposed in several studies. The following sources were employed for the elaboration of the table: a study about QoS from the University of St. Gallen in Switzerland (Brenner, Dous, Zarnekow, & Kruse, 2007), a book from authors affiliated to Cisco Systems about end-to-end QoS network design (Szigeti & Hattingh, 2004), and an ITU-T recommendation (ITU-T, 2002).

The first group of metrics corresponds to an interactive voice service such as VoIP. The delay ranges from 100 ms to 200 ms, even though the ITU-T has proposed 400 ms.

The values of delay variation are similar, they are between 30 ms and 50 ms, and the packet loss ratio is 1%, even though the ITU-T in its Y.1541 recommendation has defined a more strict packet loss rate (0.1%).

The interactive video service has similar values of delay, delay variation, and packet loss ratio. The non-interactive video service has completely different values in comparison with the values of the services described previously. The delay ranges from 400 ms to 5 seconds; for the delay variation, in two cases no significant requirements were specified. The packet loss ratio is around 0,1% in two cases, where in the other case it is 5%.

Regarding the last service, non-interactive data, there were just few values specified. One of the reasons is because this type of traffic does not have strict QoS requirements. Another reasons might be because this traffic is diverse. For example, a company that generates traffic from applications that need to transmit large amounts of data might have different QoS requirements than a company that basically generates traffic of web browsing or e-mail with small attachments. In this sense, traffic from data applications generated from corporate users might require specific parameters and, hence, the managers of these networks might be motivated to set up specific QoS parameters that meet the requirements of a specific group of applications.

Table 2-3:   QoS class definitions

Class	Source	Delay	Delay variation - jitter	Packet Loss Ratio	Bandwidth
Interactive voice	Study Univ. St. Gallen	100-200 ms	< 30 ms	1%	16-500 Kbps
	Szigeti & Hattingh	150 – 200 ms	30 ms	1%, assuming PLC Packet Loss Concealment is enabled.	21-320 Kbps depending on sampling rate, codec, and link layer overhead
	ITU-T Y.1541 (Classes 0 and 1)	100 – 400 ms	50 ms	0,1 %	not defined
Interactive video	Study Univ. St. Gallen	100 – 200 ms	< 30 ms	1%	16-500 Kbps
	Szigeti & Hatting	150 ms	30 ms	1%	No precise value was given
	ITU-T Y.1541 (Classes 0 and 1)	100 ms 400 ms	50 ms	0,1%	not defined
Non-interactive video	Study Univ. St. Gallen	400 – 1000 ms	< 100 ms	< 0,1%	384 Kbps – 14 Mbps
	Szigeti & Hattingh	< 4 – 5 s	No significant requirement	< 5%	Bandwidth depends on the encoding format and rate of video stream
	ITU-T Y.1541 (class 4)	1 s	No significant delay variation objective	0,1 %	not defined
Non-interactive data	Study Univ. St. Gallen	< 2000 ms	not available	not available	Up to line rate
	Szigeti & Hattingh	unspecified	Unspecified	Unspecified	unspecified
	ITU-T Y.1541 (Class 5)	no specific network performance objective	no specific network performance objective	no specific network performance objective	unspecified

Source: WIK

2.2.2 Main QoS solutions

This section reviews the main QoS solutions that have been implemented in the networks. As it is often described in the literature on QoS, QoS provisioning entails a network resource allocation task. The following aspects should be taken into account when choosing a resource allocation scheme:

- Provisioning of enough network resources: If the resources provided by the network are sufficient, then it is not necessary to deploy resource allocation schemes. In other words, when the over-provisioning QoS methodology is used,

users should have enough resources. A key important aspect in network design is the provisioning of network resources for network failure events.

- Resource reservation and/or admission control: Resource arbitration schemes are used in case there is competition for scarce resources. The admission control and resource reservation are schemes that can be used together.

- Traffic arbitration: A network device with the function of allocating resources to packets should classify first the different traffic streams, analyze the type of resource each traffic group deserves, and execute then the corresponding resource management policy.

- Failures in the network: In case of network interruptions, which are motivated by node or link failures, alternative routes should be used and packets with high priority, such as packets originated by calls to emergency services, should be given the highest priority.

The QoS solutions are classified into the following groups: PSTN QoS solutions, Layer-2 solutions, IP QoS solutions, transport-layer and application-layer solutions, and cross-layer solutions.

2.2.2.1   PSTN QoS Solution

The PSTN QoS solution has the following characteristics: admission control, resource reservation, and resource allocation in an exclusive way. At the moment of trying to place a call, the admission control determines whether there are enough resources in the network. If this is the case, an end-to-end circuit will be set up, which will be used exclusively by one voice communication.

2.2.2.2   Layer-2 QoS Solution

Asynchronous Transfer Mode (ATM), Frame Relay and Ethernet networks implement Layer-2 QoS solutions. ATM is a connection-oriented technology that needs to set up Virtual Circuits (VCs) before the communication takes place. ATM supports resource reservation and admission controls. The ATM Forum defined five service categories. Nowadays ATM is used basically as transport network; IP traffic is carried on top of it. One of the advantages and disadvantages of ATM is its QoS solution, which is sophisticated but difficult and expensive to implement.

Frame Relay uses virtual circuits and is a connection-oriented technology. Frame Relay usually works over leased lines and over technologies such as Synchronous Digital

Hierarchy (SDH) and in some cases also over ATM. Therefore, the traffic transported over Frame Relay does not depend exclusively on Frame Relay QoS solutions[2].

Ethernet is the dominant Layer-2 technology nowadays and has been substituting ATM and Frame Relay networks during the last years. The Ethernet QoS solution is based on the IEEE 802.1p protocol, which defines different priority levels in the Ethernet frame header. The standard IEEE 802.1p was defined as part of the standard IEEE 802.1q, which defines Virtual Local Area Networks (VLANs) architectures and that specifies a procedure for tagging Ethernet frames with information about VLAN membership (IEEE, 2009).The Ethernet QoS solution uses prioritization for resource arbitration, and it has neither resource reservation nor admission control.

2.2.2.3 IP QoS Solution

The most important techniques for the implementation of QoS in IP networks are Integrated Services (IntServ), Differentiated Services (DiffServ) and Over-Provisioning[3].

- Integrated Services: it consists in reserving capacity along the end-to-end path between the sender and the receiver before a transmission takes place. Resource Reservation Protocol (RSVP) is one of the most important signalling protocols that belong to this category[4]. The main disadvantage of the IntServ solution is the amount of state information needed to maintain the connections, which generates a serious problem of scalability.

- Differentiated Services: the network devices (routers, switches, etc.) prioritize packets according to the traffic class the packets belong to, and treat it according to the local traffic situation. The priority information is included in the packet header. The packets of a flow are treated with a different priority in comparison with the priority given to the rest of packets in a node, but not in a manner that guarantees end-to-end quality. It simply is a node per node decision process. DiffServ does not have a scalability problem and it has been deployed by many IP network operators.

- Over-Provisioning: The over-provisioning model consists in deploying enough capacity in order to avoid congestion in any case.

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2 The Frame Relay technology is outdated and will no longer be used in modern efficient networks, thus we will not consider it further on.
3 A more detailed description of QoS techniques appears in the study conducted by WIK for the German Regulator, Bundesnetzagentur (Jay & Plückebaum, 2008).
4 RSVP-Traffic Engineering (TE) is an extension of the RSVP protocol and it is used to establish Label-Switched Paths in Multi-Protocol Label Switching.

2.2.2.4 Transport-Layer and Application-Layer Solutions

Mechanisms that help to improve Quality of Experience can also be deployed at the transport and application layers. If the solution is only implemented in the end user's device, then it will not be considered by an LRIC cost model. There are a few transport-layer and application-layer solutions that rely on information provided by lower-layer protocols. There are many solutions at the transport layer that help improve the transmission of packets. For example, the IETF RFC 5681 gives recommendations about the management of the congestion control of the Transmission Control Protocol (TCP) (IETF, 2009).

2.2.2.5 Cross-layer Design solutions

So far, this section has described the different QoS techniques that are applied independently at each layer. This procedure has its roots in the OSI approach, which recommends that in an end-to-end communication the layer of an end node must exchange information with the same layer of the other end node. In practice, this has been done so. However, one of the hot topics that have been studied by networking researchers over the last years is the suitability of cross-layer solutions for QoS improvement. These solutions advocate the delivery of information that belongs to a specific layer to a higher or lower layer in order to obtain more information about the status of the transmission in a specific link. For example, information from layer 2 in a cellular wireless link could be used by TCP protocol from layer 4 to adjust the TCP transmission windows according to the losses or delays observed in layer 2; or information from the physical layer (layer 1) could be used by the routing protocols of layer 3 to update the routing table according to the probability of failure of the physical links. See (Setton, Taesang, Zhu, Goldsmith, & Girod, 2005) for an example of a cross-layer design for video streaming traffic in wireless networks. The functions and processes dealing with QoS in the three lowest layers, thus being performed in the network nodes, should been considered when allocating QoS cost.

2.2.2.6 Summary of QoS solutions

Table 2-4 shows the main QoS solutions described in this section.

Table 2-4:   Summary of QoS solutions

QoS Solutions	Characteristics
Transport-Layer and Application-Layer Solutions	Any solution that is implemented at the transport and application layer. Example: TCP solutions that reduce the number of packets transmitted when congestion is detected.
IP- QoS Solutions	Integrated Services, Differentiated Services, Over-Provisioning
Layer-2 QoS Solutions	Implemented by ATM, Frame Relay and Ethernet. Each network has its own solutions.
PSTN QoS Solutions	Admission control, resource reservation, resource allocation in an exclusive way.
Cross-layer solutions	A layer uses information derived from a different layer in order to obtain information about the status of a link.

Source: WIK, based on information provided in (Xiao, 2008), p. 37-51

2.3 Soft-assurance and Hard-assurance models for QoS provisioning

The Service Level Agreement (SLA) between the end user and the network service provider specifies the type of QoS that will be contracted. Generally, there are two QoS business models that are being used by network service providers: the soft-assurance model and the hard-assurance model (Xiao, 2008). Both models are differentiated by the QoS that can be provided during normal and abnormal network conditions, and by the level of penalty that must be paid in case the QoS specified in the SLA is not met.

In the soft-assurance model, the users pay a fee for the regular connectivity and they pay an additional fee for QoS provisioning. Even though the SLA contains information about the values of some QoS parameters such as bandwidth and delay, there is not a hard guarantee that these values will be respected. It is considered that if the service quality does not meet the conditions specified in the SLA for a period of time, the user will not have to pay for the service provided in that period of time. The soft-assurance model does not provide service quality assurance during abnormal network conditions. In addition, it is characterized by mild penalties that should be paid in case SLA conditions are not fulfilled.

In the hard-assurance model, the network service provider tries to provide service quality during all the time. The network should be designed so that the effects of abnormal network conditions are minimized. Therefore, the network availability must be high. However, catastrophic events or large-scale Denial of Service (DoS) attacks that might arise could lead to an interruption of the service provided. In these cases, the penalties specified in the SLA might be high.

The hard-assurance model implies more technical challenges than the soft-assurance model because the network reliability conditions are much more strict. The provisioning of a service with the hard-assurance QoS model will have an impact on the cost of the service. The analysis performed in Chapter 3 considers QoS techniques that follow the soft-assurance model. A brief description of the QoS techniques that enable the provisioning of services with the hard-assurance QoS model are given in Section 3.1.5.

2.4   Interim conclusions

The main conclusions of this chapter are the following:

- For the definition of a network with QoS, it is possible to use network design, network engineering and traffic engineering tools. Network design is used for the definition of a new network topology, i.e. node placement, link placement and capacity assignment. Network engineering consists in improving an existing network topology by means of capacity expansion and/or structural engineering techniques. Traffic engineering helps to re-route traffic from congested network links to segments of the network that are not so congested.

- There are QoS techniques that can be used at different levels of the OSI layer model. Some techniques are typical of the PSTN QoS model, which relies on an admission control that analyzes if there are resources available in the network for the service required by the user. There are also Layer-2 QoS solutions used by ATM, Frame Relay and Ethernet. The most well-known IP QoS solutions are integrated services, differentiated services and over-provisioning. Transport-Layer and Application-Layer solutions can also be implemented to enhance user's application performance. Cross-layer solutions permit that one layer uses information generated by another network layer. Network operators can use several QoS solutions concurrently.

- For QoS provisioning operators can implement a soft-assurance model and/or a hard-assurance model. Both models are differentiated by the service that can be provided during normal and abnormal network conditions. The service quality and the network reliability are higher with the hard-assurance mode, which will be reflected on the cost of the service.

3 Efficient networks with QoS

The objective of this chapter is to describe the main aspects that should be taken into account when designing an efficient network with QoS capabilities. There is not a single answer to the question of which QoS technique to implement due to the following reasons:

- there are different access networks (FTTx, cable, and wireless),

- there are several QoS mechanisms available,

- operators have different targets/levels of QoS (soft-assurance and hard-assurance models).

Moreover, many operators are upgrading their networks or are in a process of migration to NGN networks, which brings uncertainty about the network architecture that will be finally adopted. However, based on the possibilities that are being pondered by operators, it is possible to outline the type of QoS techniques that could be used in the definition on an efficient network architecture with QoS. This chapter describes the design of a network with QoS techniques that were used to provide soft-assurance QoS capabilities. The first section of the chapter contains a compilation of the state-of-the-art/most used QoS mechanisms. This section explains in detail the techniques used in the soft-assurance QoS model, and it provides a brief explanation of the main techniques used in the hard-assurance QoS model. The second part of the chapter describes some preliminary points that should be evaluated before designing an efficient network. Finally, the network architecture of an efficient network with QoS is explained and depicted in section 3.3.

3.1   State-of-the-art/most used QoS mechanisms

3.1.1 Components of an NGN network

An NGN network consists of the following sections: core network, aggregation network, and the subscribers' access network (see Figure 3-1).

Figure 3-1:   Components of an NGN network

IP Core Network   Aggregation/Concentration   Subscriber's Access
                            Network   Network
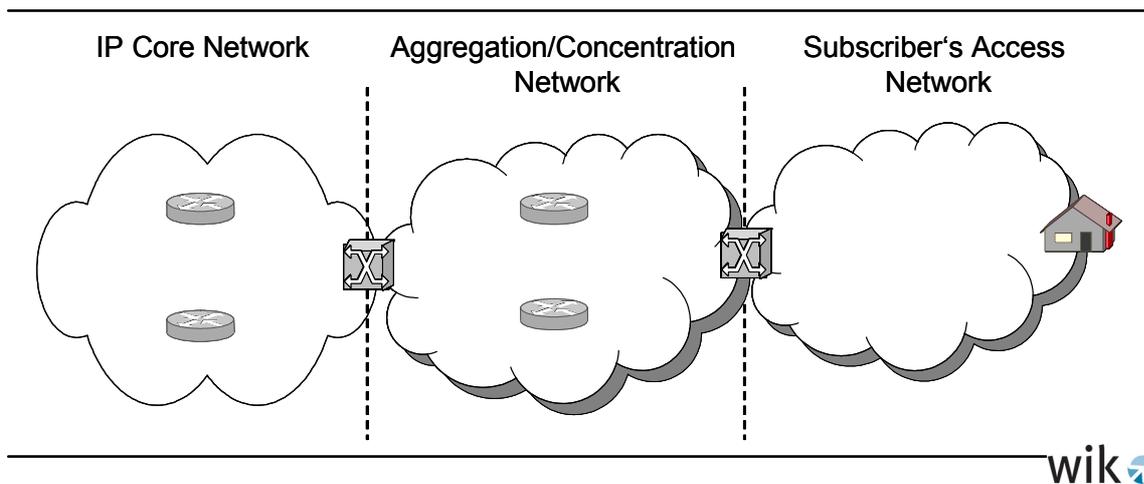
Source: WIK

For many years it was clear where the border between the different networks was located. However, with the deployment of IP-based Next Generation Networks the location of the nodes that separate the access network from the aggregation network and the aggregation network from the core network can change.

For cost modelling purposes of wholesale termination rates in fixed networks, the European Commission has defined the concept that permits determining the location of the border between the access and aggregation networks (Official Journal of the European Union, 2009): "The default demarcation point between traffic- and non-traffic-related costs is typically where the first point of traffic concentration occurs. In a PSTN network this is normally deemed to be the upstream side of the line card in the (remote) concentrator. The broadband NGN equivalent is the line card in the DSLAM/MSAN[5]".

The access network is the customer dedicated part of the network, whereas the commonly used part, which is where several customers/users compete for the same bandwidth, is already part of the aggregation layer. This means that the subscribers' equipment, the access line (which is used exclusively by the subscriber) and the port of

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[5] Multi-Service Access Node

the network node, where this access line ends, belong to the access network. The rest of the network node belongs to the concentration network

With the roll-out of FTTx technologies, the border between the concentration and the access layer is moving closer to the customers' premises according to the FTTx technology implemented. The border location may be in the Main Distribution Frame/Metropolitan Point of Presence (MDF/MPoP) for FTTH/P2P, in the street cabinet for FTTC/VDSL, or in the basement of the building for FTTB.

3.1.2   Implementation of QoS Technical Solutions

This section discusses the typical QoS solutions that are being deployed in the core, aggregation and access networks nowadays. According to the target of QoS that should be provided and the manufacturer's equipment capability, a specific QoS mechanism or a combination of different QoS mechanisms will be deployed. As explained below, a few QoS techniques are used in several sections of the network (e.g. DiffServ can be used in the core network and in the aggregation and access networks as well).

3.1.2.1   Core network

The following QoS techniques are used in the core network:

a) Over-provisioning: If it is possible, operators try to implement over-provisioning in the core network so that there will be enough capacity[6].

b) Multi-Protocol Label Switching (MPLS): MPLS is a traffic engineering technique that consists in inserting an MPLS header, which is called an MPLS label, into an IP packet. This label is inserted at the ingress edge router of the MPLS domain, and it determines the path that the IP packet will take within the MPLS domain. This path is predefined in the network like a circuit. Each router in the MPLS domain will look at the label and not at the IP destination address to determine how to forward the IP packet (IETF, 2001). With MPLS the packets are forced to follow a pre-determined path.

Packets can be forwarded by means of MPLS as long as they are within the MPLS domain. If the MPLS domain starts in the access network, then the Label Switch Router (LSR) should be located in the access network. MPLS can be used in the access network, in the aggregation network and the core network.

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6 One example that shows the possibility of using over-provisioning in the core network is the following: When a network operator identifies bottlenecks or insufficient capacity in one of the fibre links, then it would be only necessary to install a transmission card at both ends of the line to upgrade the capacity with a second link.

Strictly speaking, MPLS is not a QoS technique in itself. With MPLS, the path is defined in advance and the labelled packets are directly switched through the routers, not needing a routing table look up or a routing decision, thus it is possible to reduce routing delays. Several operators use IP/MPLS networks because there is a common perception that MPLS improves end-to-end QoS capabilities. DiffServ and MPLS are techniques that work well together. The MPLS technique is widely used in the core network.

c) Prioritization techniques:

Prioritization mechanism: One of the technical QoS solutions that are being implemented by operators nowadays is explained next. The network includes three types of network devices: an ingress network device, an intermediate network device and an egress network device. The example of Figure 3-2 shows how these three network devices are distributed inside the network. The ingress network device classifies the packets by using one of the DiffServ classes, then the packets are forwarded through the network, and this classification is used later at the egress network device to dispatch the packets to the end customer. The functions of the input and output interfaces in all network devices are not the same. Figure 3-3 shows the interfaces of the ingress network device.

Figure 3-2:   Traffic management in a network
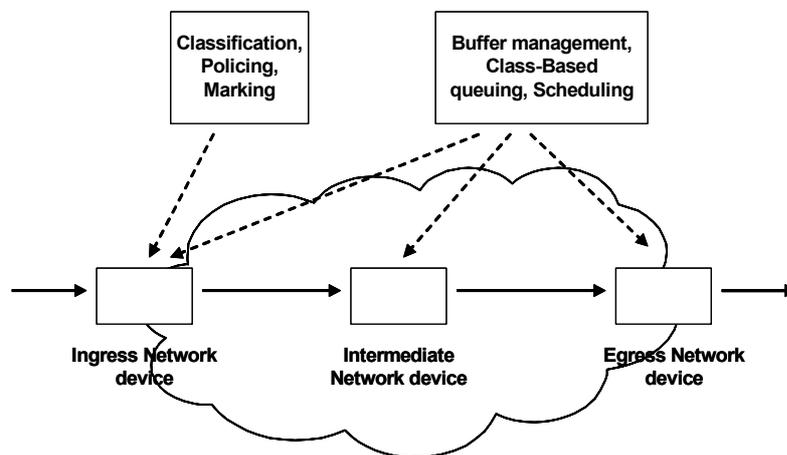
Source: (Xiao, 2008), p. 58

Figure 3-3:   Input and output interfaces of the ingress network device
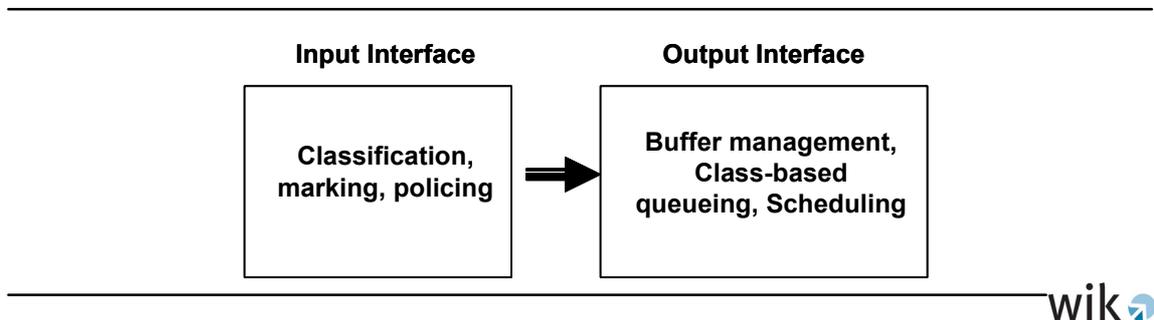
Source: (Xiao, 2008), p. 58

The functions of the input and output interfaces of the ingress network device are located at:

- the input interface: to classify packets and to mark the class of every packet. Traffic policing techniques are needed in order to drop packets that do not meet SLA specifications. Traffic shaping might be also needed.

- the output interface: buffer management techniques such as Random Early Detection (RED) or Weighted Random Early Detection (WRED) can be used to determine if a packet should be dropped or not. If the packet is not discarded, then it is put into the appropriate queue (class-based queuing). A scheduling algorithm is used to transmit packets from the different queues (e.g. Weighted Fair Queuing, WFQ).

Input and output interfaces of intermediate and egress network devices have the following functions:

- at the input interface: generally, there is neither classification, marking nor policing.

- at the output interface: a class-based queuing/scheduling algorithm can be used to dispatch the packets.

Classification of packets: DiffServ defines up to eight traffic classes. The following two approaches are used commercially for traffic classification:

1.- Classification of traffic according to the user application's needs: In this case the traffic could be classified as voice, interactive video, non-interactive video, interactive data, and non-interactive data. Another possibility would be to classify traffic as real-time, non-real-time business, and best effort traffic.

2.- Classification of traffic according to the price that the user pays. The Olympic model is quite common and it consists in classifying the traffic by using the Gold, Silver, and Bronze categories.

Differentiated Services: The most well-known and used prioritization technique is DiffServ. Many operators tend to implement a prioritization technique such as DiffServ in the access network.

Differentiated Services uses a few bits of the IP header. According to the DiffServ terminology, these bits are called Differentiated Services Code Point (DSCP). They are located in the type of service (TOS) field of IPv4 and in the IPv6 traffic class field. Six bits of the TOS field are used for DSCP. DSCP indicates the packets' Per-Hop Behaviour (PHB), which is the DiffServ treatment applied by a router to all the packets that belong to the same PHB group. Each Router in a transmission path, which is also called a Hop, will treat the packet with the same priority (behaviour).

Routers along the end-to-end path should be configured so that the DSCP value of the IP header can be recognized. As is illustrated in Figure 3-4, routers at the edge of the DiffServ domain classify microflows and mark packets. Routers in the core of the DiffServ domain identify the PHB class of the packets and forward it with the corresponding priority.

Figure 3-4:   DiffServ processing
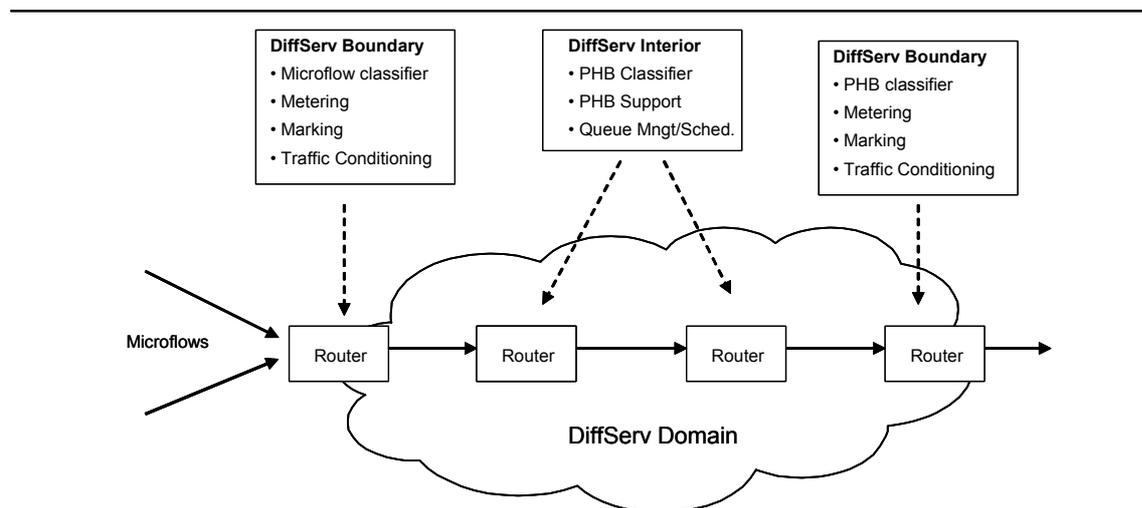
Source: (Ash, 2007), p. 424

Many networks today consist of routers with DiffServ features. Therefore, the usage of DiffServ would consist in configuring the classes in all the nodes along the end-to-end path.

The DiffServ domain can also start at the end-user's premises. Network equipment that is located at the premises of corporate users can be in charge of marking the packets with the DiffServ classes. For residential users this is not quite so common.

The effectiveness of DiffServ is more perceived in sections of the network where there are bottlenecks, or in cases of network failures and rerouting. It can be deployed in the access network, the aggregation network and the core network. However, if the core network uses an over-provisioning mechanism and there is enough bandwidth available, then the effect of DiffServ will not be so much perceived.

Moreover, the unit cost of a network element that uses DiffServ might be lower than the unit cost of a network element that uses over-engineering or traffic routing over separated virtual channels QoS mechanisms. Figure 3-5 depicts the results of the simulations performed by (Rodriguez de Lope, Hackbarth, Garcia, Plückebaum, & Ilic, 2008).

In the study of Rodriguez de Lope et al., a Total Element based Long Run Incremental Cost (TELRIC) cost model was used to assess the cost of three traffic engineering methods: priority queuing (PQ), over-engineering (Over-eng) and traffic segregation implemented by means of separated virtual tunnels (Segg). The network architecture is based on an NGN platform and the results were obtained for a connection between a Digital Subscriber Line Access Multiplexer (DSLAM) and the first concentrator, which could be an ATM or Ethernet node. Four types of users were taken into account in the analysis: standard and premium business users, and standard and premium residential users. These users generate real-time, streaming, guaranteed data and best-effort traffic.

The results of Figure 3-5 show the Unit Cost for every type of technique in monetary units (m.u.). The values of the bandwidth capacity are 10, 34, 50 and 100 Mbps, and the demonstrated results were obtained for a standard residential user. As is shown, in the four cases the Unit Costs of the Priority Queuing technique are lower. When there is more capacity available in the link, as is the case of the link with 100 Mbps, the difference between the Unit Costs of the three mechanisms is more fuzzy.

Figure 3-5:   Comparison of Unit Costs of traffic engineering techniques
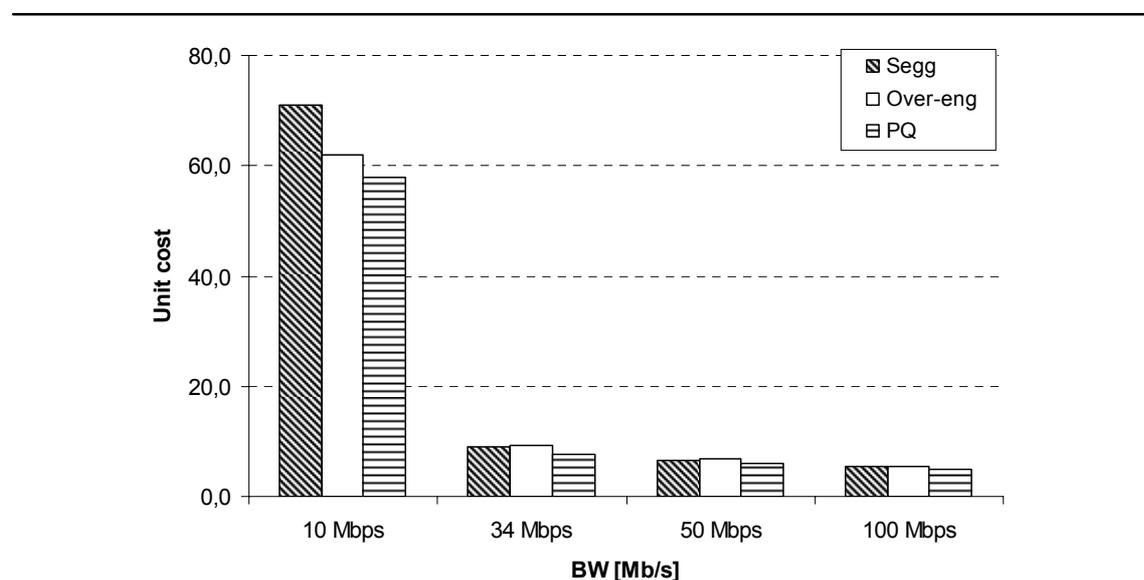
Source: (Rodriguez de Lope et al., 2008)

By using the results of only one study that compares different traffic engineering techniques it can not be concluded that a specific mechanism is always better or worse than another one. A study of this kind is made taken into consideration *inter alia* a particular network topology with a specific amount of traffic generated by the clients. Therefore, its results reflect the particular circumstances of the scenarios employed for the study. However, as there are almost no studies that compare in terms of cost the performance of different QoS techniques, the results presented in the above mentioned study should be considered as initial results. To derive final conclusions it would be necessary to make further analysis, simulations and experiments.

3.1.2.2   Concentration/Aggregation network

Usually, operators employ Ethernet networks in the aggregation layer. In this layer, there is a situation similar to the one that exists in the access networks: there are several possibilities to deploy QoS. The most relevant techniques that help to improve QoS are described next.

a)   Ethernet 802.1p

Ethernet IEEE 802.1p is a Layer-2 OSI QoS solution that consists in classifying and marking the Ethernet frames. Later these frames will be prioritized according to the values that appear in the three-bit field of the Ethernet frame header. The IEEE 802.1p

field is used in Local Area Networks (LANs) and in some Ethernet Metro Area Networks. IEEE 802.1p can also be used in the core network.

A related technique is IEEE 802.1q, which enables the creation of different logical LANs, refered to as Virtual LANs, in the same physical infrastructure. The edge switch inserts a tag in the header of the Ethernet frames that belong to the same VLAN, a process known as VLAN tagging. This tag is removed after the Ethernet frames are switched through the network and before reaching the final destination.

b) *MPLS:* MPLS can be used in the aggregation network.

c) *DiffServ:* DiffServ is also used in the aggregation network.

d) *Over-provisioning*: This technique can also be used in the aggregation network.

e) *Traffic Management methods:* The following methods are usually deployed at the border between the access network and the concentration network.

- *RACS:* One way to guarantee QoS in the access is by using a Resource and Admission Control Subsystem (RACS). This system can be used to prevent the entrance of traffic that can cause the rest of the traffic a performance degradation. If there are no resources to support the QoS demand of a user, then the access will be denied. RACS is similar to the Call Admission Control (CAC) function applied in circuit-switched telephone networks. It follows, hence, a Bell-head philosophy, not a Net-head philosophy[7]. However, in Net-head networks RACS is also employed (Xiao, 2008) p. 63.

- *Traffic Shaping:* Traffic shaping optimizes the performance, low latency and/or bandwidth of network traffic. Traffic shaping involves packet classification, enforcing policies, queue disciplines, congestion management, QoS, and fairness (Ash, 2007) p. 416. It contains a mechanism that controls the volume of traffic injected into the network and the rate at which the traffic is being delivered. Traffic shaping is applied at network edges to administer the traffic that is being sent into the network. Traffic shaping smoothes the peaks and troughs of data injected into the network by imposing additional delay on a set of packets so that a large number of packets can be sent with the same transmission rate. For example, if 20 packets arrive at the same time, a switching device with no traffic shaping would try to send all the 20 packets in 1 second and 0 packets in the next second; with the traffic shaping tool, the packets would be sent every 0.1 seconds.

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7 A Bell-head operator is a circuit-switched network operator that has a high control of the services provided in the network, whereas a Net-head service operator provides services in packet-switched environments.

- *Traffic Policing:* Traffic policing consists in monitoring network traffic to verify conformance to traffic contract. If necessary, packets in excess of the contracted traffic rate and burst size will be dropped (Ash, 2007) p. 417. Networks of OSI-layer 2, like ATM, use traffic policing. The transport protocol of OSI layer 4, Transmission Control Protocol, also uses a traffic policing mechanisms by reducing the transmission window when the TCP transmitter perceives network congestion.

3.1.2.3　Access network:

There are several QoS techniques that can be used in the access network. Moreover, operators tend to use several QoS solutions in the access network concurrently.

a) *Traffic Management methods:* The RACS, Traffic Shaping and Traffic Policing methods can also be used in the access network.

b) *Ethernet QoS solutions:* A few operators use Ethernet in the access network.

c) *Prioritization techniques*: The DiffServ technique can also be used.

d) *MPLS:* It can be employed if the devices in the access network support MPLS.

3.1.3　General Design procedures

The most used QoS techniques have been described in the previous section. Operators tend to use a combination of different QoS technologies. Table 3-1 shows an overview of the QoS techniques employed in different sections of the network.

Table 3-1:   QoS techniques used in different sections of the network

QoS Technique	Access Network	Aggregation Network	Core Network
DiffServ	Frequently used	Frequently used	Can be used, but if over-provisioning is used, then it is not necessary
MPLS	It can be used if the MPLS domain includes the access network	It can be used if the MPLS domain includes the aggregation network.	Frequently used
Ethernet IEEE 802.1p	A few operators use it	A few operators use it	Rarely used
Over-provisioning	It can be used if there is enough capacity[8]	It can be used	Frequently used
RACS (Resource and Admission Control Subsystem)	A few operators deploy it.	It can be used here.	It can not be used here

Source: WIK.

DiffServ, MPLS and IEEE 802.1p are based on packets prioritization, and they can be work together. To obtain an improved QoS, there should be a mapping of the different classes employed by DiffServ, MPLS and IEEE 802.1p.

A main general guideline would be to use DiffServ at the ingress network device's interface and then over-provisioning in the core network.

(Aravantinos & Papagiannopoulos, 2008) argue that in FTTH access networks DiffServ in combination with MPLS could be used as QoS strategies. However, this requires that the router in the end users' premises is programmed to support DiffServ and MPLS, which is not always the case.

To summarize, there are several possibilities for the provisioning of QoS. In fact, operators use several types of mechanisms that improve QoS at the same time: DiffServ, MPLS, over-provisioning, etc.

3.1.4 Failure scenarios

Network failure scenarios occur when nodes or links stop working for some time. The failures can be caused by flaws in the hardware or software of the equipment (routers, switches, transmission equipment, etc.), errors in the transmission link (physical

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8 For example, if an xDSL access networks with limited capacity is used it would be difficult to provide over-provisioning. Conversely, if an FTTH access is used, then over-provisioning would be feasible (this depends on the demand).

damages in the transmission link and even cuts of the physical link) or also catastrophic events such as earthquakes or fires.

At least the more important parts of a telecommunication network, the core network and parts of the concentration network, should be constructed so that in case of link or node failures the traffic is not interrupted, but rerouted on redundant paths. Network redundancy is the most well-known solution to failure cases. A lot of different redundancy measures exist. For example, SDH or Wavelength Division Multiplexing (WDM) systems reroute complete links within 20 – 50 ms. Rerouting on an IP layer is lasting longer, several hundreds of milliseconds. But with predefined MPLS links it may get faster. Rerouting on an Ethernet level, using the spanning tree algorithms, normally is even slower than IP. That depends on the network structure, the amount of hops and the variant of the algorithms used.

Manual interactions can also be used to repair the nodes and links. In many cases, it is possible to repair the connection remotely through the Operations & Maintenance (O&M) monitoring system. However, if this is not possible, the field service will have to go to the site of the failure, which could take several hours or days. Depending on the operator's philosophy, there are some parts of the concentration and access networks, close to the end customers, which may be connected point-to-point without any redundancy and which then will need manual interaction. Both techniques, O&M and field service, are used only after the network has tried to reroute the traffic on a redundant path.

The main techniques used to deal with network failures are the following ones:

- Automatic rerouting techniques: For example, with Fast Rerouting (FRR) it is possible to reroute the traffic through a new path after a network failure (Le Faucheur, Evans, & Lo, 2006). When a node or a link fails there is a topology change and the traffic affected by this change will be routed then to a new path.

- Over-provisioning: This technique consists in allocating enough capacity to assure that traffic with QoS requirements can be delivered properly during a failure scenario. In case of interruptions in the network, over-provisioning enables IP or Ethernet rerouting on the remaining links with sufficient capacity. The drawback of this technique is that it might be expensive.

- Prioritization: This mechanism enables the network to route important (high priority) traffic in a preferred manner and throttle down, or even delete, less important traffic. Hence the high priority traffic may remain unchanged, but the low priority traffic may be affected by additional jitter, delay or packet loss.

3.1.5 Techniques for the hard-assurance QoS model

In the hard-assurance QoS model, it is important to provide the end user a reliable transmission. A few of the techniques that are used for the provisioning of this type of model are mentioned below:

- A DiffServ technique that provides the user the highest priority
- Virtual Private Networks
- Over-provisioning
- Fast Rerouting
- Integrated Services techniques such as RSVP-TE

3.2 Design of an efficient network with QoS

3.2.1 Network Efficiency: technical efficient networks and cost efficient networks

Efficiency is a term that refers to a number of concepts. In economics, *efficiency means that society is getting the most it can from its scarce resources* (Mankiw, 1998) p. 5. An economic efficient system is a system where the production is generated at the lowest possible per-unit cost. In the telecommunications field, the term *production* of a network can correspond to the amount of traffic that is carried by the network (Heckmann, 2006). In this sense, the efficiency of the network can be defined by the following equation:

$$\text{Network Efficiency} = \frac{\text{Cost}}{\text{Transported Traffic}}$$

The transported traffic could correspond to one of the following points:

- Volume of traffic carried out by the network.
- Number of customers served.
- Number of flows or sessions.

And the costs mentioned in the formula could be monetary or non-monetary. Examples of monetary costs are the following ones:

- Costs of network equipment (routers, switches, etc.).
- Costs of deploying the links.
- Costs of maintaining the network (e.g. technical and administrative staff).

Examples of non-monetary cost are:

- Complexity in computation time.

- Quality of the transmission.

- Speed of the transmission.

- Network reliability and resilience.

- Network security.

- Technical effort to change resource allocation.

As is shown in the formula, an economic efficient network is more efficient than another network when the total cost to deploy the network or to implement the solution is lower. The total cost embraces the cost of the nodes, links and network operation and maintenance.

Efficient network are designed by taking into account monetary and non-monetary costs. As a general rule, it can be said that a technical efficient network will be designed taking into account non-monetary costs, whereas a cost efficient network will be designed taking into account monetary costs. Network operators deploy networks that meet the technical requirements of the service that will be provided and that enable the operator to have a satisfactory business case.

3.2.2 Efficient networks with QoS.

The question that is addressed in this section is the network architecture that will be chosen as an efficient network. Given the boundary conditions of the QoS metrics values (delay, delay jitter and packet loss rate), how should an efficient network be defined? Should it be a cost efficient network or a technical efficient network? Which network will be the most efficient network in a time period of 5 or 10 years? The following two arguments will help answer these questions:

- Cost-efficient networks are based on technical-efficient networks: Operators have to deploy networks that meet the QoS requirements of the services that will be provided. Otherwise, the operators can not offer these services.

- There is a trade-off between the price and the quality of the network.

Operators take into account both arguments when choosing an efficient network[9]. Hence, an LRIC cost model should also take into account both approaches. Moreover, as there are different types of operators, there are different ways of deploying a network

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9 This analysis was made by taking into account only the cost modelling perspective. Operators choose a network architecture by considering additional factors such as commercial aspects, business strategic issues, regulatory conditions, etc.

that provides QoS capabilities. To identify the technical efficiency of the network it is helpful to make a comparison in terms of bandwidth of the capacity supported by each technology. Table 3-2 shows a comparison of the capacity of different NGA technologies.

Table 3-2:   Comparison of NGA technologies

Technology	Maximum Capacity Downstream	Maximum Capacity Upstream	Average capacity per user Downstream (20 users)	Average capacity per user Upstream (20 users)
FTTC / VDSL2	50 Mbps	15 Mbps	50 Mbps	15 Mbps
FTTB / VDSL2	100 Mbps	20 Mbps	100 Mbps	20 Mbps
FTTH GPON (max 128 users[10])	2,5 Gbps	1,25 Gbps	125 Mbps	62,5 Mbps
FTTH P2P	100 Mbps 1 Gbps	100 Mbps 1 Gbps	100 Mbps 1 Gbps	100 Mbps 1 Gbps
DOCSIS 3.0	160 Mbps and more with bundling techniques	120 Mbps and more with bundling techniques	8 Mbps and more with bundling techniques	6 Mbps and more with bundling techniques

Source: Based on (OECD, 2008).

In Table 3-2 the average capacity per user is derived by dividing the value of the maximum capacity (downstream and upstream) by 20, which is the number of users that was taken as an example. The following explanation clarifies the procedure used to derive the capacity values of each access technology presented in the table.

FTTC/VDSL2 and FTTB/VDSL2: Both techniques use fibre and copper lines in the last end to reach the customer home. The difference between FTTC/VDSL2 and FTTB/VDSL2 lies in the fact that the transmission capacity of VDSL2 decreases the longer the copper cable used to transmit the signal is. Network Operators provide users with asymmetrical upstream and downstream transmission rates. With FTTC the copper cable starts in the street cabinet, with FTTB in the basement of the customer's premise, thus only covering the in-house cabling[11].

FTTH GPON: In the case of FTTH GPON, the capacity per user is variable, because the maximum capacity of the link will be shared by all the concurrent users. Therefore, it can be much lower or much higher than the average capacity shown in the table. The GPON technology has some regulatory disadvantages: it can not be effectively

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10   There are different versions of GPON such as Time Division Multiplexing (TDM)-GPON, Wavelength Division Multiplexing (WDM)-GPON, Dense Wavelength Division Multiplexing (DWDM)-GPON, etc. WDM techniques use multiple wavelengths on the same fibre, which increase the overall capacity.

11   Between FTTC and FTTB VDSL the number of customers sharing the same DSLAM normally differ strongly, since in the basement all customers of a home share the DSLAM, while in the street cabinet all customers of the area (may be several hundreds) share it. This difference is neglected in our comparison.

unbundled on the physical layer at the MPoP site and, therefore, infrastructure competition is not simple. Only wholesale bitstream access would then be possible through the GPON technology. Moreover, the capacity of the link is shared by all the users and this technology may not be the best future-proof solution (Elixmann, Ilic, Neumann, & Plückebaum, 2008).

FTTH - P2P: With this technique, all the bandwidth is assigned to one user.

DOCSIS 3.0: By using channel bonding techniques, Docsis 3.0 could support a few hundreds of Mbps downstream and upstream, which have to be shared between all users of a fibre node. Unbundling would be hard to achieve. Only a bitstream option might exist, but as far as we know, this option is nowhere implemented yet.

All the technologies that are described in the table are being deployed nowadays by a number of operators around the world and all of them can be considered efficient network architectures. However, for this report we have chosen two of these technologies as examples of efficient technologies. In terms of average capacity per user, the technique FTTH P2P is the most efficient. On the other hand, several operators in Europe have deployed or announced that they will deploy FTTC/VDSL2. For these operators the lower product features (e.g. bandwidth) are sufficient to satisfy their customers during the depreciation period of that equipment and, therefore, are valued more efficient to meet their business goals Therefore, both networks were taken as examples of technical efficient networks.

3.3   An efficient network architecture with QoS

This section describes the location of QoS mechanisms deployed in FTTC/VDSL2 and FTTH/P2P networks. It shows where the hardware and software elements should be installed. Both networks can have the same aggregation and core network. Figure 3-6 depicts the network architecture of the core and aggregation networks without indicating the QoS mechanisms, whereas Figure 3-7 shows the location of the QoS mechanisms. The network architecture uses QoS techniques of the soft-assurance QoS model.

Figure 3-6:   Generic Architecture of the Core Network, the Aggregation Network and the Access Network
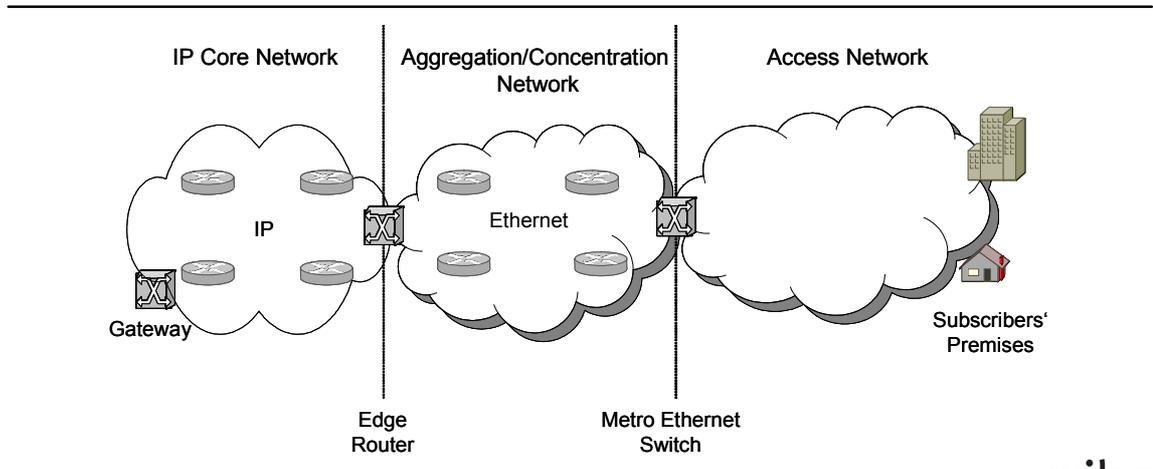
Source: WIK

Figure 3-7:   Generic Architecture of the Core and Aggregation networks with QoS mechanisms
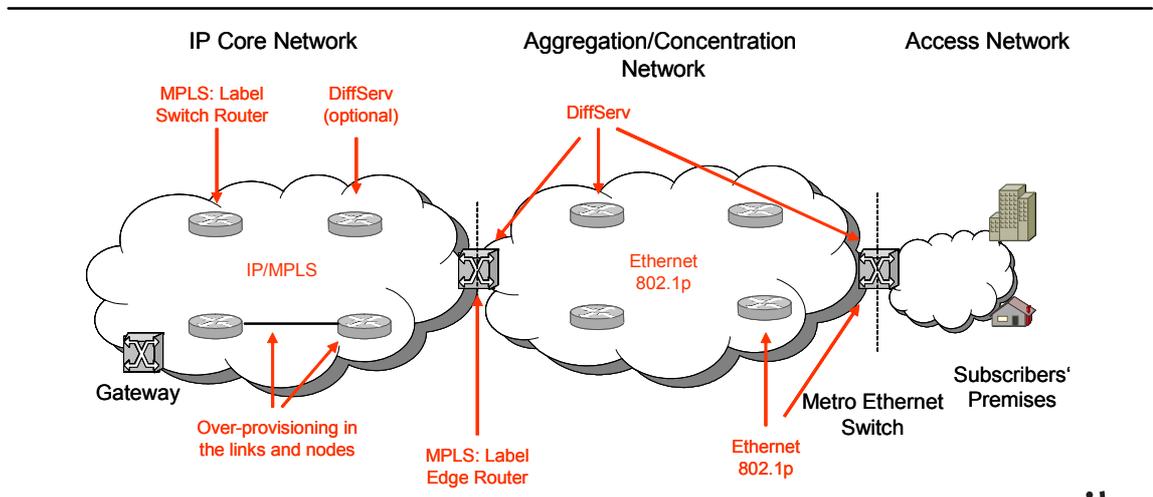
Source: WIK

In the IP Core network, the routers support MPLS and DiffServ. DiffServ is a piece of software that in many cases is installed in the routers. Over-provisioning can be implemented by installing links of capacity of 10 Gbps instead of links of 1 Gbps.

In the aggregation/concentration network the DiffServ capability of the routers can be used to provide QoS. The implementation of Ethernet 802.1p functionalities in the switches is useful for the improvement of the customers' Quality of Experience.

The location of the QoS mechanisms in the core and aggregation networks has been explained so far. The network architectures of the access networks FTTC/VDSL2 and FTTH/P2P are explained in the next section.

The effect of QoS techniques is perceived when there is a large amount of traffic in an environment with limited transmission capacity and the use of these techniques enables an improvement in the traffic delivery. However, it is not evident whether the beneficial consequences of the deployment of QoS mechanisms will be perceived if there is still transmission capacity available, as is the case of an access network based on fibre.

The next two sections describe examples of FTTC/VDSL2 and FTTH/P2P networks with QoS mechanisms. There are a number of possibilities for the provisioning of QoS in these networks; both examples are by no means the only solutions available in the market.

3.3.1 FTTC/VDSL2

Figures 3-8 and 3-9 identify the network elements that contain QoS capabilities in an FTTC/VDSL2 network. Figures 3-8 and 3-9 show implementations of DiffServ and Ethernet 802.1p prioritization mechanisms, respectively.

In Figure 3-8, the DiffServ functionality is installed in the router of the customer premises. In this case, IEEE 802.1p is not used because the prioritization scheme is already provided through the DiffServ functionality. The DiffServ functionality can be implemented physically in the router in Hardware or in Software. This depends on the manufacturers' preferences. In both cases, a software tool for programming the DiffServ classes is needed.

In Figure 3-9, the IEEE 802.1p prioritization mechanism is deployed in the Ethernet switched located in the concentration network.

Figure 3-8:   FTCC/VDSL2 Architecture with a DiffServ mechanism
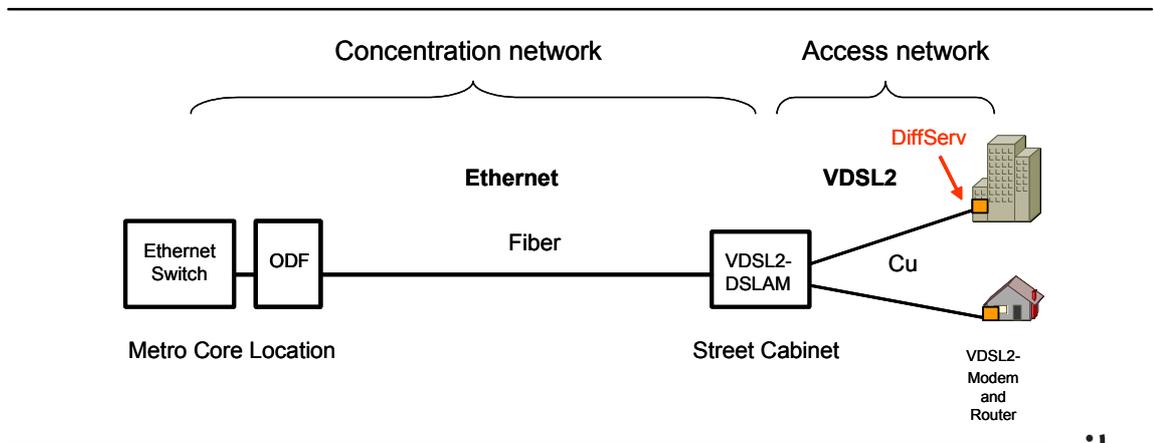
Source: WIK

Figure 3-9:   FTCC/VDSL2 Architecture with an Ethernet 802.1p mechanism

Source: WIK

3.3.2 FTTH/P2P

In Figure 3-10, the network elements with QoS functionalities of an FTTH/P2P architecture are shown. The Ethernet 802.1p prioritization scheme is located in the Ethernet switch that is in the concentration network.
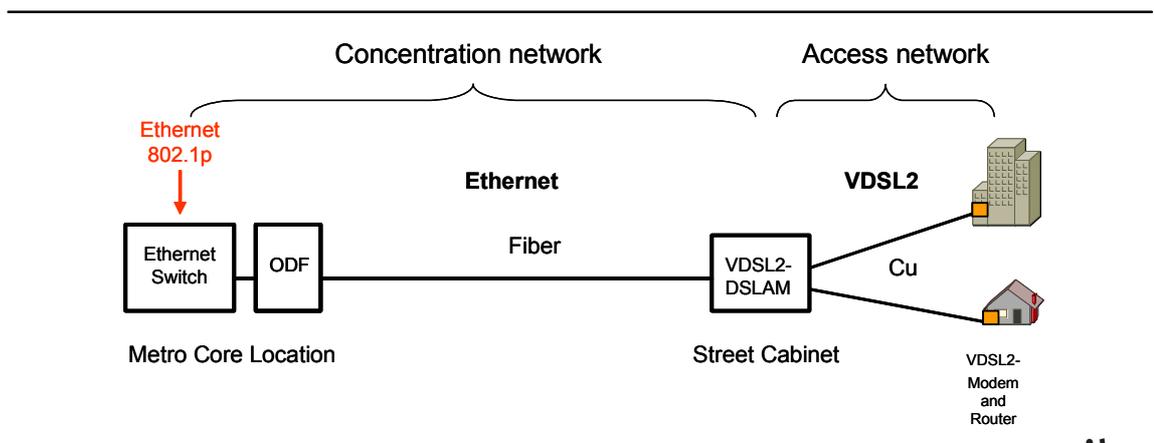
Figure 3-10:   FTTH/P2P Architecture with QoS
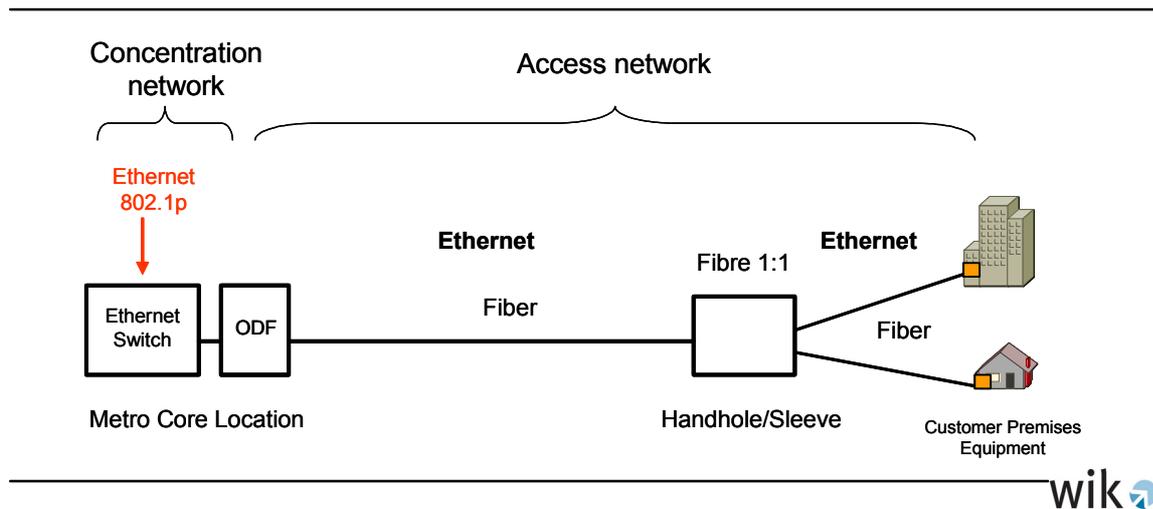
Source: WIK

3.4 Interim conclusions

This chapter has described two efficient networks that provide QoS services. The main conclusions of this chapter are explained below.

- There are several QoS techniques that can be used in the access, aggregation/concentration and core network. In the access network, operators are inclined to deploy the DiffServ, Ethernet IEEE 802.1p and RACS QoS mechanisms. In the aggregation/concentration network, DiffServ and Ethernet IEEE 802.1p are also deployed. In the core network, MPLS and over-provisioning are frequently used.

- The network efficiency can depend on monetary and non-monetary costs. Monetary costs are the cost of the network equipment, the cost of deploying the links and the cost of maintaining the network. Non-monetary costs are related to the degree of satisfying actual and future customers' expectation, which includes the complexity in computation time (hardware and software resources allocated to the processing of data), the quality of the transmission, the speed of the transmission, network reliability and resilience, network security and the

technical effort to change resource allocation. Operators deploy networks that meet QoS requirements of the services that will be provided and that also keep a price/quality balance.

- Two access networks were taken as examples of efficient networks: FTTC/VDSL2 and FTTH/P2P. It was identified where the QoS mechanisms in both networks are located. The IP core network and the aggregation core network might be the same for both networks. In the IP core network MPLS and DiffServ techniques may be deployed; also over-provisioning is used for the links and nodes. For the aggregation/concentration network, Ethernet 802.1p and DiffServ are employed. In the access network, DiffServ and Ethernet 802.1p can be used as well.

4   QoS in LRIC cost models

This chapter describes what should be taken into account to design an LRIC cost model for applications and services that are provided by using QoS techniques. Section 4.1 discusses if there is any conceptual difference between an LRIC cost model for services without QoS and an LRIC cost model for services with QoS. Section 4.2 expands on the differences found between the utilization of both cost models. Two examples of the utilization of a cost model for the calculation of costs of services provided with QoS are given in Section 4.3. Finally, Section 4.4 addresses the conclusions.

4.1   LRIC cost models for services with and without QoS

The first point that should be addressed is whether the LRIC cost model used for services provided without QoS is also valid for services provided with QoS. To identify the possible differences, the basic formulas used for the determination of the cost of a service will be explained first, and then it will be explained which changes should be taken into account at the moment of calculating the cost of a service with QoS.

For the determination of the cost of a service in an IP-based network the following formula is employed:

$$\text{Cost\_per\_Kbps}_{\text{Service\_i}} = \sum_{NetworkElements\_j} \text{Unit\_costs}_{\text{NetworkElement\_j}} * \text{UF}_{\text{NetworkElement\_j}}^{\text{Service\_i}}$$

where UF is the Usage Factor that identifies how much of the network element is being used by a specific service. The Unit Cost corresponds to the annual cost of a network element divided by the annual traffic using that network:

$$\text{Annual Unit Cost of a Network Element\_i} = \frac{Annual\_Cost\_of\_network\_element\_i}{Annual\_traffic\_on\_network\_element\_i}$$

For the calculation of costs of services provided with QoS the LRIC cost model methodology will be the same. However, a few parameters that appear in the equations might be different. Figure 4-1 shows the parameters that may change.

Figure 4-1:   Possible changes in a cost model of a service provided with QoS

Source: WIK

The following parameters, which are marked in the formulas of Figure 4-1, should be analyzed in detail:

1.- Cost drivers: For circuit-switched telephony services the cost driver is the number of minutes that a user spends on a phone conversation. For IP-based applications the main cost drivers are the transmission rate, which is measured in Kbps, and the volume of data transmitted, which is measured in Kbytes. It should be determined whether applications provided with QoS could have a different cost driver.

2.- Cost of network elements: As the network architecture is different, network elements of applications provided with QoS might not be the same as the network elements of a network without QoS capabilities.

3.- Traffic carried by IP networks: The nature of the traffic of applications provided with QoS is different to the traffic generated as best effort.

4.- Usage factor of a network element that provides a service with QoS: The usage of a network element that provides a service with QoS will probably lead to a different consumption of the bandwidth capacity of nodes and links, which will be reflected in a change of the value of the usage factor.

Each one of these factors is explained more in detail in the next Section.

4.2   Particularities of a cost model for services with QoS

4.2.1   Cost drivers

The discussion about which cost driver to use for applications with QoS requires a definition of a cost-driver. "A cost driver is a variable, such as the level of activity or volume, that causally affects costs […]. That is, there is a cause-and-effect relationship between a change in the level of activity or volume and a change in the level of total costs" (Horngren, Datar, & Foster, 2006), p. 32.

In the telecommunications arena, the definition of the cost-driver depends on the type of traffic that is transmitted. In circuit-switched networks, for example, the voice traffic transmitted is measured in minutes, whereas an Erlang is a statistical measure of the offered traffic load.

Conversely, IP networks carry IP packets that can transport any type of information: voice, video, data, etc. In best-effort IP networks, network designers make an estimate of the amount of traffic that will be carried out in the network. The unit used for the calculation of the traffic is the average capacity consumption of the network in the peak hour, which can be Kbps, Mbps or Gbps and that depends on the volume of traffic to be transmitted. Therefore, it makes sense to consider the capacity of the network as the main cost-driver. The capacity defines the maximum volume of traffic (or the maximum amount of packets) that can be transported at a time through the network.

Another cost-driver, which is usually not taken into account in IP-based networks, is the distance of the transmission. This cost driver is caused by the length of the transmission links. In circuit-switched PSTN networks, generally there are three types of costs of termination rates defined according to the network topology and the number of network elements used for the transmission of the information: local, single tandem and double tandem calls. IP-based networks follow a different philosophy and the distance between the subscriber and the remote server or user is not the metric used in this type of networks for the calculation of costs.

Now it will be analyzed what is the cost driver of networks designed to provide QoS capabilities. The cases for the following three QoS mechanisms will be described: over-provisioning, prioritization and capacity reservation.

Over-provisioning: To design a network with over-provisioning, network designers will have to take into account additional transmission capacity. If the capacity of a link is not large enough to meet customers' demand for traffic, then more links will be deployed. For fibres that are already deployed, additional wavelengths (colours) could be used,

which will enlarge the transmission capacity[12]. Therefore, the cost-driver of the additional increment will be measured in capacity. For network nodes, such as routers and switches, probably it could be necessary to deploy more routers and switches, or to deploy more Network Interface Cards. But again, what is relevant here is the capacity that might be supported by the Network Interface Cards. Capacity is then the cost-driver to take into account when using over-provisioning in the nodes and links.

Prioritization: Regarding the prioritization techniques, the capacity of the network remains the same and the traffic routed with the prioritization techniques will consume a certain transmission capacity of the network. Therefore, capacity is a cost-driver. However, when using prioritization what changes is the way the resources are allocated. Prioritisation techniques may use more computing power of the routers and switches' processors[13]. Therefore, processing power in the routers of switches is a complementary cost-driver to be considered. In the links the only cost driver is the transmission capacity.

Capacity reservation: With regard to capacity reservation, the transmission capacity is one of the cost drivers. The transmission capacity reserved is employed exclusively by the user during the transmission of information. Moreover, additional processing power is needed to provide capacity reservation in the routers. One of the classical drawbacks of the Integrated Services architectures has been the scalability problem, which is caused by the high consumption of hardware and software resources necessary for maintaining the different connections.

What can be concluded then is that the main cost driver of applications with and without QoS is the capacity that can be supported by network elements (the transmission bandwidth). The processing power is another cost driver that could be considered when using prioritization and capacity reservation QoS techniques. Table 4-1 describes the cost drivers used according the QoS technique employed.

Table 4-1:   Cost drivers for different QoS mechanisms

QoS Technique	Over-provisioning	Prioritization	Capacity Reservation
Links	Transmission capacity	Transmission capacity	Transmission capacity
Nodes	Transmission capacity	Transmission capacity Processing power	Transmission capacity Processing power

Source: WIK

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[12] For example, the capacity of the fibre could be split into 16 wavelengths (channels or colors), and each independent channel can transmit at a data rate of 2.5Gbps, 10 Gbps or 40 Gbps.

[13] A study conducted by WIK-Consult for the German telecommunications regulator describes the cost drivers of several network elements in broadband networks (WIK-Consult, 2005).

However, there is a widely used case that should be taken into account and this case refers to the VoIP service. VoIP is a service that requires good QoS capabilities to be provided properly. VoIP uses IP networks and, therefore, the resource that will be consumed will be the capacity of the IP network. However, when a VoIP network exchanges traffic with a circuit-switched network, the VoIP operator counts the number of minutes allocated to a voice conversation as the metric of traffic transmitted inside the VoIP network. At a first glance, this might seem a contradiction because the usual cost driver in IP-based networks is the capacity used, which is measured in Kbps, Mbps or Gbps, and not the number of minutes required by a VoIP conversation. The solution to this situation is provided by using a conversion factor that transforms the number of minutes spent on the conversation into the number of bits generated by the same conversation.

Even though it is not the scope of this study to analyze cost recovery issues for IP-based networks, it should me mentioned that two of the most relevant charging mechanisms proposed for wholesale services do not use the duration of a voice call as the charging metric. These charging mechanisms are Capacity Based Charging (CBC) and Volume Based Charging (VBC) (Vogelsang, 2006). In Capacity Based Charging the unit used for charging is the capacity of the link that is employed (e.g., Kpbs, Mbps, Gbps). In Volume Based Charging the unit used is the number of Kbytes, Mbytes or Gbytes that are transmitted.

4.2.2 Cost of network elements

For the identification of the network elements it is necessary to know which network architecture will be employed for the provisioning of services with QoS. Section 3.3 describes a few of the possible network architectures that might be used. The network elements are pieces of hardware and software necessary for QoS provisioning. Figures 3-7, 3-8, 3-9 and 3-10 show where it is necessary to consider hardware and software elements for QoS provisioning. In many cases the network architecture of an operator that provides QoS will be similar to a network architecture that does not support QoS. If this is the case, many network elements will be common. What should be identified therefore is if there is something specific that needs to be installed to provide QoS.

Some aspects to consider regarding QoS techniques are explained below:

- Cost of over-provisioning: With over-provisioning more capacity is needed and, therefore, more links and routers/switches are needed. This can have an important impact on the cost.

- Cost of DiffServ: Currently the cost of provisioning DiffServ might be quite low because several manufacturers include the DiffServ functionality as part of the software/hardware that is delivered with the router; this functionality permits

reading the TOS field in the IP header and forward the packet accordingly. A cost that should be taken into account is the cost of programming the routers with the DiffServ functionality. Running this software consumes additional processor power and thus causes costs even if there is no dedicated software price.

4.2.3 Traffic carried out by network element

This section discusses how the value of the traffic generated by services provided with QoS should be included in a cost model. An important input to a cost model is the annual traffic. The following formula defines the annual traffic which may be carried out by a network element:

$$\text{Annual Traffic} = \left(\frac{\text{Busy Hour Traffic}}{\text{Percentage Busy Hour Day}} \right) * \text{Number of Days}$$

This formula helps to convert the Busy Hour Traffic into annual traffic. It extrapolates the Busy Hour Traffic to the traffic the network element could carry assuming the same (peak) amount of traffic will be produced throughout the (relevant days of a) year. The Busy Hour Traffic defines the amount of traffic that is supported by a network element in the busy hour. The percentage of busy hour in a day represents the share of daily traffic carried out during the busy hour. Thus the quotient describes the maximum amount of traffic the network element could carry per day. The number of days is not 365 days, but rather the number of typical business days in one year. Figure 4-2 shows an example where the busy hour traffic load is 9% of the traffic load during all the day.

Figure 4-2:   Example of busy hour traffic generated in a day
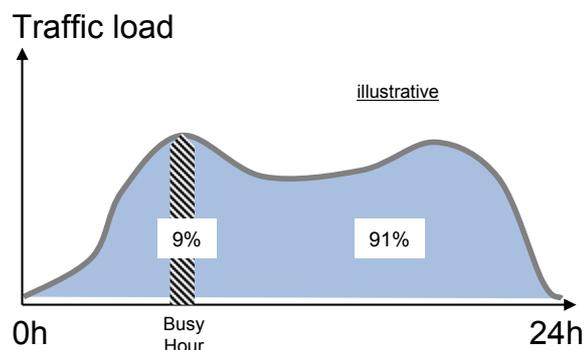
Source: "Mobile Termination Cost Model for Australia", p92 (WIK Consult, 2007)

Network operators obtain the values of traffic by installing network analyzers that measure the traffic. The implementation of QoS mechanisms in the network will generate different traffic patterns and traffic volumes. In an NGN network, the capacity of the links and nodes will be shared by several applications such as VoIP, Video, web browsing, etc.

To summarize, the formula does not change, but the values might change according to the traffic requirements of services provided with QoS.

4.2.4 Usage factor of a service with QoS

When there are shared resources, a cost model uses cost allocation methods. In this sense, the usage factor – which is also called the routing factor - identifies how much of a resource is being used by a specific service. This value, therefore, helps to determine the proportion of cost of a network element that should be allocated to the service.

To determine the cost allocation of a service with QoS in an LRIC model, it is necessary to obtain the usage factor of the service. These Usage Factor values will be later included in the Routing Matrix (see Figure 4-3).

Figure 4-3:　　　Routing matrix: Usage factors for network elements and services
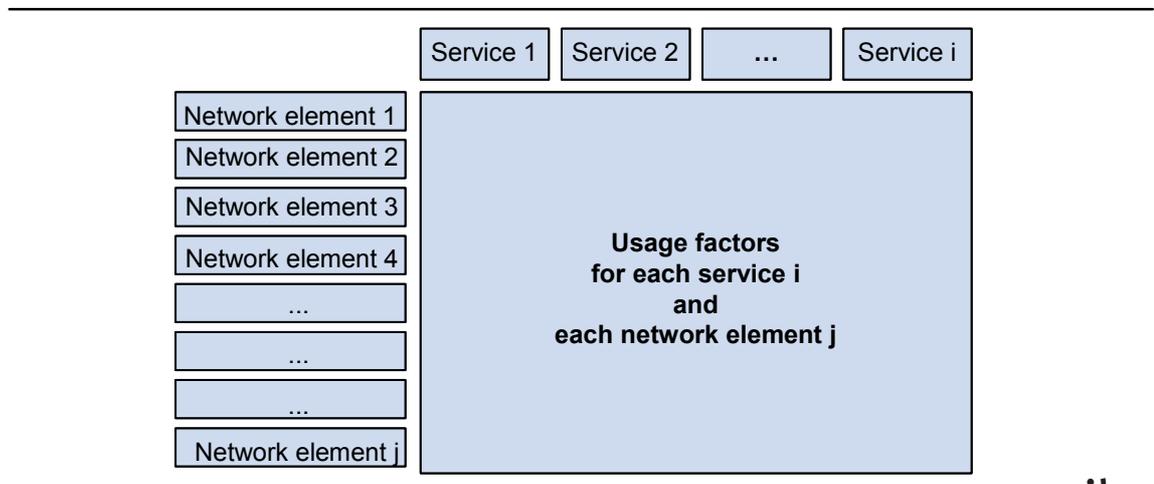
Source:　Based on "Mobile Termination Cost Model for Australia", p91 (WIK Consult, 2007)

The usage factor is derived by evaluating how many times a group of network elements are used by a specific service.

The question that arises at this point is whether the Usage Factor of a network element changes when QoS is provided. The answer is positive because the intensity of use of a network element will change according to the number of resources required by every class of service[14]. There could be different classes of services, such as Gold, Silver and best effort services (Bronze), and each class of service will use the network elements with different intensity. For example, if a Gold Service must provide a good quality of service for services that consume more bandwidth, then this type of service will use with more intensity the network elements (nodes and links) in comparison with other services. Moreover, the routing path taken by the traffic of an application provided with QoS could be different to the routing path taken by an application that is not provided with QoS. Therefore, the usage factor of the nodes and links will be different.

**14** Applications provided with QoS can have capacity and processing power as cost drivers.

4.3 Examples of cost models for the calculation of the cost of services provided with QoS

This section describes two examples that illustrate how QoS concepts are incorporated into a routing matrix of a cost model. In the first example an FTTC/VDSL2 access network is used, whereas an FTTH/P2P network is used for the second example.

4.3.1 Example of a routing matrix for an FTTC/VDSL2 network with QoS techniques

Figure 4-4 shows an NGN network based on an FTTC/VDSL2 access network that contains network elements with QoS capabilities. In this example, the access network does not have any type of QoS techniques, whereas Ethernet 802.1p is used in the aggregation/concentration network. Over-provisioning is used in the core network.

Figure 4-4: Example of an FTTC/VDSL2 network with QoS techniques
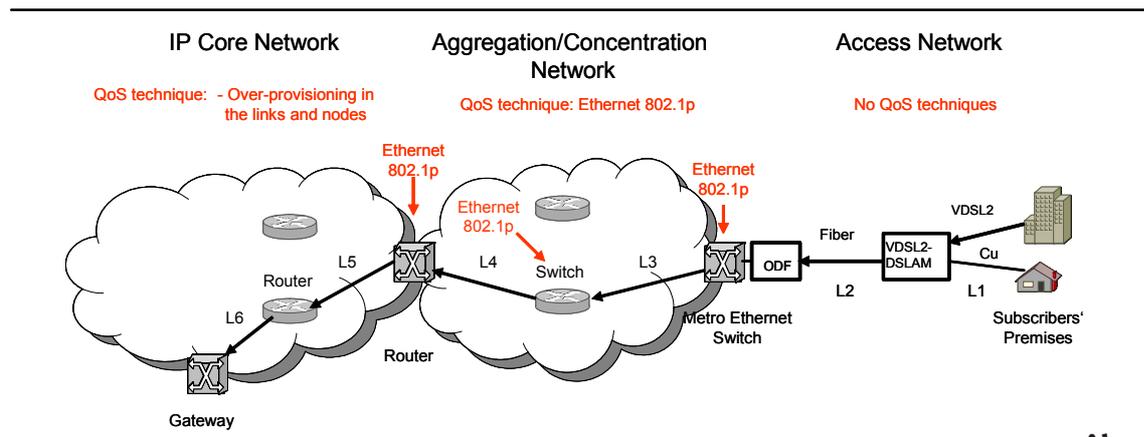
Source: WIK

The routing matrix of this network is shown in Table 4-2. This case corresponds to an on-off-net transmission. The first column describes the most relevant network elements of the example: the links L1, L2, L3, L4, L5, L6 and L7 and the nodes of the access, aggregation and core networks. The column titled "without QoS" contains the usage factors of network element that do not have QoS capabilities, whereas the other columns contain the usage factors of network elements with QoS capabilities. The cost drivers used are capacity and processing power. The cost driver of the ODF is the amount of customers served and in this example the usage factor of the ODF is not affected by the deployment of QoS techniques.

Table 4-2:   Routing matrix for an FTTC/VDSL2 network with QoS

QoS category	Prioritization (IEEE 802.1p) in the aggregation network				Over-provisioning in the core network		Total
	Capacity without QoS	Additional capacity	Processing power without QoS	Additional processing power	Capacity without QoS	Additional capacity	
L1 in the access network	-	-	-	-	-	-	-
L2 in the access network	-	-	-	-	-	-	-
L3 in the agg. Network	C3	**C3*%**	-	-	-	-	C3 + C3*%
L4 in the agg. Network	C4	**C4*%**	-	-	-	-	C4 +C4*%
L5 in the core network	-	-	-	-	C5	**C5*%**	C5 + C5*%
L6 in the core network	-	-	-	-	C6	**C6*%**	C6 +C6*%
VDSL2-DSLAM	-	-	-	-	-	-	-
ODF	-	-	-	-	-	-	-
Metro Ethernet Switch	C9	**C9*%**	PP9	**PP9*%**	-	-	C9+C9*% PP9 +PP9*%
Switch in the agg. network	C10	**C10*%**	PP10	**PP10*%**	-	-	C10 + C10*% PP10 + PP10%
Router	C11	**C11*%**	PP11	**PP11*%**	C11a	**C11a* %**	C11 + C11*% PP11 + PP11*% C11a + C11a*%
Router in the core network		-	-	-	C12	**C12* %**	C12 + C12*%
Gateway	-	-	-	-	C13	**C13'* %**	C13 + C13*%

Source: WIK

Table 4-2 shows that the usage factor of a network element with QoS capabilities is higher. The increments C3*, C4*, C5*, C6*, C9*, C10*, C11*, C11a*, C12*, and C13* are represented in percentages and depend on the additional capacity that is being used in every network element. PP9*, PP10* and PP11* represent the additional processing power that is required when using prioritization in the aggregation network.

4.3.2   Example of a routing matrix for an FTTH/P2P network with QoS techniques

Figure 4-5 shows an FTTH/P2P network with QoS mechanisms. DiffServ mechanisms were implemented in the access network and in the core network, whereas Ethernet 802.1p is used in the aggregation network.

Figure 4-5:   Example of an FTTH/P2P network with QoS techniques
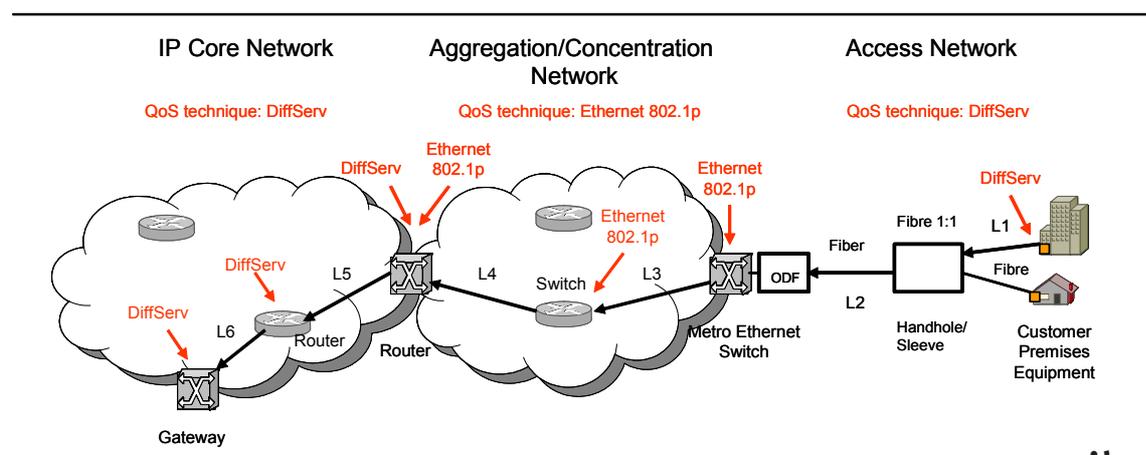
Source: WIK

Table 4-3 shows the usage factor values of the routing matrix. The increments caused by the additional consumption of capacity are C1*, C3*, C4*, C5*, C6*, C7*, C9*, C10*, C11*, C11a*, C12* and C13*. The increments caused by the additional consumption of processing power are PP7*, PP9*, PP10*, PP11*, PP11a*, PP12* and PP13*.

Table 4-3: Routing matrix for an FTTH/P2P network with QoS

QoS category	DiffServ (Prioritization) in the access network				IEEE 802.1p (Prioritization) in the aggregation network				DiffServ (Prioritization) in the core network				Total
	Capacity without QoS	Additional capacity	Processing power without QoS	Additional processing power	Capacity without QoS	Additional capacity	Processing power without QoS	Additional processing power	Capacity without QoS	Additional capacity	Processing power without QoS	Additional processing power	
L1 in the access network	C1	C1*%	-	-	-	-	-	-	-	-	-	-	C1 + C1*%
L2 in the access network	-	-	-	-	-	-	-	-	-	-	-	-	-
L3 in the agg. Network	-	-	-	-	C3	C3*%	-	-	-	-	-	-	C3 + C3*%
L4 in the agg. Network	-	-	-	-	C4	C4*%	-	-	-	-	-	-	C4 + C4*%
L5 in the core network	-	-	-	-	-	-	-	-	C5	C5%*	-	-	C5 + C5%
L6 in the core network	-	-	-	-	-	-	-	-	C6	C6*%	-	-	C6 + C6%
Router in the customer premises	C7	C7*%	PP7	PP7*%	-	-	-	-	-	-	-	-	C7 + C7* PP7 + PP7*%
ODF	-	-	-	-	-	-	-	-	-	-	-	-	-
Metro Ethernet Switch	-	-	-	-	C9	C9*%	PP9	PP9*%	-	-	-	-	C9 + C9*% PP9 + PP9*%
Switch in the agg. network	-	-	-	-	C10	C10*%	PP10	PP10*%	-	-	-	-	C10 + C10*% PP10 + PP10*%
Router	-	-	-	-	C11	C11*%	PP11	PP11*%	C11a	C11a*%	PP11a	PP11a*%	C11 + C11*% PP11 + PP11*% C11a + C11a*% PP11a + PP11a*%
Router in the core network	-	-	-	-	-	-	-	-	C12	C12*%	PP12	PP12*%	C12 + C12*% PP12 + PP12*%
Gateway	-	-	-	-	-	-	-	-	C13	C13*%	PP13	PP13*%	C13 + C12*% PP13 + PP13*%

Source: WIK

4.4   Interim conclusions

This chapter has described the main points that should be addressed when an LRIC cost model is used to derive the cost of a service provided with QoS. The conclusions of the chapter are as follows:

- Utilization of the LRIC cost model: It is not necessary to change the procedure used to apply the LRIC cost model. The formulas of the LRIC cost models will be the same, and the way they are used will be the same, but only a few parameters will change. With the implementation of services that are provided by means of QoS mechanisms, the following concepts and parameters change: the cost drivers, the network elements and their cost, the traffic generated by QoS applications, and the usage factor of a service with QoS.

- Cost drivers: In circuit-switched telephony networks the cost driver is the number of minutes generated by a communication. In IP services, and also in IP services provided with QoS, the main cost driver is the peak capacity of the network, which can be measured in Kbps, Mbps or Gbps. Another cost driver to take into account in nodes when using prioritization or capacity reservation is the processing power.

- Cost of network elements: A few hardware and software elements should be included so that the IP network is capable of providing services with QoS. The deployment of these network elements, which leads to investment and operational expenses, will have an impact on the cost.

- Traffic generated by QoS applications: The main QoS mechanisms (over-provisioning, prioritization and capacity reservation) use the capacity of the networks in different ways, which leads to a different network traffic pattern.

- Usage factor: The traffic generated by applications provided with QoS could take a specific routing path according to the routing policies determined by the network layer QoS solutions. If this is the case, the usage factor of the network elements that are in the routing matrix might change due to the fact that a few nodes and links might be used with different intensity.

- Two examples based on FTTC/VDSL2 and FTTH/P2P networks illustrate how a routing matrix should be constructed when designing a cost model for services with QoS capabilities. It is necessary to determine the appropriate increments in the values of the usage factors carefully when deploying a QoS technique.

5   Conclusions

A number of operators are deploying or have already deployed Quality of Service techniques that will help improve qualified service production and that can have an impact on the cost of the service. The goal of this study is to discuss how the utilization of Quality of Service techniques should be included in an LRIC cost model. The conclusions of the report are presented below.

- There are QoS techniques that can be used at different levels of the OSI layer model. Some techniques are typical for the PSTN QoS model, which relies on an admission control that analyzes if there are resources available in the network for the service required by the user. There are also Layer-2 QoS solutions used by Ethernet, ATM and Frame Relay. The most well-known IP QoS solutions are integrated services, differentiated services and over-provisioning. Transport-Layer and Application-Layer solutions can also be implemented to enhance user's application performance. Network operators can use several QoS solutions at the same time.

- For QoS provisioning operators can implement a soft-assurance model and/or a hard-assurance model. Both models are differentiated by the service that can be provided during normal and abnormal network conditions. The service quality and the network reliability are higher with the hard-assurance mode, which will be reflected on the cost of the service that will be provided.

- To improve the consumer's Quality of Experience, there are several techniques that can be used in the access, aggregation/concentration and core network. In the access network, operators are inclined to deploy DiffServ, Ethernet IEEE 802.1p and RACS QoS mechanisms. In the aggregation/concentration network DiffServ and Ethernet IEEE 802.1p techniques are also deployed by operators. In the core network, MPLS and over-provisioning are frequently used.

- The network efficiency can depend on monetary or non-monetary costs. Monetary costs are the cost of the network equipment, the cost of deploying the links and the cost of operating and maintaining the network. Relevant non-monetary costs are the complexity in computation time (consumption of processing power in the nodes), the quality of the transmission, the speed of the transmission, network reliability and resilience, network security, and the technical effort to change resource allocation. Operators deploy networks that meet QoS requirements of the services that will be provided and that also keep a price/quality balance.

- Two networks were taken as examples of efficient access networks. FTTC/VDSL2 and FTTH/P2P. The QoS mechanisms have been identified and allocated to the network elements. The IP core network and the aggregation core network might be the same for both networks. In the IP core network, MPLS and DiffServ techniques may be deployed; also over-provisioning is used

in the links and nodes. For the aggregation/concentration network Ethernet 802.1p and DiffServ are used. In the access network, DiffServ and Ethernet 802.1p can be used as well.

- It is not necessary to change the procedure used to apply the LRIC cost model. The formulas of the LRIC cost models will be the same and the way they are used will be the same, but only a few parameters will change. With the implementation of services that are provided by means of QoS mechanisms, the following concepts and parameters might change: the cost drivers, the network elements and their cost, the traffic generated by QoS applications, and the usage or routing factor of network elements that provide QoS. In this latter case, the routing table may be expanded.

- In circuit-switched telephony networks the cost driver is the number of minutes generated by a communication. In IP services, and also in IP services provided with QoS, the main cost driver is the capacity of the network, which can be measured in Kbps, Mbps or Gbps. For VoIP services, the cost drivers can be transformed into the other one.

- Processing power is a complementary cost driver to take into account in nodes when using prioritization or capacity reservation.

- A few additional hardware and software elements should be included so that the IP network is capable of providing services with QoS. The deployment of these network elements, which leads to investment and operational expenses, will have an impact on the cost.

- The traffic generated by QoS applications will have an impact on the cost of the service provided. The main QoS mechanisms (over-provisioning, prioritization and capacity reservation) will use the capacity of the networks in different ways, which will lead to a different network traffic pattern.

- The traffic generated by applications provided with QoS could take a specific routing path according to the routing policies determined by the network layer QoS solutions. If this is the case, the usage factor of the network elements that are in the routing matrix might change due to the fact that a few nodes and links might be used with different intensity.

- Two examples based on FTTC/VDSL2 and FTTH/P2P networks illustrate how a routing matrix should be constructed when designing a cost model for services with QoS capabilities. It is necessary to determine the increment in the value of the usage factor that is generated when deploying a QoS technique.

The report has shed light on the possible impact of QoS mechanisms on cost modelling. The conclusions that are derived from this study will help the reader reflect on a number of issues to be taken into account when elaborating a cost model for services provided over networks that support QoS mechanisms.

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