Masterthesis

Pricing and Regulating Quality of Experience

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Abstract

The current Internet is experiencing an enormous traffic growth partially caused by the emergence of new interactive media services (e.g., Voice over IP or video streaming). Paired with the Internet Service Providers' (ISPs) difficulties for gaining new revenues through prevailing flat-rate pricing models and inrobust alternatives, this situation has obtained an economic dimension hampering the investments in future network technologies or capacity improvements.

This thesis aims at tackling these problems by establishing a novel concept centering the price and quality decisions on the customers' quality perceptions, i.e., *Quality of Experience (QoE)*. For this purpose, we investigate a *Quality of Service (QoS)* differentiation mechanism based on *Paris Metro Pricing (PMP)*, which in the second step integrates QoE aspects. Our models encompass three actors: a monopolistic ISP offering Internet access to users and an independent regulator. The regulator controls the fraction of the premium service class and may influence the ISP's pricing decisions.

Our findings demonstrate that it is economically desirable for ISPs in terms of revenue to base the price discrimination on QoE. From the inclusion of QoE aspects to the traffic classification process we can observe a significant increase on user utility, although the demand is even further stimulated. Hence, our proposal may contribute to the currently ongoing Net Neutrality (NN) debate.

Current and further work advance the present model by capturing competitive situations and effects of (in-) elastic traffic, as well as by further detailing the mapping between QoS and QoE parameters.

Keywords: Net Neutrality, QoS, QoE, user utility, multiple service classes, application differentiation, Paris Metro Pricing, PARQUE, social welfare

Kurzfassung

Bedingt durch eine steigende Verbreitung interaktiver Dienste (wie Übertragung von Videos u. Fernsehsendungen in hoher Auflösung), wird das heutige Internet mit einer stark steigenden Auslastung konfrontiert. Die jährliche Verdoppelung des Datenaufkommens[1] bewirkt allerdings beim vorherrschenden "Flat-Rate" System kaum steigende Umsätze der Internetanbieter, was Investitionen in Verbesserungen oder Kapazitätserweiterungen erschwert.

In dieser Arbeit möchten wir diesen Problemen mittels eines neuartigen Preismodells entgegenwirken. Dabei setzen wir Qualitätsempfindungen von Nutzern mit Preis- und Qualitäsentscheidungen von ISPs in Verbindung. Unser Modell umfasst drei Aktoren: einen monopolistischen ISP, einen Kundenstamm und einen unabhängigen Regulator. Während der ISP Quality of Service (QoS) differenziert, ähnlich der bekannten Paris Metro Pricing (PMP) Methode, kontrolliert der Regulator die Zuteilung der Kapazität zur Prämiumklasse bzw. beeinflusst die Preisentscheidungen.

Diese Arbeit zeigt, dass ein höherer Umsatz erwirtschaftet werden kann, wenn QoE bei der Preisdifferenzierung verwendet wird. Das Einbinden von QoE in das Klassifizierungsverfahren erhöht den Nutzen der Kunden, auch bei höherer Verstopfung. Diese Resultate dürften auch der Diskussion rund um die so genannte Netz-Neutralität (NN) neue Nahrung geben.

Möglichkeiten weiterer Forschungstätigkeiten in diesem Bereich können folgende Aspekte umfassen: eine genaue Beschreibung des Zusammenhangs zwischen QoS und QoE, die Integration von Konkurrenz, sowie die Untersuchung der Effekte von elastischem und unelastischem Verkehr.

[1] "Internet Verkehr explodiert", n-TV, Jänner 2012, `http://www.n-tv.de/technik/Internet-Verkehr-explodiert-article2455696.html`

Statutory Declaration

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt und die den benutzten Quellen wörtlich und inhaltlich entnommene Stellen als solche kenntlich gemacht habe.

Ort	Datum	Unterschrift

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I dedicate this thesis to my parents – Fritz and Stefanie Wahlmüller – who unremittingly and altruistic supported me during my years of study. They made this work possible.

Stefan Wahlmüller
Graz, 6th February 2012

[2]Telecommunication Research Center Vienna, `http://www.ftw.at`

Contents

Chapter 1

Introduction

Contents

1.1 Motivation

Communication ecosystems are very diverse and cover technical issues, business models as well as human behavior [34]. Thus to model or analyze such an ecosystem a fundamental knowledge of all aspects is needed – this diversity awoke interest within academia. Beside that, the following issues motivate to investigate in telecommunication economics.

The Internet is experiencing an enormous traffic growth[1] due to new broadband applications such as Youtube increasing the risk of congestion without mandatory implicating higher revenues for *Internet Service Providers (ISPs)*. Therefore to maintain a good quality network, ISPs have to steadily invest into infrastructure and/or to control and regulate traffic, either ways are hampered by the prevailing flat-rate pricing system which provides difficulties for the ISPs to gain supplemental revenues. A possible way to generate additional income for ISPs as discussed in [6] are side payments, where a ISP charges a *Content Provider (CP)* (e.g., Youtube) for better *Quality of Service (QoS)*. From the current point of view both strategies, namely (a) *traffic management* or even *blocking* of certain appli-

[1] "Cisco Visual Network Index: Forecast and Methodology", Cisco, June 2011, `http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360_ns827_Networking_Solutions_White_Paper.html`

cations or traffic and (b) *side payments* violate the principles of *Net Neutrality (NN)* as stated in [19]. Although the need for QoS differentiation in the future Internet has been widely recognised [35], no such services are actually offered by ISPs. In particular the ongoing NN debate might be a reason for the lack of QoS mechanism [54].

1.2 Problems

First, Net Neutrality is a sensitive issue which separates the parties involved in Internet matters. Since Net Neutrality discussion emerged, it has become more and more a juridical issue as well, as the rising upcoming number of work interest in this area indicates, e.g.,[19, 63] and [62].

Second, in times where the usage of real-time applications over the Internet increases technical network performance (i.e QoS in terms of packet loss or delay) is attached greater importance. Consequently, Internet tariffing concepts are often based on QoS parameters – an overview is provided by [58]. However, hardly any of these mechanism has undergone serious attempts to be realized [47]. A variety of reasons has led to the lack of QoS differentiation in nowadays Internet and in general may be driven from demand and supply considerations [54]. Besides, the NN issues, this may be explained by the following problems: First, differentiated service quality levels without involving any kind of *usage sensitive pricing schemes*, hence price discrimination may not imply higher revenues for ISPs [35]. But in reality the trend to the simple *flat rate pricing* can be observed [39]. Indeed user seem to be willing to pay more for flat rate fees than they would for usage sensitive charges, on the other hand an effect of flat rate pricing is that usually Internet traffic significantly increases [37]. Second, plain capacity expansion could be more attractive from the ISP's effort and cost perspective relative to hardware (HW) and software (SW) investments, in order to monitor the user's Internet traffic. Third, there is a trade-off between QoS and scalability, where the intensity is depending on the used QoS mechanism, but could also prevent deployment of QoS [60].

Finally, there exists a variety of research on simple and more sophisticated QoS mechanism, but hardly any approach efficiently combines *Quality of Experience (QoE)* as a possible game changer.

1.3 Solution

This work sheds light on an active role of QoE – quality as experienced by the end user – in a novel approach for Internet pricing, using a well known QoS approach underneath, i.e., Paris Metro Pricing (PMP). PMP integrates pricing with traffic management, where QoS differentiation is achieved as a side effect of price differentiation. Already Reichl in [47] argued that "price discrimination should be based on QoE instead on QoS". This work adds a QoE based pricing mechanism to an PMP framework. This can only be achieved by a proper mapping between the users' utilities for quality levels and QoS. Additionally the QoS based classification process is revised, by holding the applications' QoE level constant. To respond to the increasing demand, the future Internet will supply different kinds of services, e.g., video, voice, email, FTP, telnet, and HTML among others [40], each of these applications requires a different QoS. In contrast to previous models we propose application specific quality differentiation by network service providers (NSPs), while maintaining an experienced end user quality level stationary. This work points out the effects of application-differentiation in such a non-neutral network on the total social welfare. This new approach is called *P*ricing *a*nd *r*egulating *Qu*ality of *E*xperience, PARQUE.

1.4 Structure

Chapter 2 introduces the fundamental definitions used throughout this thesis. Explicitly, it starts by establishing a differentiation between *Quality of Service (QoS)* and *Quality of Experience (QoE)*, while thereafter heading to *Net Neutrality (NN)*. We briefly survey the portfolio of *traffic management* and describe Paris Metro Pricing (PMP). An overview of diverse Internet pricing mechanisms in literature is given in Chapter 3. In Chapter 4 we define mathematical pricing models: First, an approach for conventional *Paris Metro Pricing (PMP)* is illustrated (cf. Section 4.1), before we have a detailed look on the mapping QoS to QoE and vice versa (cf. Section 4.2). Then a model for *QoS priced PARQUE* in Section 4.3 and in Section 4.4 for *QoE priced PARQUE* is introduced. To this end Section 4.5 compares these approaches, illustrates key elements and the differences. In Chapter 5 the optimal access prices for each model are shown for maximizing either revenue, user utility or a combination of both, namely social welfare. Finally, Chapter 6 concludes this work with an outlook on future issues.

Chapter 2

Fundamentals

Contents

This Chapter covers the fundamental definitions this work is based upon. In most pricing schemes users pay for a certain QoS (cf. Section 2.1) or even QoE (cf. Section 2.2), as discussed in recent research, e.g., [47]. As some of the schemes may be seen in conflict with the principle of *Net Neutrality*, Section 2.3 briefly overviews NN and being complemented in Section 2.4 by surveying the portfolio of methods to control or manipulate web traffic. Finally, Section 2.5 presents the *Paris Metro Pricing (PMP)* concept in detail as this work is strongly based on some ideas behind it.

2.1 Quality of Service

Quality of Service (QoS) is a term to describe the guaranteed performance of a network with engineering parameters. In other words "QoS is a set of service requirements to be met by the network while transporting a flow. As inferred from this definition, QoS is a concept, rather than a specific technology." [37]. Kilkki in [34] sees QoS "purely as a technical concept that is used to facilitate the interactions between applications and network services".

Typical examples for QoS metrics are the bandwidth (kbps or mbps), end-to-end delay (ms), jitter (ms) and packet loss (%), bit error rate, and more. Jitter can be seen as the variation in delay or response time [32, p. 3]. QoS requirements are application-specific [25, 58], i.e., e-mail has different requirements than video streaming. Table 2.1 summarizes the QoS parameters listed in [33] – i.e., commonly used metrics, tolerated ranges, and consequence of exceeding these ranges – for real time IP voice and video communications.

QoS Metric	tolerated range	consequence of exceeding the ranges
jitter	20-50 ms	jerky video or stuttering
end-to-end delay	200 ms	long pauses, unnatural
packet loss	1%	jerky video, stuttering or popping audio

Table 2.1: QoS metrics for real time IP applications [33]

Packet loss represents a relative value (or percentage) of transmitted packets which have never reached their destination. The primary reason for packet loss is congestion, causing the router to drop the packets [33]. [32, p. 3] subdivides network QoS parameters in three categories: First, characteristics regarding *timeliness*, e.g. response time, jitter. Second, *bandwith* specifying parameters as data rates and third, *reliability* might be expressed in terms of mean time to failure (MTTF) or packet loss rate. [25, p. 856] surveys the requirements of the most common Internet applications regarding used bandwidth and type of service (e.g., conversational, streaming, interactive).

2.2 Quality of Experience

In contrast to QoS, *Quality of Experience (QoE)* describes network performance as experienced by the end-user. Reichl in [46] provides a description of the evolution from QoS to QoE. [1] defines QoE as "The overall *acceptability* of an application or service, as perceived *subjectively* by the end-user". Another worked out alternative at the Dagstuhl seminar[1] embossed: "The *degree of delight* of the *user* of a service, influenced by content, network, device, application, user expectations and goals, and context of use".

QoE is a interdisciplinary approach[2] as illustrated in Figure 2.1 and distinguishes from QoS in two major points: First QoE includes the whole system efficiency and effectiveness (cf. Figure 2.1), therefore Reichl in [46] suggested the term "End user-to-end user concept".

[1] "From QoS to QoE", Dagstuhl Seminar 09192, May 2009, `http://www.dagstuhl.de/en/program/calendar/semhp/?semnr=09192`

[2] Utility Functions, Quality-of-Experience and the Weber-Fechner Law,Schatz, Egger, Reichl, Tuffin, COST ISO605 WG3 Meeting Lubljana, May 2010

While network efficiency can be expressed by the maximal utilization of network resources [47], the whole system consists of several subsystems, i.e., the network and the multimedia device and additionally needs to implicate the application types QoS requirements [32, p. 2]. Second, the overall acceptability of the network performance may be influenced by the user expectations and context, hence it becomes a subjective perception of the customer. QoE is expressed in mean opinion score values (MOS) on a five-point scale ranging from 1.0 to 5.0, the interpretation of MOS levels is summarized in Table 2.2.

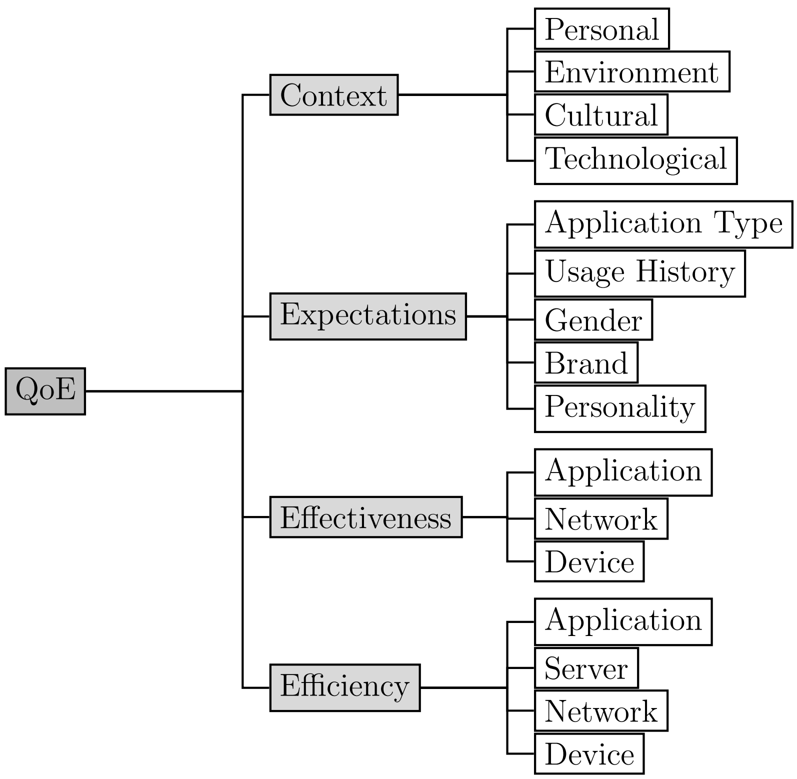


Figure 2.1: An interdisciplinary approach to QoE [45]

MOS value	5	4	3	2	1
Quality	Excellent	Good	Fair	Poor	Bad

Table 2.2: Mean Opinion Score (MOS) values

Today, there are currently ongoing research endeavours for systematically mapping technical QoS parameters to perceptual QoE values. While [48, 49] proposed that the correlation follows the well-known *Weber-Fechner Law*[3] and thus a logarithmic relationship can be observed, further research proposed that an exponential relationship provides better approximations [21, 65]. A typical relationship between QoS and end-user quality perception can be found in Figure 2.2. [21] subdivides the curve into three areas denoted with 1, 2 and 3, separated by the thresholds x_1 and x_2. In area 1 – *constant QoE* – the QoE is experienced by the user as nonvarying, e.g., small delays can be eliminated by a jitter buffer, without noticing by the end-user. Area 2 – *sinking QoE* – is characterised by a sinking user satisfaction. Finally in area 3 *unacceptable QoE* the user might give up using the service. It can be seen from Figure 2.2 that in area 2 at high QoE even a small QoS disturbance effects a significant drop-off, therefore the *subjective sensibility* is highly correlated to the existing or expected quality level.

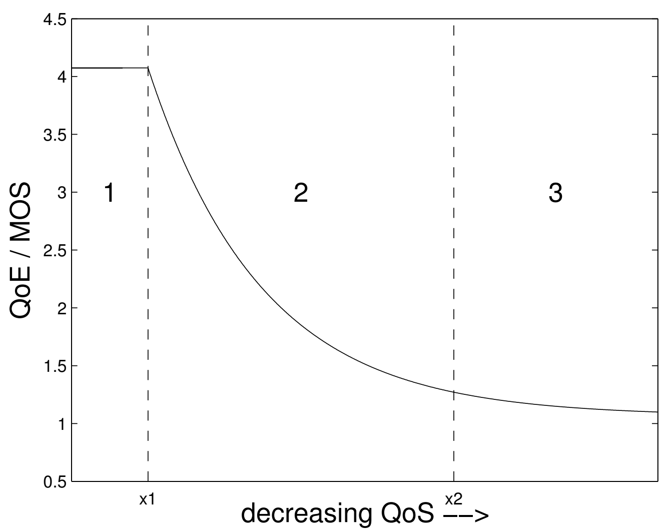


Figure 2.2: Schematic mapping from QoS to QoE [21]

It is obvious that the relationship depicted in Figure 2.2 strongly depends on the application used on the network. [21] expresses a quantitative relationship between QoE and QoS for web browsing and [65] to the case of video. QoE can be seen as a complement to the QoS perspective rather than replacing it[4].

[3]"The Weber-Fechner Law describes the relationship between the magnitude of a physical stimulus and it's perceived intensity" [48]. For the human body this sensitivity often follows a logarithmic nature (e.g., touching, hearing, human vision, smelling, ...). Reichl et al. in [48] apply this on network parameters and explain this surprising link in more detail.

[4]Quality of Experience - More than just another Buzzword?,R. Schatz, EuroView Workshop Würzburg

2.3 Net Neutrality

During the past years, *Net Neutrality (NN)* emerged as a very controversial topic in Internet policy, this section tries to summarize most recent discussions. By now, only vague concepts or definitions for NN are present such as sketched in the following:

- "Net Neutrality (...) usually means that broadband service providers charge consumers only once for Internet access, do not favor one content provider over another, and do not charge content providers for sending information over broadband lines to end users. In other words, Net Neutrality is actually a friendly-sounding name for price regulation" [24].

- "Article 8 (§4) (g) of the Framework Directive requires national regulatory authorities to promote the interest of the citizens of the European Union (EU) by promoting the ability of end-users to access and distribute information or run applications and services of their choice." [19].

- For Berners-Lee Net Neutrality is[5]: "If I pay to connect to the net with a certain QoS, and you pay to connect with that or greater QoS, then we can communicate at that level."

- From a more juridical perspective NN describes "a set of data management regulations that proponents wish to impose on broadband network owners" [11].

The understanding of the term NN has shifted, from an engineering approach about neutrality of the content and applications on the transport layer[6], towards an interdisciplinary approach including regulatory and political facets. At first the Internet was intended to work as a so-called "dumb network" that does not differentiate on the transported contents (packets). The interpretation of packets has been shifted to the end of the communication line [63]. Proponents of NN regulations e.g., Google or Amazon fear that ISPs could charge an extra fee for certain traffic, or use any QoS mechanism for traffic, with particular content or from a certain source or application. [11] defines NN in the most common sense as "a legislative or regulatory fiat that requires network operators to manage all Internet traffic on equal terms". From a consumer perspective, by looking at the current data of

Germany, Aug 2011

[5]"Net Neutrality : This is serious", timbl's blog, June 2006, `http://dig.csail.mit.edu/breadcrumbs/node/144`

[6]The transport layer is part of the *Open System Interconnection model* (OSI model) where the functions of a communication system are analysed in abstract layers, further information can be found on Wikipedia, Wikipedia, September 2011, `http://en.wikipedia.org/wiki/OSI_model`

supply and demand, the marketplace for broadband service is very healthy (a healthy market is responsive to consumer demand), which for Chong in [11] means that "consumers are reaping the rewards of vigorous competition". On the other hand opponents of NN argue that they have to violate the NN principles to deal with the steady rising demand.
The diverse literature on NN – as suggested by [50] – may be structured in the following three groups: (a) engineering aspects [15, 20], (b) legal perspective [62, 63], as well as (c) empirically driven economical research [56] and economic modeling analysis e.g., [18, 28, 38] and a comprehensive insight provides [56]. Later on this work targets (a) the engineering aspects of NN and especially in (b) the economical aspects of NN, but overviews in (c) juridical aspects and laws relating to NN at its end.

(a) **Engineering Aspects of NN**: For Yoo in [62] represent "deviations from Net Neutrality nothing more than network owners' attempts to satisfy the increasingly intense and heterogeneous demands imposed by end-users". The NN discussion, however, ultimately provides a suitable basis for discussing, if any arbitrary discrimination may be feasible for the society. Wu in [62] thinks about discrimination in the internet as nutritionists about fat: "There are good and bad types", i.e., packet discrimination may be used to mitigate congestion problems in order to maintain proper service provisioning or on the other hand in order to intentionally discriminate specific people, organizations or delivered contents.

    Crowcroft in [15] took a largely technical look at the NN issue and concluded his paper with the words "We never had Net Neutrality in the past, and I do not believe we should engineer for it in the future either". Among other things Crowcroft argued that the lack of fairness (irrelevant of the definition of fairness, whether max/min, proportional, or other) in the Internet , e.g., aroused by firewalls or the distance-depending throughput in TCP networks ("the further you are from a sender, the less capacity you get"), still infringes NN [15]

    [11] describes NN as an issue regarding the regulation of public networks involving: (i) content neutrality, (ii) blocking and rerouting, (iii) denying IP- network interconnections, (iv) network management, and (v) premium service fees. Section 2.4 below covers points (i - iv) in more detail, while Section (b) among other things discusses (v).

(b) **Economical Aspects of NN**: Greenstein in [23] presents the economic substance behind NN and names four nightmare scenarios. The first one might be called *inequity nightmare*, there firms with market power offer a premium tier with higher profit margin. Investments to this higher tier may lead to a more expensive advanced Internet. *Corporate bureaucracy nightmare*, the second scenario means that e.g., a CP offers an innovative web site, then ISPs insist that end users connect to the higher tier and broadband providers may require an extra charge for this access, thus the network may become more expensive for the user. The third scenario named *bad incentive nightmare* illustrates that ISPs block or throttle competitive applications to favour their own ones (e.g., VoIP). The last scenario is a *less innovative content nightmare* that describes the situation of a broad band firm producing new applications and protecting their interests giving no chance by using them by other providers. The abolishment of the NN regime may have six economical consequences as discussed in [18]. First, ISP may charge CP or *application providers (AP)* "on the other side" of the network, this is called *two-sided pricing*. *One-sided payments* in contrary is where CPs and APs only pay ISP if they are directly connected to them and have a contractual relationship. The question if ISPs should be allowed to charge CPs or APs for the access to users is subject to a variety of related work e.g., [4, 5, 38]. Second, it will introduce the possibility of *prioritization of QoS* of paying CPs over non-paying firms and third the possibility of *identity-based discrimination and prioritization*, e.g., one search engine over another. Fourth, a *reduction of innovation* might appear, because new firms with small capitalization have substantial drawbacks in the prioritization auctions. The fifth scenario equals Greenstein's *bad incentive nightmare* discussed above. Finally, *multiple fees* will be charged for a single transmission if not just the final consumer access network charge CP or AP, but every interconnected network on the path of traffic. This can cause a significant reduction in trade on the Internet.

(c) **Juridical Aspects of NN**: There exists a vast range of work investigating the legislative aspect which have generated much discussion and controversy. This Section lists actual rules for mobile and fixed networks.

Wong et al. [61] derives Internet access as a fundamental right out of the human right declarations. NN touches on a number of rights and principles enshrined in the EU Charter of Fundamental Rights such as the freedom of expression and information or the protection of personal data [19]. In 2005 the Federal Communications Commission (FCC) adopted four key principles in the United States (US), largely corresponding to the EU's "open Internet " principle [19]. These were extended by new rules on transparency and a clarification whether blocking is permitted or not for fixed and mobile broadband providers in December 2010. For fixed and mobile broadband providers blocking lawful websites and VoIP or video-telephony applications that compete with their own VoIP services is forbidden by law. There is no collective European law for NN in that kind, although Norway adopted a voluntary agreement in February 2009

[19] and the Netherlands as the second country made NN a law in June 2011[7]. Regarding the new law, Vodafone Netherlands warned that they may raise subscription prices and the former Dutch state Telecom KPN announced they may charge customers extra for using e.g., Skype.

Other rules closely related to the NN issue adopted on 25 May 2011[8] as part of EU telecoms rules are eliminating *barriers of switching ISPs*, ensure higher *transparency* and *Quality of Service*.

- *Switching ISP:* switching should be possible within one working day
- *Service transparency:* information such as management techniques must be available before signing a contract
- *Quality of Service:* Information such as available connection speed or bandwidth caps must be available

Recapitulating Section 2.3, the NN issue may be described as a conflict of interests involving CPs or AP, ISPs and Internet users. APs and end users second the NN in the most stringent version, this involves no service differentiation and to handle traffic in the Internet in best effort manner. Several circumstances may authorize the usage of *traffic management* (cf. Section 2.4) – although the question "Authorization by whom?!" has not been clarified yet. One reason to advocate traffic control mechanism might be that new Internet applications and the number of Internet users are growing significantly. One of the fathers of the Internet, Roberts, predicts that in the year 2018 99% of the world's population will be online and additionally traffic per user increases resulting in the requirement of a 60 times increase in capacity[9]. Furthermore, real-time video and television applications need higher QoS assurances and are also rising rapidly.

[7] Netherlands makes net neutrality a law, BBC News Technology,23 June 2011, `http://www.bbc.co.uk/news/technology-13886440`

[8] European Commission underlines commitment to ensure open Internet principles applied in practice, European Commission,2011, `http://ec.europa.eu/unitedkingdom/press/press_releases/2011/pr1143_en.htm`

[9] L. Roberts, OFC/NFOEC, `http://www.ofcnfoec.org/osa.ofc/media/Default/PDF/2009/09-Roberts.pdf`

2.4 Traffic management

Traffic management names the process of measuring and controlling of the network traffic in order to optimize or guarantee performance, improve latency and thus avoid congestion. To ensure a proper QoS especially for real time applications, [33] names *over provisioning*, *queuing* and *classifying* as fundamental concepts, while [19] lists the following ways how ISPs can control traffic, namely *Blocking and Throttling* and *Traffic Management*. The following definitions rely on [19], where not denoted elsewise.

Blocking and Throttling

There are two forms of *blocking*, first to make it difficult to access certain services or websites on the Internet and second that ISPs are restricting access. A classic example is blocking of VoIP applications (e.g., Skype) on mobile networks. Wu in [62] admitted that blocking "is the clearest case where discrimination is bad" and that there is a need for NN rules. *Throttling* on the other hand means to slow certain traffic down and thus decrease the quality of content, e.g. Comcast throttling BitTorrent traffic to control congestion as P2P file sharing increased [9]. Blocking and throttling P2P traffic has been done in some countries although the network was not stressed [5].

Advanced Mechanism

It is widely accepted that for online games, voice and video applications, real-time IP television services or even file-sharing to operate properly, ISPs need to adopt special methods to control traffic and to ensure high QoS. There are different ways to control traffic in a network [19]:

- **Packet differentiation**: To treat diverse classes of traffic differently and thus guarantee a certain minimum QoS level to the end-user.
- **IP routing**: Method, which routes packets via different communication paths to avoid congestion or provide better services.
- **Filtering**: Means to block harmful traffic to improve efficiency of the network's legal traffic.

According to [17] there are three different approaches to ensure QoS. *Best effort*, as a very simple principle, the only way to maintain QoS in this principle is over provisioning capacities. Over-provisioning is the intentional establishment of excess resources of network bandwidth. Kelly in [33] expresses a general rule of thumb: "The maximum bandwidth required for all applications added together, including voice and video real time applications, should not exceed 75% of the available network bandwidth. Consequently, over provisioning to some extent is necessary; however, by itself, over provisioning is not sufficient to guarantee adequate QoS." Second, *standard QoS architectures*, where an explicit classification process assures QoS, e.g. Paris Metro Pricing (PMP). Another idea is called *Flow Aware Networking (FAN)* introduced in [17, 42]. [17] describes the concept of FAN and compares it to the well known mechanisms like *IntServ* or *DiffServ*[10] as a possible way to ensure QoS requirements in networks. IntServ tries to provide per-flow QoS for specific applications [32, p. 108ff]. Regarding the NN issue FAN stands out with its conformity, while DiffServ or IntServ violate the NN principles. DiffServ provides means for the ISPs to differentiate service without any limitations. It is possible to distinguish different applications to discriminate traffic based on source or destination addresses or traffic volume. It is even possible to police traffic based on the content. Yuksel et al. in [64] investigates the benefits of *Class-of-Service (CoS)* compared to simply over provisioning of the network. Proponents of NN suggest that ISPs should not differentiate traffic to meet the *service level agreements (SLAs)* of their business customers but all performance requirements should be met by over-provisioning the network. Yuksel et al. showed that CoS differentiation is more efficient (from a capacity viewpoint) for performance-sensitive traffic (e.g., video, games and VoIP applications) and regular best-effort traffic.

Section 2.3 summarizes the NN issue and Section 2.4 gives a short overview on the engineering aspects, especially how ISP can control traffic and the thin line whether or not conflicting the NN principles. As this work is based on an architecture, where a classification process differentiates certain levels of QoS, called Paris Metro Pricing, the following Section 2.5 captures the details.

2.5 Paris Metro Pricing

Paris Metro Pricing – as introduced by Odlyzko [39] – is a market-based mechanism and pricing scheme for resource allocation for providing differentiated services. There is a vast body of network QoS literature studying PMP such as [22, 31] and [35]. The PMP proposal – as the name implies – was inspired by the metro system of Paris about 20 years ago, where users were offered a choice of travelling in first or second class carriages, while the only difference was the charged price. Both carriages had the same number of seats with

[10] Diffserv is a framework that supports providing of a certain QoS on a class level [32, p. 169ff]

identical quality and obviously both reached the destination at the same time. The first class ticket costs twice as much as the second class ticket, thus the first class cars were less congested, since only passenger with a higher willingness to pay for obtaining a seat paid the premium fare. The system was self-regulating depending on the congestion and the willingness to pay of the individual passengers.

Applying PMP to a packet based network like the Internet means to partition it into separate logical channels with different charges applied (different access prices) on each sub-network . Packets in every sub-network are treated on a best effort basis just as in the Internet today. Users would choose the sub-network and pay the access price accordingly. ISPs would not have to guarantee a certain QoS, but the expectation of the QoS level in the sub-networks would be different. Thus applying PMP the price becomes the key control parameter, which influences the user demand based on the users' willingness to pay for QoS. This leads to the big question, whether or not customers will be willing to pay even more than today for not guaranteed QoS [37]. ISPs have to come up with solutions to guarantee a high degree of certainty that customers in a more expensive channel is served better than in a cheaper channel.

There are two main variants in which PMP could be realised: either by using physically separate channels or by using the same physical channel but treating packets according to their priority [37]. The first approach involves higher investment in infrastructure since this would mean extending the existing infrastructure by including more wires at a high cost and thus this would not be feasible [37]. A logical separation of the packets controlled by priority bits seems a lot more efficient. Today's IPv4 Internet protocol contains three unused priority bits which would be a lot more efficient to run up to eight different QoS channels ($2^3 = 8$). To prevent from customer confusions a partitioning into even more channels should be avoided. Odlyzko in [39] suggested a separation into a small number of channels –namely two, three or four channels – to minimize aggregation losses. Regarding from an economic perspective, almost the same gains can be achieved with fewer classes of service [39].

According to [39], the most major adjustments needed to meet PMP requirements must be made in routing and application software. Routers must be able to treat packets according to their priority and application software must be able to set priority bits accordingly to its needs [39]. A primitive kind of PMP already exists on the Internet today. Different ISPs offer the same product, namely Internet access, doubtless with different QoS [37]. It is up to the customers to choose the right ISP satisfying their personal needs, but the state of the art Internet lacks one of the main characteristics of PMP, namely differentiated traffic throughout the net. What you can get from an ISP offering high QoS is a fast and reliable connection from your Internet device to the Internet access point. But beyond that, more expensive and cheaper ISPs may share the same backbones and systems and this thus may lead to a reduced quality gap.

In today's Internet despite the technological possibility of providing differentiated services, no such service are actually offered by the ISPs [51] outlines five main reasons for the persistence of this situation. First, due to uncertain demand ISPs worry that QoS differentiation involves a profit risk and therefore ISPs miss incentives to explore offering QoS. Second, coordination between ISP is needed for QoS provision as the path between two users may not only be assigned to a single ISP. A scheme how to divide the QoS revenue between the involved ISPs and a solution for an ISP not offering QoS differentiation is required. Third, introducing QoS provision appears to be economically more intensive, than plain capacity expansion. Fourth, the current threat (see Section 2.3) of NN regulations hampers ISPs' incentives for QoS. Fifth, one crucial problem is how to allocate the capacities to and set prices for the channels, the existing QoS pricing research indicates the difficulties of robust pricing of QoS.

2.6 Summary

This chapter provides an overview of the general framework of this work. Section 2.1 and Section 2.2 introduce two different perspectives on describing quality – QoS and QoE – as there slowly sprouts a paradigm shift towards Internet pricing mechanism for QoE, e.g., [47]. In Section 2.3, we briefly summarize the intensively discussed Net Neutrality (NN) issue which might be – among others – a possible reason for the lack of QoS provisioning in the current Internet. We quickly survey traffic management techniques in Section 2.4, but then we illustrate Paris Metro Pricing (PMP) as a very simple mechanism for providing differentiated services. We argue that QoE aspects in conventional Internet mechanism (i.e., not only for pricing) might enhance effects. The next chapter provides an overview on related work.

Chapter 3

Related Work

This Chapter surveys the vast body of related work in the context of the pricing approaches presented in Chapter 4 and consists of three parts. First, we provide a general overview of Internet pricing. Second, we survey related work investigating in Paris Metro Pricing (PMP). Third, we summarize related work which argues to integrate Quality of Experience (QoE) as an integral element in Internet pricing schemes.

Although [22, 31] investigated the idea of QoS differentiation some time ago and pointed out that ISPs' profits and user welfare are higher than in a single service class, there are no such services actually offered by ISPs. One possible reason might be that there exists a trade-off between QoS granularity and scalability [60]. Another issue might be that there exists an insecurity if the costs for e.g., the initial investment in infrastructure pay off. The lack of QoS differentiation may partly be explained by a raised awareness of Internet issues nowadays [19, 20]. Indeed the threat of regulating Net Neutrality (NN) hampers the ISP's incentives for QoS. [28] investigates on the effects of product-line[1] restrictions on welfare. For the monopolistic ISP the imposition of a single product line frequently reduces surplus as consumers at the bottom of the market are harmed. Regarding the NN issue (cf. Section 2.3) Schwartz et al. in [50] explore a *x-network*, in which a certain pre-specified fraction depending on x of an ISP's capacity cannot be affected by any NN regulations, while the rest functions as the present Internet. A x-network enables the deployment of QoS by establishing the ISPs property rights on a fraction controlled by a social planner (i.e., a regulator). On the other hand, Prieger et al. in [44] pointed out that any regulation might hamper companies' incentives to innovate in the Internet industry.

[1] Several variants of the same product are referred as *product-lines*, e.g., student or professional software versions [28].

Another reason worth mentioning why no such service classes are currently offered by ISPs might be arising out of difficulties in QoS pricing under competition. In the next part we have a closer look on the various Internet pricing possibilities.

Internet Pricing Schemes

A comprehensive view on this issue is provided by [14]. In general, we can distinguish *dynamic* pricing, in which prices fluctuate as a result of some network conditions, or from *static*, in which prices are independent of the network load [16]. [58] and [16] survey common Internet pricing mechanisms. Pricing is primarily a marketing and strategic decision but engineering concerns are influenced as well, e.g., pricing can be used to control congestion within a network, compare Section 2.5. The right pricing policy should satisfy user objectives (which will influence service choice and offered traffic) as well as ISP objectives (e.g., revenue, profit).

In many cases the user's preferences are modelled through *utility functions*. In this context, the utility describes the sensitiveness of the user in regard to QoS changes or in other words the user's valuation relating to her/his willingness to pay for certain QoS guarantees [16], e.g., utility is often expressed as a function of actual QoS parameters, such as delay or packet losses. [16] pointed out that there exist different utility functions for different kind of applications. For instance, real-time voice and video are very sensitive to delay and jitter, while traditional data applications are more sensitive to losses [16]. Therefore real-time applications are *inelastic* in their demand for bandwidth and their utility is modelled as a step-function. On the other hand, traditional data applications such as mail are *elastic*, they tend to be tolerant of variations in delay and can take advantage of even minimal amounts of bandwidth. The precise modelling of the customer behaviour is the critical part of the pricing problem. There are at least two possible ways how to find the prices. If the Internet is seen as a public good, to maximize customer surplus and alternatively ISP's revenue maximization if it is viewed as a private good.

In [58] Tuffin classifies pricing schemes in eight different families and gives an mathematically review when available, of those without resource reservation. Due to their simplicity of special interest for this work are the following: The first group relies on *over-provisioning* of the link-resources to adapt to the demand – the common quality approach for best effort (BE) Internet. The second group is *Paris Metro Pricing (PMP)*. The approaches introduced in Chapter 4 are based on this suggestion.

One of the debates of the Internet pricing has to do with whether *flat rates* or *usage-sensitive* charges should be levelled on users [40, 58]. Usage-sensitive prices take into account the actual amount of traffic through a connection. Altman et al. in [4] investigates among other issues the implication of usage-based prices in a non-neutral network. Historically seen, there exists only a slight relation between costs of the usage and the price charged [40] and there is a trend towards simplicity (i.e., flat rate fees). Odlyzko in [40] summarized that costumers tend to tolerate variations in quality but are averse to varying service fees and are willing to pay more in flat fees than for metered billing. ISPs and Internet user profit of the simplicity accompanied by flat rate fees, e.g., conventional infrastructure can be used because no metering mechanism are needed [37] and the predictability of money flows [40]. On the other hand, findings show that along with the imposition of utility-sensitive charges usage decreases [40]. [16] provides an overview of the main advantages and disadvantages of each of these two pricing approaches summarized in Table 3.1. Although, it is often suggested to apply a usage sensitive pricing

Pricing Scheme	Pros	Cons
Flat rate	+ no/fewer equipment for tracking user behaviours required + no dedicated usage based billing mechanism required + little overhead for billing	– unfairness: low demanding customers subsidize powerusers – no recovery of congestion costs – server overgrazing – not appropriate for differentiated QoS
Usage sensitive pricing	+ can play a role in congestion control and prevention + increased fairness	– adverse response from customers – difficult to budget for – increased billing complexity – may discourage usage

Table 3.1: Pros and Cons for selected pricing models [16]

scheme if service differentiation is provided (e.g., [35, 39]), it is common to investigate QoS differentiation with flat rate fees e.g., [53].

Pricing – especially – if it comes to application differentiation is an important issue, although comparing the revenues from different basic pricing schemes like *flat-rate pricing* or *PMP* it is surprising, that the current simple flat-rate pricing adopted by many ISPs is quite efficient in extracting revenue for elastic traffic [52]. The *Price of Simplicity (PoS)*, the ratio of profitability of the simple entry fee pricing to the maximal value of consumer surplus was calculated in [52] therefore. Elastic traffic, such as e.g., file transfer (using ftp) or web applications is characterized by flexible QoS requirements [32].

Next, we survey related work investigating PMP as this work's pricing models (cf. Chapter 4) are based on this mechanism.

Paris Metro Pricing

Paris Metro Pricing was first proposed by Odlyzko in [39] (cf. Section 2.5 for a detailed introduction to PMP) and since then is often investigated in further work e.g., [22, 31, 53]. An overview of the PMP approach and its feasibility in the real Internet is given in [35].

[31] analyzes the profitability of PMP for a monopolistic ISP, while [22] investigates the competing duopoly case. This work is based on a model introduced in [53] that permits robust pricing of differentiated services similar to PMP. In that paper welfare effects of transition from a single-service class to two service classes is investigated and results show that multiple service classes are socially desirable if controlled by a regulator. Results show that price differentiation improves profits and interestingly two service classes are socially preferable to a single service class, but only in the presence of a proper regulator, users do not suffer a loss of surplus. In contrast to other related work on PMP, in [54, 55] the previous discussed model is extended for any number of ISPs under competition. [22] concentrates on the duopoly case only. In [54, 55] the focus is on QoS pricing when ISPs compete and the reasons for the lack of multiple service classes in today's Internet. They find that even with perfect competition between ISPs, QoS differentiation remain optimal and thus ISP competition alone is no valid explanation of the presence of two service classes in contrast to [22] where "competition effects always outweighs a segmentation effect" (i.e., PMP might not be viable under competition). A more detailed overview on [53] and [54] is provided in Section 5.1.
Another closely related paper is [51], which models the impact of transition of a two-class QoS differentiation on the user welfare. Schwartz et al. propose a regulatory tool to facilitate the transition, where the fraction of capacity that the ISP is allowed to allocate to the provision of QoS services is fixed [51].

QoE based Internet Pricing Schemes

Although, there exist a strong interest in QoE (e.g., [34]) and a lot of effort is made to express QoS in terms of QoE (e.g., [21, 65]), but related work integrating QoE aspects in pricing schemes is rare. Reichl et al. in [47] encourage for a paradigm shift towards a QoE framework for pricing IP-based services. They argue that price discrimination[2] should be based "more on the quality as perceived by the end-user (QoE)" rather than on pure engineering parameters (QoS). In [47] two approaches for QoE aware Internet pricing are proposed: First, QoS is metered and translated in QoE in real-time, this happens with the help of an additional module, which is integrated to a standard QoS-aware charging architecture. In IP based systems the billing calculation and accounting might be done by an Internet Charge Calculation and Accounting Subsystem (ICCAS), where Service Level Agreements (SLAs) are now expressed in MOS values. Second, "Reactive Charging" a mechanism based on direct user feedback is proposed. In this mechanism the user signals his/her quality evaluation by pressing a button and thus service differentiation via real-time user feedback can be achieved.

This Chapter provides an overview on Internet pricing and particularly lists closely related work on PMP. It compares common simple pricing mechanism such as flat rate and usage sensitive pricing. Finally, it introduces the innovative idea from [47] to base price discrimination on the user's QoE expectations. The following chapter introduces Internet pricing schemes based on PMP presented in [53] with and without a framework integrating QoE aspects.

[2] Price discrimination is a common business tactic, where price vary by the customers' willingness to pay [40].

Chapter 4

Pricing Models

Contents

In this chapter we present three pricing mechanism that offer QoS classification to deal with the increasing Internet demand. Therefore, we model a "non neutral" network as a regime where an ISP is allowed to establish two QoS classes and even differs between application types. We stepwise enhance this concept by integrating QoE aspects being captured by two novel pricing mechanism, referred to as Pricing and Regulating Quality of Experience (PARQUE). We analyse the impact on the ISP's revenue and the user utility.

For the analysis of these pricing approaches we consider a common scenario as depicted in Figure 4.1. In general, a monopolistic ISP offers Internet access to a specific number of

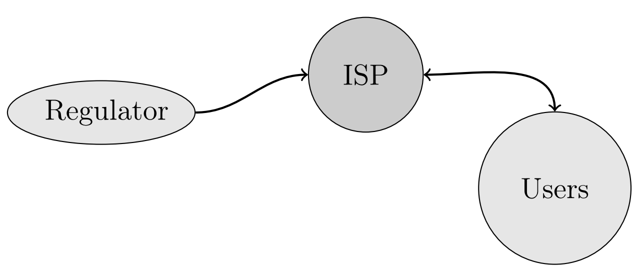


Figure 4.1: The analyzed scenario

end users controlled by a regulating authority. This work is based on an approach presented in [53] using *Paris Metro Pricing (PMP)* for QoS differentiation. We concentrate on the allocation of two different QoS classes only, where similar to [53] a regulator defines the maximum capacity dedicated to a premium QoS class. Like in [53] we assume that the end users' quality expectation – independent if expressed in terms of QoS or QoE – and the willingness to pay coincide. Hence, a user with low quality needs is willing to pay a low charge for Internet access and user with high quality expectations are ready to pay more expensive fees. In this work we distinguish between QoS and QoE requirements. The users QoS requirements are denoted by θ, while QoE is denoted by the term Φ.

As starting point, Section 4.1 defines the *conventional PMP*. While in PMP QoE has no impact on the user classification, it plays a key role in the following approaches. For this purpose, Section 4.2 describes the *relationship between QoS and QoE* in detail. Then in Section 4.3, we integrate this mapping and by demonstrating a utility-based quality differentiation idea, i.e., a novel *QoS priced PARQUE*. While in this concept pricing is still done on QoS properties as suggested in various related works (cf. Chapter 3), the advanced approach in Section 4.4 applies a direct QoE based price differentiation, i.e., *QoE priced PARQUE*. Finally Section 4.5 concludes this chapter.

4.1 Conventional Paris Metro Pricing

PMP as introduced in this section provides the basis for the later on constructed PARQUE approaches. First, we illustrate this model with the help of the big picture. Thereafter, we have a detailed look on the *classification of users*, the *user utility* and the *pricefinding*.

The big picture of this approach is illustrated in Figure 4.2. An **ISP** uses PMP for providing two service classes, namely class 1 (basic service) with access price p_1 and class 2 (premium service) with higher access price p_2, i.e., $p_1 < p_2$. First, the ISP invests irreversibly in capacity c and a **Regulator** announces x, the capacity fraction allocated to the provision of premium service 2. Then in the sub-game **Pricefinding** the ISP sets the prices p_1 and p_2. Each **User** is characterised by θ, which is a random variable with support on $[0, 1]$. For a user with type θ, the lowest acceptable service quality is $q = \theta$, the highest affordable access price is $p = \theta$, i.e., $p < \theta \leq q$.

Thus $\theta = 1$ represents very high willingness to pay and high quality requirements of the user, if $\theta = 0$ then the user's quality evaluation is zero. Finally – in the **PMP** block –

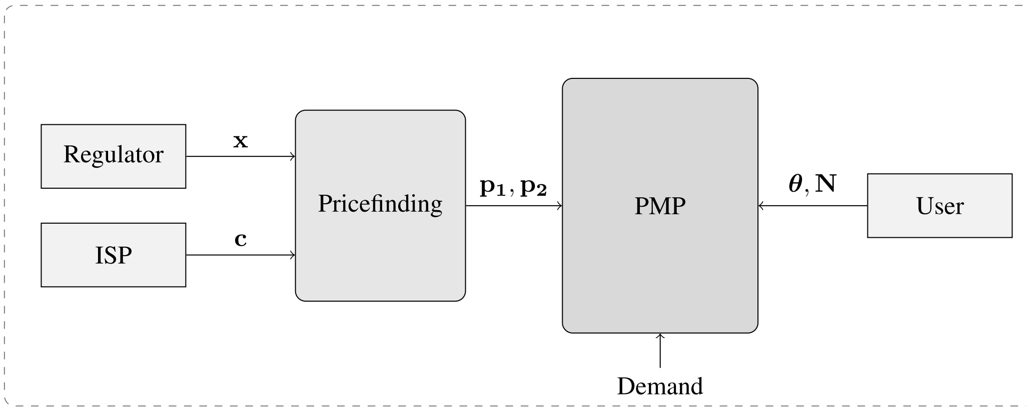


Figure 4.2: Big picture of the PMP model

classification according to the users θ value is done, the quality q_i in each class i leads to an actual *user utility* and a achieved *revenue* can be evaluated.
The next part of this Section has a closer look on the *classification*, the *user utility* and the *pricing* in PMP.

Classification of User

In the classification phase the users decide whether to buy a service or not and which particular service they will take. This happens after the ISP has announced capacity and pricing details. In general, PMP partitions a network into several logically separate classes. Each class has a fixed fraction of the total capacity. For the two class case used by our model the fraction of the capacity allocated to the premium service is set by a network regulator with x, where $x \in [0, 1]$ (cf. Equations (4.1)). There exists several work on how to set x in the two-class-monopolistic-ISP case to maximize revenue [22, 31, 39]. Figure 4.3 illustrates the simplified classification process for this model. The bottom line represents the monopolistic ISP's total capacity c, where the partitioning follows Equations (4.1) as discussed previously. The upper line in Figure 4.3 illustrates the user, where each of the in total N user can be represented by his/her θ value on the line. User with a $\theta < p_1$ are not willing to pay the access price, if $p_1 \leq \theta < p_2$ user belong to class c_1, and $\theta > p_2$ the user is assigned to the premium class in c_2. As already discussed before, the users θ also describes a quality expectation. A user drops the service, if the quality q_i in the class c_i, where $i \in \{1, 2\}$ is lower than his/her expected quality (also represented by θ).

$$\begin{aligned} c_1 &= (1 - x) \cdot c \\ c_2 &= x \cdot c \end{aligned} \tag{4.1}$$

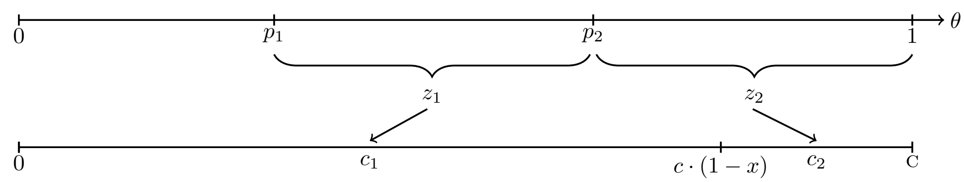


Figure 4.3: Simplified illustration of the classification process in PMP

The quality of service q_i (cf. Equation (4.2)) observed by the user is depending on the capacity c_i and z_i. Where the parameter z_i is the amount of traffic in either standard or premium class and can be calculated as the sum of applications (whether video or web) within one class $i \in \{1, 2\}$. The traffic causes congestion K_i which we model as the ratio of applications z_i and capacity c_i, $i \in \{1, 2\}$.

$$q_i = 1 - K_i = 1 - \frac{z_i}{c_i}, \quad i \in \{1, 2\} \tag{4.2}$$

Equation (4.2) implies that for a fully congested class the quality of service is zero, in other words the quality of the class decreases linearly with increasing congestion.
Like in [53] we assume that the user's willingness to pay and the required quality coincide, i.e., user are willing to pay more for better quality, thus we expect that, in most cases, price and quality requirements are highly correlated.

User Utility

The *utility* for the user, denoted by U_θ – or *user surplus* – in the network (cf. Equation (4.3)) depends on the quality of service q_i he/she receives and the difference between the price p_i he/she has to pay for the service and his/her willingness to pay (θ), only if the quality of service $q_i \geq \theta$.

$$U_\theta = (\theta - p_i) I(\underbrace{q_i - \theta}_{=\beta}), \ where \quad I(\beta) = \begin{cases} 1 & \text{if } \beta \geq 0 \\ 0 & \text{if } \beta < 0 \end{cases} \tag{4.3}$$

Thus the user utility U_θ as a way of quantifying aggregate user happiness in this model is given by two parts. First, a part depending on the access price p_i and second a simple step function $I(\beta)$, which takes into account the user's quality requirements and the actual quality in the class q_i. If a user adopts the network service for e-mail only, then he gains no extra utility from the fact that the actual network quality permits him to use streaming video (which he does not utilize). The maximum user utility can be 1 and in the worst case it is set to 0.

In the general case, for any probability distribution $p(\theta)$ of user types $\theta \in [0,1]$, the aggregated utility is given by $U_{total} = \int_0^1 U_\theta p(\theta) N d\theta$. With the assumption that user types are uniformly distributed in $[0,1]$ and let $U = \frac{U_{total}}{N}$ be the surplus per user in the base, then Equation (4.4) follows:

$$U = \int_0^1 U_\theta d\theta \tag{4.4}$$

For analysing PMP the term U_{sum} is calculated (cf. Equation (4.5)). U_{sum} is the sum of the utilities over all user Z adopting either the standard or the premium service. Note that Z is not equal N as not every user buys a service of class i.

$$U_{sum} = \sum_{n=1}^{Z} \sum_{i=1}^{2} (\theta_n - p_i) I(q_i - \theta_n) \tag{4.5}$$

Pricefinding

While the user utility can play a role in the pricefinding as we present in this section, it is definitely important for classification (i.e., a user who gains no utility from the service might change the service or generally opt out). The pricefinding process encompasses two actors as indicated in Figure 4.4: an ISP and an independent regulator. Pricefinding is a sub-game, where the ISP announces the prices p_1 for standard class and p_2 for premium class considering the regulator's choice variable x. This happens before the classification process can occur and is therefore called a sub-game. While in [53] several ISP are competing with each other, this work investigates the monopolistic case only. Shetty et al. in [53] showed that the

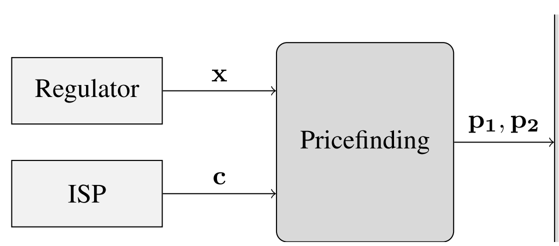


Figure 4.4: The pricefinding sub-game

access prices p_i, where $i \in \{1, 2\}$ must satisfy Theorem 1, a proof can be found in [53, 54].

Theorem 1 *For any fixed capacity c and any fraction x (4.6) must be satisfied.*

$$p_1(c, x) < \frac{1}{2} \quad \textit{and} \quad p_2(c, x) > \frac{1}{2} \tag{4.6}$$

In the absence of a regulator the ISP objective is to maximize revenue, in the presence of a regulating authority other ways to find the access prices might be required. For instance to maximize utility, or a combination of revenue and utility. This Section summarizes (a) revenue maximization from [53] and then illustrates (b) utility maximization and (c) social welfare maximization.

(a) **Revenue maximization**: The ISP's incentive primarily is to maximize his profit Π, which is basically the revenue minus the costs for capacity. In more detail the profit Π is the price p_i, either for the premium or basic service, times the number of user in the service z_i minus the unit costs per bandwidth τ times the capacity c (cf. Equation (4.7)).

$$\Pi = \max_{c,x,p_{i=\{1,2\}}} \left\{ \sum_{i \in \{1,2\}} p_i z_i - \tau c \right\} \tag{4.7}$$

While Shetty et al. in [53] and in further work relying on their model [54, 55] investigate the role of the unit costs for capacity τ on the system, especially on the ISP revenues, the fraction of capacity reserved for standard service, etc., this work concentrates stronger on the user utility aspects and has a look at the corresponding revenues. The next part shows the derivation of the optimal prices from revenue maximization, denoted by $p_1^\dagger$ and $p_2^\dagger$. For constant unit costs τ either revenue or profit maximization leads to the same results. The prices can be found by solving the maximization problem given by Equation (4.8), the proof of the results can be found in [53, 54].

$$R = \max_{c,x,p_i} \left\{ \sum_{i \in \{1,2\}} p_i z_i \right\} \tag{4.8}$$

As already mentioned above, each user is characterized with a certain QoS expectation $\theta \in [0, 1]$, where θ also reflects its willingness to pay. In the two class case users with types $\theta \in (\underline{\theta_1}, \overline{\theta_1}]$ adopt standard service 1 and users with types $\theta \in (\underline{\theta_2}, \overline{\theta_2}]$ adopt the premium service 2 respectively (i.e., $\theta_i \in (\underline{\theta_i}, \overline{\theta_i}]$ for $i \in \{1, 2\}$). Hence, a user adopts service $i \in \{1, 2\}$ only if $p_i < \theta \leq q_i$. This implies that all users with θ higher than p_i can afford the service and join the service if the quality is higher than some critical value of θ [53]. Thus the highest affordable access price of a class p_i can be expressed by $\underline{\theta_i}$ and the minimum quality q_i as given by Equation (4.2) represents the critical value $\overline{\theta_i}$. The quality q_i in class i depends on congestion and thus the number of applications z_i in the class has a strong impact (cf. Equation (4.2)). The term z_i corresponds to the number of user in the class, therefore $z_i = \overline{\theta_i} - \underline{\theta_i}$. Combining $z_i = \overline{\theta_i} - \underline{\theta_i}$ and Equation (4.2), Equation (4.9) can be derived.

$$\overline{\theta_i} = 1 - \frac{\overline{\theta_i} - \underline{\theta_i}}{c_i} \iff \overline{\theta_i} = \frac{c_i + p_i}{1 + c_i} \tag{4.9}$$

In the ISP optimum, $\overline{\theta_1} = \underline{\theta_2} = p_2^{\dagger}$, this implies that there is no gap between service classes, proof can be found in [53]. This ends up with:

$$\underline{\theta_1} = p_1^{\dagger}, \quad \overline{\theta_1} = \underline{\theta_2} = p_2^{\dagger}, \quad \overline{\theta_2} = \frac{p_2^{\dagger} + c_2}{1 + c_2} \tag{4.10}$$

Using Equation (4.9), the term z_i can be expressed as given in Equation (4.11).

$$z_i = (\overline{\theta_i} - \underline{\theta_i}) = \frac{p_i + c_i}{c_i + 1} - p_i \Rightarrow z_i = (1 - p_i)\frac{c_i}{1 + c_i} \tag{4.11}$$

The monopolistic ISP's revenue as given by Equation (4.8) simplifies for the two class case to $R = p_1 z_1 + p_2 z_2$, including the result from Equation (4.11) it ends up with Equation (4.12).

$$R = \underbrace{p_1 \frac{c_1}{1 + c_1}(1 - p_1)}_{\kappa} + p_2 \frac{c_2}{1 + c_2}(1 - p_2) \tag{4.12}$$

Where κ is a function of p_1 and the capacities only, and p_2 can be substituted with Equation (4.9) and Equation (4.10), where $\overline{\theta_1} = p_2 = \frac{p_1 + c_1}{1 + c_1}$. Then after a few steps the revenue can be expressed as a function of p_1, c_1 and c_2 only (cf. Equation (4.13)), where c_1 and c_2 can be expressed by c and x with Equation (4.1).

$$R = \kappa + \frac{(c_1 + p_1)c_2(1 - p_1)}{\underbrace{(c_1 + 1)^2 (c_2 + 1)}_{B}} \Rightarrow$$

$$R(p_1, c_1, c_2) = \frac{(1 - p_1)\left[A p_1 + c_1 c_2\right]}{B} \tag{4.13}$$

$$\text{with} \quad A = (1 + c_1)(1 + c_2)c_1 + c_2 \quad \text{and} \quad B = (1 + c_1)^2 (1 + c_2)$$

To find the optimal price $p_1^{\dagger}$ Equation (4.13) is differentiated w.r.t p_1 and ends up with

Equation (4.14).

$$\frac{dR(p_1, c_1, c_2)}{dp_1} = A - c_1 c_2 - 2Ap_1^\dagger \stackrel{!}{=} 0 \tag{4.14}$$

Further calculations, namely $\frac{dR(p_1,c_1,c_2)}{dp_1} = 0$ and solving for $p_1^\dagger$, were done with the help of MATLAB[1]. After $p_1^\dagger$ is determined, $p_2^\dagger$ can be calculated by inserting $p_2^\dagger$ in $p_2^\dagger = \frac{p_1^\dagger + c_1}{1+c_1}$.
The results for the optimal price $p_1^\dagger$ and $p_2^\dagger$ as a function of capacities only can be seen below in Equations (4.15-4.16). Note that $p_1^\dagger(c,x) < \frac{1}{2}$ and $p_2^\dagger(c,x) > \frac{1}{2}$ [53].

$$p_1^\dagger(c,x) = \frac{1}{2} - \frac{c_1 \cdot c_2}{2A} = \frac{1}{2} - \frac{c_1 \cdot c_2}{2\left[(1+c_1)(1+c_2)c_1 + c_2\right]} \tag{4.15}$$

$$with \quad A = (1+c_1)(1+c_2)c_1 + c_2$$

$$p_2^\dagger(c,x) = \frac{p_1 + c_1}{1 + c_1} = \frac{1}{2} + \frac{1}{2}\frac{(1+c_2)\cdot c_1^2}{(1+c_l)(1+c_h)cl + c_h} \tag{4.16}$$

(b) **Utility maximization**: Similar analytical calculations can be done to maximize the user utility U_θ. Utility has a major impact in PMP, especially investigating a stressed network situation, a high utility might prevent user from dropping out of the service. Setting $U_\theta = (\theta - p_i)$, which implies that the actual quality q_i in class $i \in \{1,2\}$ is higher than θ, and including the assumptions summarized in Equation (4.10) the integral from Equation (4.3) can be expressed as given below:

$$U = \int\limits_{\underline{\theta}_1 = p_1}^{\overline{\theta}_1 = p_2 = \underline{\theta}_2} U_{\theta_1} d\theta_1 + \int\limits_{\underline{\theta}_2 = p_2}^{\overline{\theta}_2} U_{\theta_2} d\theta_2 \tag{4.17}$$

Solving the integral results in Equation (4.18), note that $p_i = \underline{\theta}_i$.

$$U = \frac{1}{2}\left[\left(\overline{\theta}_1 - p_1\right)^2 - \underbrace{(\underline{\theta}_1 - p_1)^2}_{=0}\right] + \frac{1}{2}\left[\left(\overline{\theta}_2 - p_2\right)^2 - \underbrace{(\underline{\theta}_2 - p_2)^2}_{=0}\right]$$

$$U = \frac{1}{2}\left[\left(\overline{\theta}_1 - p_1\right)^2 + \left(\overline{\theta}_2 - p_2\right)^2\right] \tag{4.18}$$

Inserting $\overline{\theta}_1 = p_2 = \frac{c_1 + p_1}{c_1 + 1}$ and $\overline{\theta}_2 = \frac{c_2 + p_2}{c_2 + 1}$ the user utility U can be expressed as a

[1] http://www.mathworks.de/products/matlab/index.html

function of p_1, c_1 and c_2 only, Equation (4.19).

$$U = \frac{1}{2}\left[\left(\frac{c_1 + p_1 - p_1 c_1 - p_1}{1 + c_1}\right)^2 + \left(\frac{c_2(1 + c_1) + p_1 + c_1 - (c_1 + p_1)(1 + c_2)}{(1 + c_1)(1 + c_2)}\right)^2\right] \tag{4.19}$$

Differentiating $\frac{dU(x,c,p_1)}{dp_1} = 0$ and solving for $p_1^\dagger$ was again done with the help of MATLAB. No plausible results for $p_1^\ddagger(c, x)$ and $p_2^\ddagger(c, x)$ representing the optimal prices for user utility maximization can be found.

(c) **Social Welfare maximization**: Shetty et al. in [53] defined the social surplus S from a social planner's view as the sum of user utility U and provider profit Π, $S = U + \Pi$. To avoid confusion the *social welfare SW* is defined as the sum of the ISP's revenue R and the user utility U weighted by ζ, cf. Equation (4.20). Thus $\zeta \in [0, 1]$ can be seen as a factor tuning the influence of the utility U to the social welfare. A value $\zeta = 0$ means pure revenue, while growing ζ increases the effect of the user utility.

$$SW = R + \zeta U \tag{4.20}$$

While in [53] a regulator maximized different social surpluses e.g., $S_1 = \max_x\{U + \Pi\}$ to set the fraction of the premium class x appropriate and thus prevents the ISP to dedicate more than a fraction x of the whole capacity to the premium class, this work investigates a different approach. As before an outside party sets x, but additionally the regulator may prescribe the term ζ. The ISP maximizes the social welfare SW with the given ζ as stated in Equation (4.20) to set the optimal prices $p_1^\star$ and $p_2^\star$ accordingly, where R can be expressed as in Equation (4.13) and U as in Equation (4.19). With MATLAB the prices $p_1^\star(c, x, \zeta)$ and $p_2^\star(c, x, \zeta)$ were calculated and presented in Chapter 5. The optimal access prices $p_1^\star(c, x)$ and $p_2^\star(c, x)$ for $\zeta = 1$ are given in Equations (4.21-4.22).

$$p_1^\star(c, x) = \frac{1}{c_1 + c_2 + c_1 * c_2 + 2} \tag{4.21}$$

$$p_2^\star(c, x) = \frac{c_1 + \frac{1}{c_1 + c_2 + c_1 \cdot c_2 + 2}}{1 + c_1} \tag{4.22}$$

The PMP model presented in this Section is based on Shetty's work from [53]. Common is the assumption that the user's willingness to pay and the quality requirements coincide, represented by only one variable θ, the calculation of the utility with Equation (4.3), the presence of a regulating party and the revenue maximization part as well as the investigation of a network with two classes. This work differs to [53, 54] that the considered network is under stress, beside the ISP's revenue the utility plays a key role in finding the access prices p_1 and p_2 for standard and premium class (e.g., social welfare maximization). As [53] surveys the impact of the costs for capacity in detail, this work treats other issues. The main aspect of the detailed investigation of PMP is to provide feasible data to simplify the comparison with PARQUE, introduced in Section 4.3 and Section 4.4. In general PARQUE uses QoS provision similarly to PMP, but with an application specific classification process, due to mapping QoS in a QoE metric. Section 4.2 introduces the mapping, which is essential for all PARQUE proposals.

4.2 Relationship between QoS and QoE

To find a proper bidirectional mapping between QoS and QoE has been intensively investigated on in literature, e.g., [21, 65]. In this section, we construct such a mapping on the basis of two unidirectional mapping functions, i.e., a mapping from QoS to QoE in Subsection 4.2.1 and the converse mapping in Subsection 4.2.2.

4.2.1 Mapping QoS to QoE

Mapping QoS in QoE plays a key role in the following approaches. To find a fundamental relationship of the quality perceptions is still in the focus of current research. Former work showed that MOS values can be transformed into QoS values mathematically, e.g., *Law of Weber-Fechner* [48], or the *IQX Hypothesis* [21, 65]. The latter one describes the relationship between packet loss and QoE mathematically. Without loss of generality and because of existing data we define *packet loss* as our QoS metric. Please note that package loss can be substituted by any other QoS characterization, if a proper mapping function is known. In the following Internet traffic is categorized in video traffic, representing higher QoS requirements, and web traffic for lower one. Mathematically, the relationship can be expressed as shown in Equation (4.23) for video applications and Equation (4.24) for web applications. This behaviour is depicted in Figure 4.5.

$$QoE_{video} = 1.37 + 2.88\ e^{-395.7 \cdot p_{loss}} \tag{4.23}$$

$$QoE_{web} = 1.065 + 3.010\ e^{-4.473 \cdot p_{loss}} \tag{4.24}$$

In Figure 4.5 it can be seen that at a packet loss of $\approx 50\%$ both curves reach an unacceptable QoE level of approximately 1.5 MOS, and further increase of packet loss has little impact on the QoE. Figure 4.5 shows, and experimental set-ups at the Telecommunications Research Center Vienna (FTW) confirmed, that QoE for video traffic saturates remarkable early, already if a packet loss of $\approx 1\%$ occurs, it comes to heavy distortions. The faster decline of video traffic ratings may be explained by the higher interactivity and the inferred infeasibility to packet loss. A possible packet loss can't be replaced by resubmitting later, as this is probably the case for mail traffic. Although the impact of packet loss on the quality of a transmitted video is depending on the codec used and the curve might vary slightly from that illustrated in Figure 4.5, the impact remains doubtlessly higher for video application as for web traffic. Starting at packet loss values of 50% even a user waiting

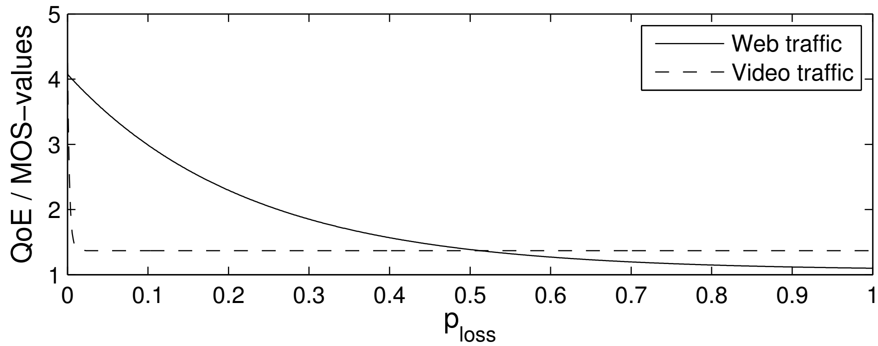


Figure 4.5: QoE-p_{loss}-mapping, [21, 65]

for web packets would typically lose the interest in using the service. For a proper QoS to QoE mapping the following two assumptions are made.

Assumption 1: The point of stabilization where the user ratings (modelled through the used QoE curves) tend to be insensitive to further quality impairments is called $p_{loss,max}$. The service provisioning at quality levels below $p_{loss,max}$ shall be generally avoided, as there may be no consumer interest. For further investigations $p_{loss,max}$ is set to $0.5 \mathrel{\hat{=}} 50\%$ as depicted in Figure 4.6.

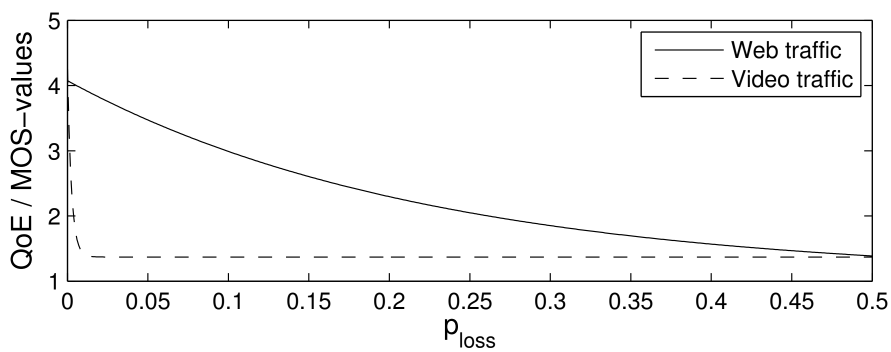


Figure 4.6: QoE-p_{loss}-mapping, with $p_{loss,max} = 0.5$

Assumption 2: In order to establish a QoE to QoS mapping, QoS is assumed to be the difference between the highest possible QoS level, i.e., QoS is 1, and the actual packet loss p_{loss} as given by Equation (4.25). Thus low packet loss implies high quality and vice versa in our model. Figure 4.7 illustrates this behaviour for web and video traffic.

$$QoS = 1 - p_{loss} \tag{4.25}$$

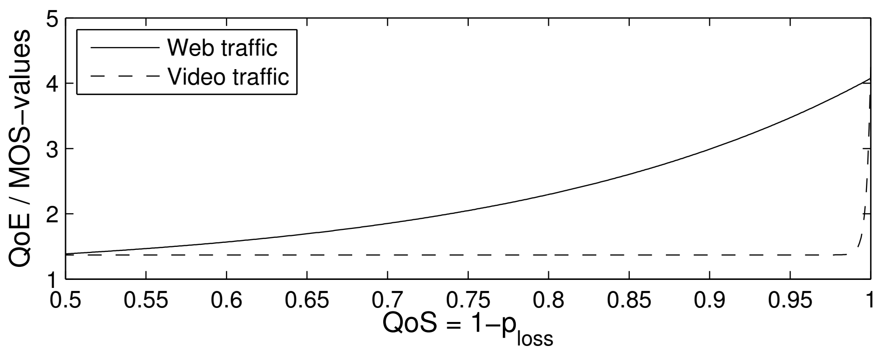


Figure 4.7: QoE-QoS-mapping, with $p_{loss,max} = 0.5$

In the models introduced below, QoS is characterized by the variable θ, where $\theta \in [0, 1]$, therefore a proper scaling is necessary to set the maximal packet loss $p_{loss,max}$ equal to 0 QoS. Our mapping procedure works as follows: Starting from a certain quality level θ with support to $[0, 1]$, by Equation (4.26) we get QoS values in the interval $[(1 - p_{loss,max}), 1]$ and these can then be transformed into QoE levels by the usage of Equation (4.23) for video applications and Equation (4.24) for web applications. The scaling as a function of $p_{loss,max}$ is depicted in Equation (4.26) and the effect of the scaling is depicted in Figure 4.8.

$$QoS = \theta \cdot p_{loss,max} + 1 - p_{loss,max} \tag{4.26}$$

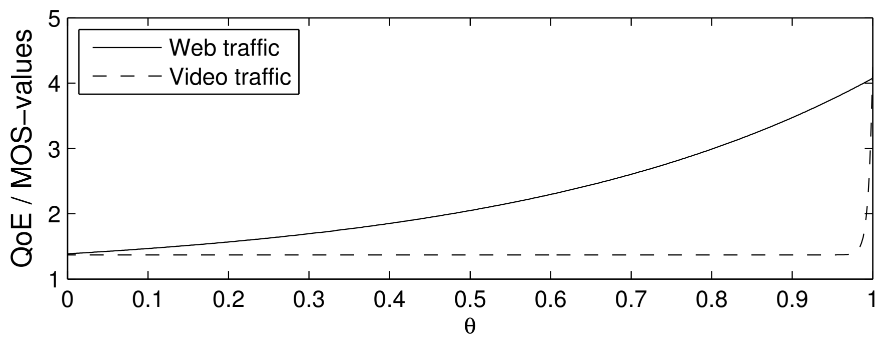


Figure 4.8: QoE-θ-mapping, with $p_{loss,max} = 0.5$

Further on, we introduce the symbol $\multimap\!\bullet$ representing a mapping from QoS into QoE. Hence, the expression thus $\theta \multimap\!\bullet\, \Phi$ formally describes the mapping from QoS values θ to corresponding QoE values Φ.

4.2.2 Mapping QoE to QoS

Mapping from a certain QoE level to a corresponding QoS level is achieved by using done the inverse functions of Equation (4.23) and Equation (4.24) for video and web applications. Consequently, the expression $\Phi \bullet\!\!\multimap \theta$ formally maps the QoE values Φ to the corresponding QoS values θ. Again a scaling function (cf. Equation (4.27)) is needed in order to infer a proper θ value in the used interval $[0, 1]$ from arbitrarily provided QoS value.

$$\theta = \frac{QoS - 1 + p_{loss,max}}{p_{loss,max}} \tag{4.27}$$

In this section we introduce a way to transform QoS to QoE and vice versa based on findings from user trials proposed in [21, 65]. This mapping provides the fundamental basis for the approach presented next.

4.3 QoS priced PARQUE

PARQUE is a novel approach for handling the enormous growth of Internet traffic without applying a traditional over-provisioning mechanism. It therefore uses QoS provisioning similar to PMP, but makes fundamental differences in the classification regarding the user and application types. This model differs from the conventional PMP by enabling an automatic and dynamic application-based QoS adjustment through holding the user's utility based quality level constant. Note that as in PMP quality (irrelevant if QoS or in PARQUE QoE) cannot be guaranteed by the ISP, but is assumed to be better in the higher priced channel due to a reduced demand leading to less congestion. The user's quality perception or QoE can be categorized in Mean Opinion Score values [21, 47, 65]. Therefore an essential issue in PARQUE is to find a proper way to map QoE in QoS and conversely, as discussed in Section 4.2. Mapping a set of independent technical QoS levels results, as the quality perception for the same QoS level would differ for different types of services, e.g., video is more sensitive to packet loss than web traffic, in different QoE values. PARQUE integrates this effect in the classification process. The name QoS priced PARQUE refers to a quality pricing optimized around stabilizing QoS values rather than QoE values. This implies that even though QoE plays a key role in PARQUE, the user still pays for QoS similar as in PMP (cf. Section 4.1).

In the following, QoS priced PARQUE is discussed in detail, starting with the big picture in the form of a simplified block diagram depicted in Figure 4.9. Our concept consists of two key processes, Mapping I and Mapping II. The interacting characters are illustrated as building blocks (i.e., User, ISP and Regulator) and there is an additional block representing the Internet traffic (i.e., Demand). In PARQUE we distinguish two quality levels illustrated in Figure 4.9 with different background color. In PARQUE the users' quality expectations are exquisitely stated on the QoE level, while the users' packets are classified on the QoS layer. Therefore, the main difference to PMP is that in PARQUE each **User** is characterized by Φ. Where Φ represents the user's random QoE expectation given in MOS-values, together with the user's willingness to pay for the service (cf. θ in PMP). We consider a division of the network in two QoS classes, where 1 stands for standard service and 2 for premium service. As in [53] an independent **Regulator** announces x, where x is the fraction of total capacity c dedicated to the premium class. A monopolistic **ISP** invests irreversible in capacity c and sets access prices p_1 and p_2 according to maximize its revenue, user utility or social welfare. Note that for social welfare maximization a regulator additionally sets ζ dedicating the influence of utility to the social welfare (cf.

Equation (4.20)). To make this approach comparable with PMP presented in Section 4.1, the access prices are set on the QoS level. This explains why this approach is denoted as QoS priced PARQUE.

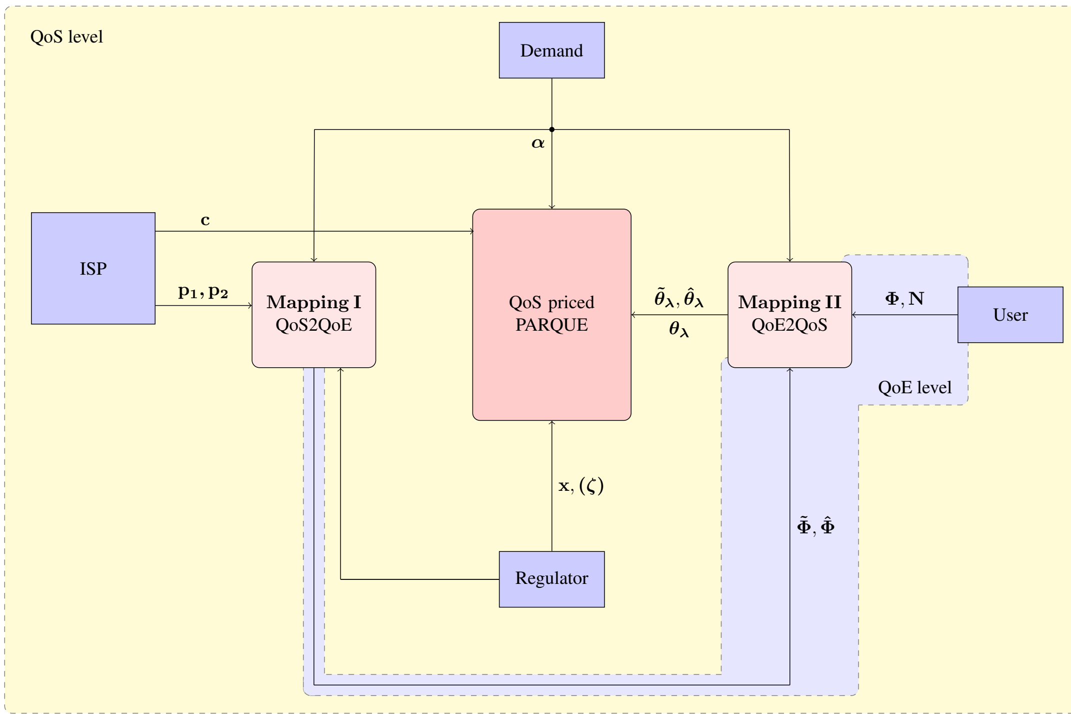


Figure 4.9: The big picture of QoS-priced PARQUE as block diagram

We assume that QoS and willingness to pay coincide [53], QoS is denoted by θ with support to $[0, 1]$, thus to be able to combine quality and pricing, the access prices p_1 and p_2 must be set within the same range, hence $p_1,\ p_2 \in [0, 1]$. If 1 indicates the standard and 2 the premium class, then $p_1 < p_2$ must be satisfied to obtain quality variations between this two segments. Another difference of this approach compared to the one introduced in Section 4.1 is that the **Demand** side distinguishes between two types of applications, video traffic and normal web traffic – representing higher QoS requirements for video than for the latter. The demand side in our approaches is characterized by the variable α as given in Definition 1.

Definition 1 (Alpha (α)) *The term α expresses the fraction of video applications of the total amount of traffic, while $(1-\alpha)$ represents the fraction of web applications respectively, i.e., $\alpha \in [0, 1]$.*

If α tends to 1 the whole demand consists of video traffic, for $\alpha = 0$ only web traffic occurs. Thus, from a total of N user $N \cdot \alpha$ utilizes applications of type video. Each user still contributes equally to the total amount of traffic (i.e., constant packet rate, constant demand), but satisfaction experienced by the user might vary with the application type.

The key element in PARQUE is doubtlessly the mapping, which we separate in two parts. First, **Mapping I** which maps QoS to QoE values (cf. Subsection 4.3.1.1). Second, **Mapping II** which transforms a vector of QoE values in QoS values as explained in Subsection 4.3.1.2. To this end a holistic view on the environment of QoS priced PARQUE is given in Section 4.3.2, where Equations modelling this approach are presented.

4.3.1 The Relationship of prices and Quality Requirements

This section explains the relevance and provides definitions and a precise description of Mapping I and Mapping II. The names for the mapping processes are chosen consciously to indicate two aspects. First, the mapping processes have different functionalities, e.g., Mapping I transforms QoS to QoE, while Mapping II maps conversely. Second, the number indicates the process sequence, i.e., Mapping II relies on the results of Mapping I. Subsection 4.3.1.1 provides a definition and a detailed survey of the Mapping I process, while Subsection 4.3.1.2 treats the Mapping II process.

4.3.1.1 Mapping I

Mapping I plays a key role in QoS priced PARQUE. Starting with the definition (cf. Definition 2) this section explains the role of Mapping I and illustrates the process by exemplary.

Definition 2 (Mapping I) *Let α be the fraction of video applications (cf. Definition 1) and p_i be the access prices (selfishly set by the ISP) which coincide with the QoS requirements θ (i.e., $p_i = \theta$), then the mapping from QoS to QoE can be formulated as follows in two variants: (i) the application sensitive mapping which determines QoE threshold values Φ as $QoE(\alpha, \theta)$ in the form of $QoE(\alpha, \theta) = \alpha \cdot QoE_{video}(\theta) + (1 - \alpha) \cdot QoE_{web}(\theta)$. This is also referred to as α-sensitive Mapping I. (ii) The linear Mapping I in form of $QoE(\theta) = (QoE_{max}(p_{loss,max}) - QoE_{min}) \cdot \theta + QoE_{min}$. The threshold values determined by the Mapping I process (i.e. $\tilde{\Phi}$ and $\hat{\Phi}$) serve for user classification on the QoE level. Where $\tilde{\Phi}$ expresses the limiting value for standard QoE class, while $\hat{\Phi}$ is the threshold between standard and premium QoE class.*

Briefly, the Mapping I process relates the ISP's pricing decisions to the QoE levels enabling a first classification of users on the QoE level. This assigns the users paying the premium or standard fees for service.

Similar to PMP, the monopolistic ISP sets access prices p_i for standard and premium QoS class $i \in \{1,2\}$. In the case where the users' willingness to pay and quality requirements coincide (i.e., $\theta = p$) then Mapping I transforms the access prices p_i to QoE level. QoE values are represented by the term Φ in MOS. In Figure 4.10 the inputs and outputs of the Mapping I are indicated. A price p_1, representing the access price for standard class, is mapped to a minimum QoE level $\tilde{\Phi}$. An access price for the premium class p_2 is mapped to $\hat{\Phi}$, hence $p_1 \multimap \tilde{\Phi}$ and $p_2 \multimap \hat{\Phi}$. Thus, from a total of N users, each characterized by his QoE expectation Φ, for all users where $\Phi < \tilde{\Phi}$ the service is not accept and affordable (i.e., the demand will remain unmet). Any user with $\Phi = \hat{\Phi}$ is indifferent whether to pay for premium or standard service. We assume that a user in the interval $\tilde{\Phi} \leq \Phi \leq \hat{\Phi}$ adopts the economy class and therefore pays p_1. While a customer with $\Phi > \hat{\Phi}$ adopts the premium class and pays the premium access fee p_2. Therefore, Mapping I transforms the ISP's pricing decision (i.e., p_i) to QoE thresholds to enable price discrimination on QoE level. It is the main challenge to find a proper mapping mechanism to achieve feasible results considering that slight changes in Mapping I have a huge impact on the whole system. Thus, for any access prices p_i, the outcome of Mapping I – $\hat{\Phi}$ and $\tilde{\Phi}$ – should achieve high ISP revenue and appropriate user utility.

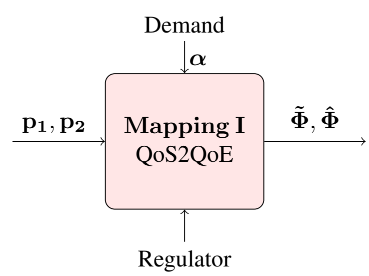


Figure 4.10: Mapping I

We target by investigating on the following three approaches (cf. Figure 4.11), which are all based on the input curves discussed in Section 4.2, [21, 65]. First, we propose a linear function which describes the relationship between QoE and QoS, characterized by the *Min* and *Max* values of a certain curve (e.g., of web traffic). This is labelled as *linear mapping* in Figure 4.11.

Second, *α-sensitve mapping*, where the demand, characterized by α affects the shape of the mapping curve. Equation (4.28) implies that if there are less video applications (i.e., α tends to be 0) then the mapping curve is dominated by the web applications' slope and for $\alpha = 1$ vice versa. The mapping curve for $\alpha = 0.5$ is depicted in Figure 4.11.

$$QoE(\alpha, \theta) = \alpha \cdot QoE_{video}(\theta) + (1 - \alpha) \cdot QoE_{web}(\theta) \tag{4.28}$$

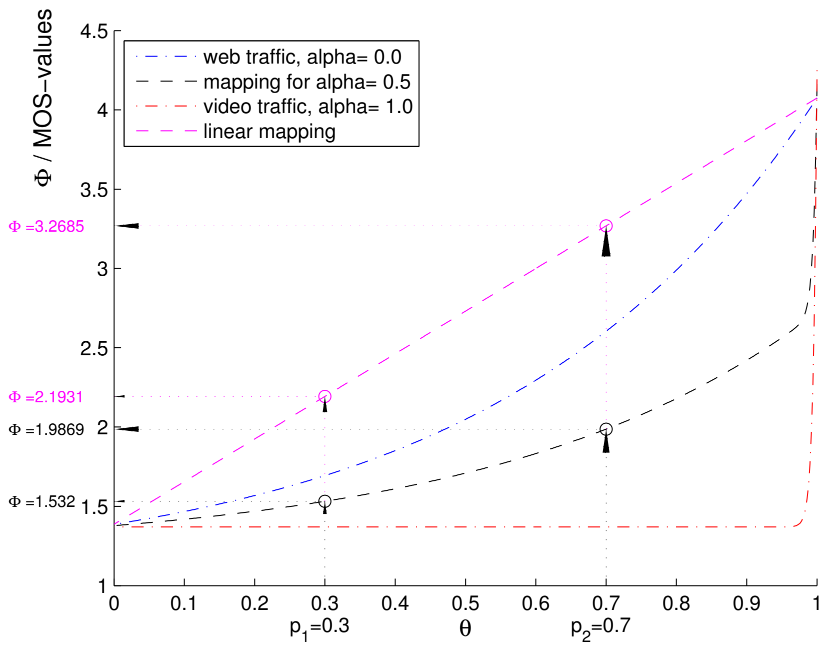


Figure 4.11: Mapping I by exemplary

Third, the mapping could be done by forming an arithmetic *mean value* between the video and web curve, note that this is equal to α-sensitve mapping for $\alpha = 0.5$. This approach differs from α-sensitive mapping that independent of the actual demand represented by α the curve does not change. Figure 4.11 depicts the mapping for $p_1 = 0.3$ and $p_2 = 0.7$ for linear and α-sensitive mapping and emphasizes the resulting difference. The investigation on applying different mapping strategies for the price limits p_1 and p_2 are intentionally left for further research. The effect of the Mapping I is further discussed in the Chapter 5.

4.3.1.2 Mapping II

This section surveys the Mapping II issue in detail, similar to Subsection 4.3.1.1 for Mapping I. Basically Mapping II transforms QoE to QoS requirements and is needed twice in QoS priced PARQUE (cf. Definition 3).

Definition 3 (Mapping II) *The Mapping II process describes the transition from users' QoE levels to QoS values, i.e., it maps a set of user characterising QoE expectations to QoS level according to their application types. Furthermore, it transforms the QoE thresholds to QoS values considering the keen differences between different applications. The corresponding values serve as threshold values in the following user classification process.*

Figure 4.12 shows the Mapping II block in detail, and inputs as well as outputs are indicated. Primarily it expresses the user characterising Φ values into application specific QoS values (i.e., θ). We differ between web and video applications denoted by $\lambda \in \{web, video\}$, where the number of video application is defined by $\alpha \in [0, 1]$ (cf. Definition 1).

Using the expression from Subsection 4.2.2, this correspondence can be written as $\Phi \multimap \theta_\lambda$, where $\lambda \in \{web, video\}$. This implies that a user's random QoE expectation Φ for a certain application type, e.g., $\lambda = video$ can be mapped to a QoS expectation θ_{video}. This must be done, because the actual classification process in PARQUE is still based on QoS values.

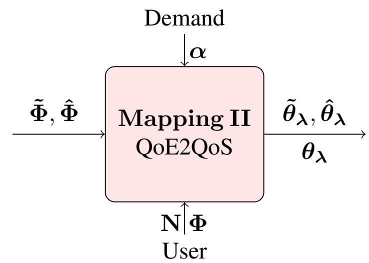
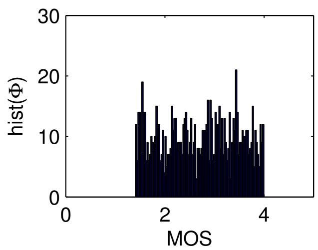


Figure 4.12: Mapping II

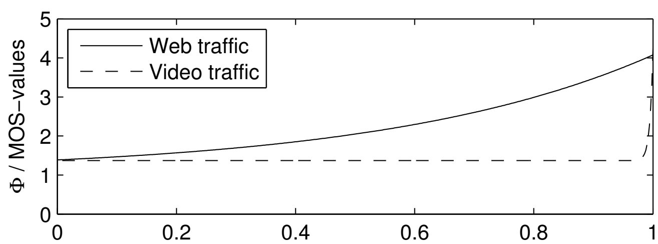
The second task of Mapping II is to calculate QoS based threshold values for classification. Note that for each application two threshold values are required, representing p_1 and p_2. Thus, for the two-class-two-application case (i.e., $i \in \{1, 2\}$ and $\lambda \in \{web, video\}$) four threshold values are generated. From Mapping I $\hat{\Phi}$ and $\tilde{\Phi}$ are known, then the Mapping II process expresses them in application specific QoS values, namely $\hat{\theta}_{vid}$, $\tilde{\theta}_{vid}$, $\hat{\theta}_{web}$ and $\tilde{\theta}_{web}$. This can be expressed as $\tilde{\Phi} \multimap \tilde{\theta}_\lambda$ and $\hat{\Phi} \multimap \hat{\theta}_\lambda$ for $\lambda \in \{web, video\}$ (cf. Figure 4.12). The input α to the Mapping II block is necessary to provide information from the demand side to map Φ accordingly, i.e., which Φ value represents video or web application.

Before we continue with further illustrating the Mapping II process, we briefly recapitulate the different usages for θ used throughout this work: In general θ expresses the users' QoS expectation and coincides with their willingness to pay, this important correlation makes the Mapping I feasible as $\theta = p$ is implied. In the conventional PMP model (cf. Section 4.1) some critical values of θ (i.e., $\underline{\theta}_i$, $\overline{\theta}_i$) define the thresholds of the interval $(\underline{\theta}_i, \overline{\theta}_i]$, where a user with a $\theta \in (\underline{\theta}_i, \overline{\theta}_i]$ adopts service $i \in \{1, 2\}$. Moreover, PARQUE introduces the differentiation between two application types $\lambda \in \{web, video\}$ which is inferred from the application sensitivity of QoE values (cf. Section 4.2). This is captured with the usage of the additional index λ. θ_λ are the application specific QoS representation of the users' QoE expectation, while $\tilde{\theta}_\lambda$ and $\hat{\theta}_\lambda$ represent application specific QoS thresholds. The outcome of Mapping II (i.e., $\tilde{\theta}_\lambda$, $\hat{\theta}_\lambda$ and θ_λ) is discussed below with the help of Figure 4.13 and Figure 4.14 to support better understanding.

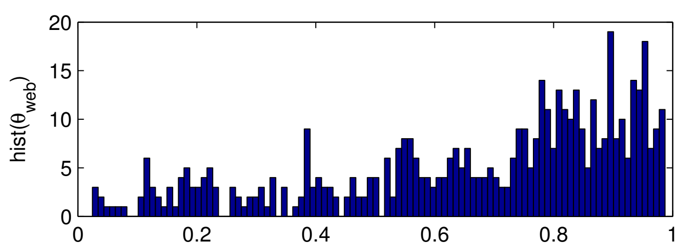
Figure 4.13 illustrates the mapping of a set of Φ values. Each of a total of $N = 1000$ user is characterized by a random Φ value, $\Phi \sim U(1.4, 4)$, depicted in Figure 4.13(a). Each user contributes with only one packet to the total demand, hence the number of user N equals the number of applications in the considered time interval. For the depicted case $\alpha = 0.5$, thus half of the applications are of type video and the other half is web traffic. Web applications are mapped following the blue curve and video applications with the green one in Figure 4.13(b). It can be seen in the histograms that the mapping has a strong impact on the QoS distribution. While QoS values for web applications θ_{web} are distributed over the whole QoS range (cf. Figure 4.13(c)), all video applications θ_{vid} lie in a narrow band of high QoS values (cf. Figure 4.13(d)).



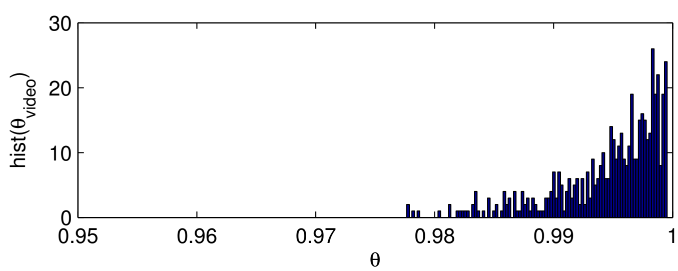
(a) Distribution of Φ



(b) Mapping curves for video and web traffic [21, 65]



(c) Distribution of θ_{web} after the mapping



(d) Distribution of θ_{video} after the mapping

Figure 4.13: Illustration of mapping Φ, for $\alpha = 0.5$ and $N = 1000$ user/applications

Because of the behavior illustrated in Figures 4.13 different threshold values for video and web applications are needed. The finding of these values is depicted in Figure 4.14 for the case of web traffic. We assume from Mapping I the values $\tilde{\Phi} = \Phi_{limit} = 1.5$ and $\hat{\Phi} = \Phi_{hat} = 2.7$ are known. Then we get for the web case $\tilde{\theta}_{web} \approx 0.135$ representing the threshold value for standard class and $\hat{\theta}_{web} \approx 0.727$ the threshold for premium class. This implies that the classification process for all web application is subject to these defined threshold values. The results are highly specific for a type of application, i.e., the alternative usage of video quality rating curves will render very different conclusions than stated above.

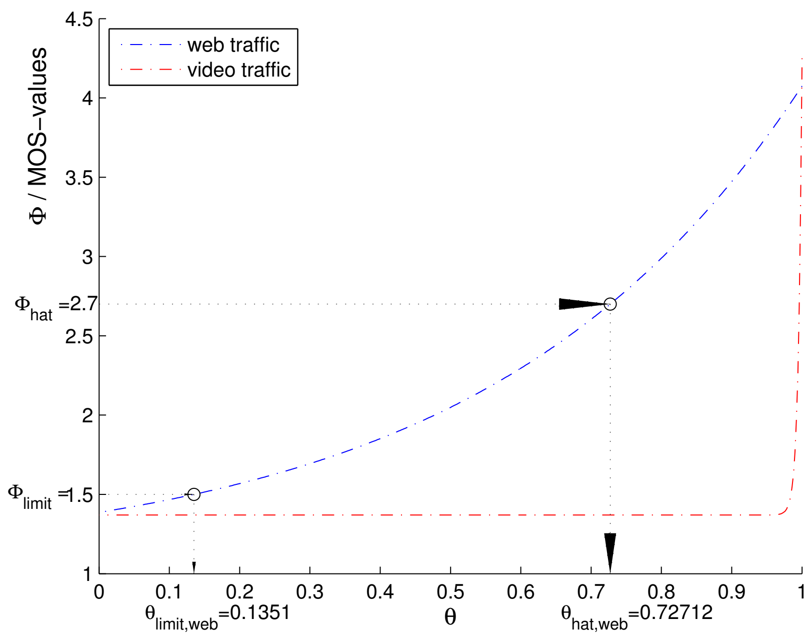


Figure 4.14: Mapping II by exemplary

4.3.2 Technical Model Setup

This subsection provides an in-depth outline on the QoS priced PARQUE approach and is organized according to [55] in Subsection 4.3.2.1 environment and Subsection 4.3.2.2 the order of moves.

4.3.2.1 Environment

First, the *classification* process on both levels (i.e., QoS and QoE level) is discussed. Second, we introduce a *Congestion Weighting Function* and its impact on *quality* and related the *user utility*. To this end we survey possible pricing mechanism for PARQUE. Last, we present the *order of moves* for the regulated case.

This model investigates the non-neutral behaviour of an ISP treating video traffic differently to web traffic – we call this *application differentiation*. Hence we distinguish the two applications video and web. We define Φ as the random MOS level expected from the end user. Thus Φ represents the stochastic end-users quality affinity, which is uniform distributed in the interval $\Phi \sim U(1.4, 4)$. From Φ the user and application specific values θ_{video} and θ_{web} can be derived, describing the minimal QoS-levels for video or web applications required by the end user – this was treated in Subsection 4.3.1.2 as a task of Mapping II. Let λ denote the application type, thus former transformation can be expressed as $\Phi \multimap \theta_\lambda$, $\lambda \in \{web, video\}$. In PARQUE two simultaneous classification occur. First, Φ is classified on the QoE level and second, θ_λ is arranged on the QoS level. This processes are discussed in detail below.

User Classification

The monopolistic ISP sets the access prices p_1 for standard and p_2 for premium class. As in Section 4.1 the index i denotes the QoS classes, where $i \in \{1, 2\}$. The access prices p_i are mapped with the Mapping I to QoE level, resulting in $\tilde{\Phi}$ and $\hat{\Phi}$ (cf. Subsection 4.3.1.1). Regarding the users expected utility based quality level Φ, user pay for premium class h, or l the basic class. This is depending on the certain threshold QoE-levels $\tilde{\Phi}$ and $\hat{\Phi}$ obtained before. When $\gamma \in \{l, h\}$ indicates the two QoE classes, then a classification on the QoE level is denoted by Equation (4.29).

$$\gamma = \begin{cases} l & \text{if } \tilde{\Phi} \leq \Phi \leq \hat{\Phi} \\ h & \text{if } \Phi > \hat{\Phi} \end{cases} \tag{4.29}$$

Equation (4.29) implies that a user within the given intervals either joins the standard QoE class l or the premium QoE class h. If Φ is lower than $\tilde{\Phi}$ then the user does not attend a service.

Application specific quality classification in PARQUE is still done on the QoS domain. But now instead of two thresholds as in PMP two values for each application are needed (cf. Subsection 4.3.1.2). These values are calculated by the Mapping II of $\tilde{\Phi}$ and $\hat{\Phi}$, ending up with $\hat{\theta}_\lambda$ and $\tilde{\theta}_\lambda$, for $\lambda \in \{web, video\}$. As shown in Equation (4.30) the congestion K_i of a QoS class i can again be expressed as the ratio of applications in this class z_i and the capacity of the class given by c_i [53].

$$K_i = \frac{z_i}{c_i}, \; where \quad i \in \{1, 2\} \tag{4.30}$$

The allocation to the class is now application specific and the access prices p_i have no direct influence. The usage of an application $\lambda \in \{web, video\}$ is attached to the standard class $i = 1$, if the application specific value θ_λ is within the specific thresholds (cf. Equation (4.31)):

$$\theta_\lambda \in z_1, \; if \quad \tilde{\theta}_\lambda \leq \theta_\lambda < \hat{\theta}_\lambda, \; for \quad \lambda \in \{web, video\} \tag{4.31}$$

And an application is transmitted in the premium channel iff Equation (4.32) is satisfied:

$$\theta_\lambda \in z_2, \; if \quad \theta_\lambda > \hat{\theta}_\lambda, \; for \quad \lambda \in \{web, video\} \tag{4.32}$$

Thus depending on the users mapped QoE expectations and very much on the kind of application θ_λ the application is dedicated to a QoS class.

Similar to PMP (cf. Section 4.1) we can express a user utility, where price and quality are affecting the outcome. In PARQUE we have to adopt a different calculation of the quality q_i of class $i \in \{1, 2\}$. In Section 4.2 the correspondence between a certain QoS value θ and the QoE value Φ is explained. [21, 65] express the relationship for packet loss and QoE for web and video applications. Therefore, θ is a function of packet loss as depicted in Figure 4.15. For PMP it was sufficient to express quality as a function of congestion K_i, but since PARQUE utilizes mapping based on packet loss, we have to transfer congestion to a packet loss metric. This could be done with the help of a *congestion weighting function* as introduced below.

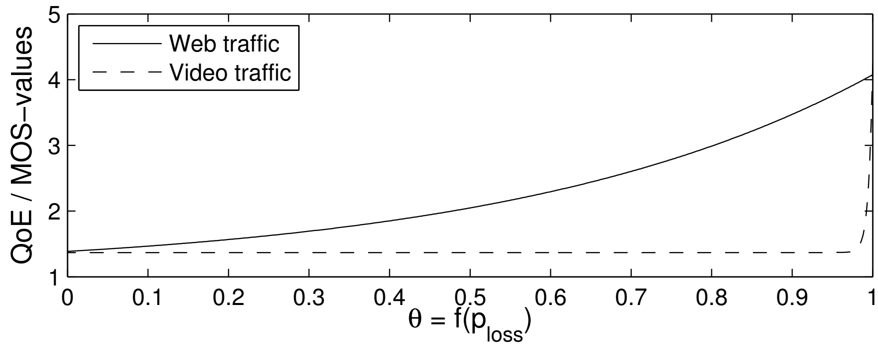


Figure 4.15: mapping curves, where θ is a function of packet loss

Congestion Weighting Function

Similar to practice, the QoS is highly dependent on congestion in our concept, i.e., if a class is congested it is very probable that failures occur, e.g., packet losses, delays. Here we distinguish between web and video traffic, each traffic requires a different QoS: for example, video needs very small delays and packet losses and e-mail can afford delay within a given bound [58]. Therefore the user characterisation θ in this approach describes the maximum tolerated packet loss (i.e., the minimum quality level) through quality preferences implicitly, as well as the implicitly inferred maximum tolerated congestion.

To adjust to the existing QoE curves (cf. Section 4.2) and without loss of generality we refrain from the congestion view and set *packet loss* as our QoS metric. To functionally translate congestion in packet loss a relationship between θ, where θ is a function of congestion, and QoE is needed.

Unfortunately, we could not observe any feasible work in literature, which evaluates the relationship between congestion of a link and the resulting packet loss. Nevertheless, it can be observed that a congestion of 50% does not represent a 50% impaired QoS. For that reason, the linear relationship of quality and congestion as in the PMP model has to be modified appropriatelyin order to enable the usage of packet loss. Therefore, a congestion weighting function $w(K_i)$ is added to the model. We found two possible ways to integrate such a congestion weighting into the quality expression (cf. Equation (4.2)), which are discussed next denoted by $w1$ and $w2$. First, a weighting function $w1(K_i)$ might be used to scale the congestion K_i, shown in Equation (4.33). Second, a weighting function denoted by $w2(K_i)$ could replace the congestion K_i as can be seen in Equation (4.34).

$$q_i = 1 - w1(K_i) \cdot K_i \quad with \quad i \in \{1, 2\} \tag{4.33}$$

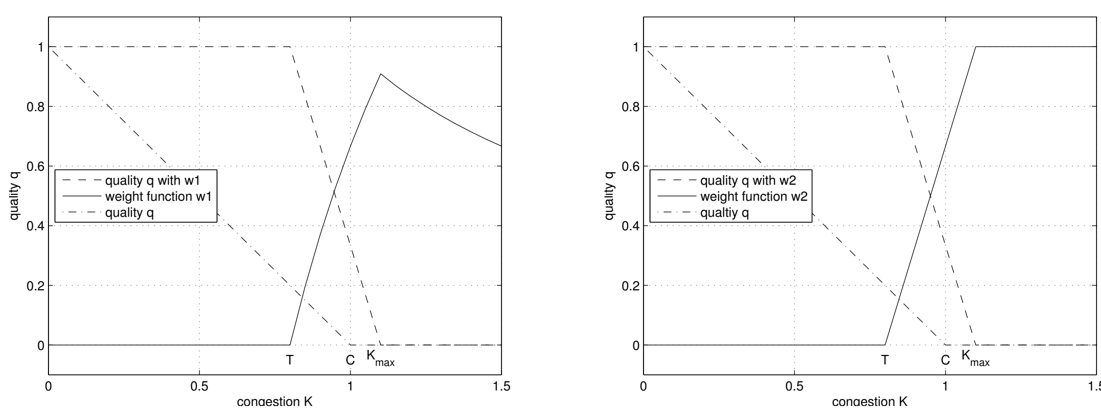
$$q_i = 1 - w2(K_i) \quad with \quad i \in \{1, 2\} \tag{4.34}$$

The function corresponding to $w1(K)$ is given in Equation (4.35) and $w2(K)$ is described in Equation (4.36). The term K is the congestion, T is the throughput of a link and K_{max} stands for a threshold congestion value, where no user receives packets with certain quality and thus gains no surplus.

$$w1(K) = \begin{cases} 0 & \text{if } K \leq T \\ \frac{-T}{K} \cdot \frac{1}{K_{max}-T} + \frac{1}{K_{max}-T} & \text{if } T < K \leq K_{max} \\ \frac{c}{z} & \text{otherwise} \end{cases} \tag{4.35}$$

$$w2(K) = \begin{cases} 0 & \text{if } K \leq T \\ \frac{K-T}{K_{max}-T} & \text{if } T < K \leq K_{max} \\ 1 & \text{otherwise} \end{cases} \tag{4.36}$$

Note that the outcome (i.e., the quality q) is equal independent which congestion weighting function is used. In Figure 4.16(a) the congestion weighting function $w1(K)$ and the resulting quality q are shown being subject to congestion K. Figure 4.16(b) depicts the case for $w2(K)$. In both Figures 4.16 the linear relationship between quality and congestion over the whole range as used in the previous PMP model is depicted. We assume, as congestion



(a) Weighting function $w1(K)$ (b) Weighting function $w2(K)$

Figure 4.16: Quality q with weighting functions $w1$ and $w2$ being subject to the congestion K

of a link as well as packet loss of a link both are related on the throughput of a link, the latter might be a possible way to connect both metrics. The throughput T characterises the actual possible data to be transmitted over a link and we denote the throughput T

in PARQUE as data packets per considered time slot. For a congestion below a certain threshold value – denoted by *throughput* T – there is no noticeable quality reduction. The throughput of a link among other factors depends on the *Internet Protocol (IP)* , for *TCP* it can be estimated by Equation (4.37), widely known as *Mathis Equation*. Mathis et al. in [36] showed that the throughput for TCP depends on the Maximum Segment Size (MSS), Round trip delay (RTT) and the probability of packet loss p. There is no dependency on the link capacity c although it is obvious that $T < c$. A useful overview on this issue has been provided by Terry Slattery[2].

$$T \leq \frac{MSS}{RTT} \cdot \frac{1}{\sqrt{p}} \quad for \quad p > 0 \tag{4.37}$$

As demand further increases we assume packet loss to increase linearly till a certain threshold K_{max}. While [53] considers the maximum congestion to be 1, this model also investigates the effects of overload on a link, e.g., 110% load, as even in a full link or slightly overloaded link the overall utility may not be zero.
To the best of my knowledge, there is no direct possibility to express packet loss in terms of congestion. Therefore we rescale the calculated congestion K into more feasible values in the scene of packet loss occurrence. The relationship up to a certain value, denoted by the throughput T no packet loss is expected to occur, where $T < c$. With increasing traffic, hence increasing congestion in the considered capacity c, the possibility for packet loss increases.

This part introduced a congestion weighting function which is needed to express quality in terms of packet loss. In the following the weighting function $w1(K_i)$ is used for calculations and is integrated in the utility calculation according to Equation (4.33). Utility plays an important role in PARQUE, it reflects the customer satisfaction with regard to the ISP's pricing decision and quality. Now we outline the method to express user utility QoS priced PARQUE in detail.

User Utility

We distinguish between two independent classes, first the QoE-classification denoted by the term $\gamma \in \{l, h\}$ and second the QoS classes with indices $i \in \{1, 2\}$ respectively. While users now express their quality expectations in MOS values, the classification process for PARQUE still remains on the QoS level. The utility obtained by the user can be expressed as a function of the price $p_i(\gamma)$ and the quality of the class q_i. The price $p_i(\gamma)$ a user in a

[2]Terry Slattery, CCIE, `http://www.netcordia.com/community/blogs/terrys_blog/archive/2009/08/10/tcp-performance-and-the-mathis-equation.aspx`

certain QoE class denoted by $\gamma \in \{l, h\}$ has to pay for service i, results of the user's QoE affinity Φ. Equation (4.38) follows the approach used in [53], but with some key differences described below.

$$U_\Phi = (\theta_\lambda - p_i(\gamma)) I(\underbrace{q_i - \theta_\lambda}_{=\beta}) \tag{4.38}$$

$$where \quad I(\beta) = \begin{cases} 1 & \text{if } \beta \geq 0 \\ 0 & \text{if } \beta < 0 \end{cases}$$

The first part again models the price sensitivity of the users utility, where the term θ_λ in Equation (4.38) functionally maps QoE values in QoS values and indicates that θ is depending on the application types represented by $\lambda \in \{web, video\}$. The second part takes the actual QoS of the class i into account. The term q_j describes the QoS of the class $i \in \{1, 2\}$, note that the QoE class has no influence on the quality aspect. Although the user pays for his QoE expectations we transfer the user's utility as shown in Equation (4.38) to QoS characteristics. From the end-user point of view QoS characteristics are unessential, but ISP require them for technical realisation and in order to measure network performance.

The next part discusses how pricing in QoS based PARQUE could be realised.

Pricing

Less attention has been paid to existing work investing the ISP's optimal pricing mechanism for utility-based quality differentiation. Because of the present dominance in reality this work concentrates on the investigation of (a) *flat rate pricing*. Other pricing schemes would be also possible to implement, (b) *application and class specific pricing* or (c) quality of service distinction, and are therefore introduced.

(a) **Flat rate pricing**:

Flat rate pricing as a very simple pricing scheme is suggested for pricing QoS differentiation in a variety of related work e.g., [31, 39, 53]. Flat rate pricing refers to a scheme that charges a fixed fee and is independent of the user's demand. Unlike to [53], where the user pays for a certain guaranteed QoS level, in this model the user pays for a QoE level. For the two QoS-class case, the ISP offers two flat rate prices, e.g., p_1 and p_2 and the threshold between this prices is a certain value for utility based quality (e.g., MOS-Value), namely $\hat{\Phi}$. A user with type Φ has to pay the higher price, if it's

MOS-Value is greater than the threshold value and conversely, thus depending on the MOS-Value the user has to pay the price $p_i(\gamma)$. With the term $\gamma \in \{l, h\}$ introduced in the previous Section the price $p_i(\gamma)$ can be expressed as in Equation (4.39),

$$p_i(\gamma) = \begin{cases} p_1 & \text{if } \gamma = l \\ p_2 & \text{if } \gamma = h \end{cases} \tag{4.39}$$

The ISP's revenue in this case is given by Equation (4.40).

$$R = \sum_{\gamma \in \{l,h\}} z_\gamma \cdot p_i(\gamma) \tag{4.40}$$

where z_γ is the number of user in the QoE class γ. This work investigates numerically how to set p_1 and p_2 according to maximize revenue R and user utility U_Φ. Note that in QoS priced PARQUE the setting of the access prices p_i for $i \in \{1, 2\}$ has an impact on both, the QoS classification and the QoE classification due to Mapping I and Mapping II.

(b) **Application and quality class specific pricing**:
In this scenario the sort of application denoted by $\lambda \in \{web, video\}$ and the end user's required QoE denoted by Φ contribute to the pricing. The corresponding price is named $p(\mu) = p(\lambda, \Phi)$. Let us assume that the consumer defines his minimum MOS-value in the contract with the ISP, thus the ISP can charge a higher price for MOS-values above a certain threshold $\hat{\Phi}$ similarly to (a). But now the ISP additionally distinguishes between the applications and asks for a higher price for video traffic, than for web traffic. This results in 4 prices, given in Equation (4.41),

$$p(\mu) = \begin{cases} p_{h,video} & \text{if } \gamma = h \text{ and } \lambda = video \\ p_{l,video} & \text{if } \gamma = l \text{ and } \lambda = video \\ p_{h,web} & \text{if } \gamma = h \text{ and } \lambda = web \\ p_{l,web} & \text{otherwise} \end{cases} \tag{4.41}$$

where γ denotes QoE class and λ the application type.

(c) **Quality of Service pricing**:
This method is based on the idea that the price is increasing e.g., linearly, with increasing QoS. Thus a user pays the price $p(\theta)$ depending on his specific θ. A user with high QoS requirements has to pay accordingly more for the corresponding network service

provisioning. The expression for price $p(\theta)$ for the linear case might look like

$$p(\theta) = p_{fix} + p_{variable}\theta \tag{4.42}$$

where p_{fix} represent a fixed part and $p_{variable}$ can be seen as variable costs.

To maintain comparability to PMP from Section 4.1, but without loss of generality we concentrate on (a) flat rate pricing. Another reason for adopting this simple scheme is that there exists a user preference for flat rate pricing, [39]. More information and the pros and cons of adopting flat rate pricing can be found in Chapter 3.
The last part of this subsection outlines the order of moves in the presence of a regulator and illustrates how to compute the ISP's actions (investments, prices). This is done according to [55].

4.3.2.2 The Order of Moves and Regulation

First, a regulating authority sets the fraction of the premium class x. Then a monopolistic ISP invests irreversible in capacity c. As in PMP, upon observing the capacities c_i the monopolistic ISP plays a subgame, in which he makes pricing decisions p_i for $i \in \{1, 2\}$. The assumption that for the two service class case the ISP choose its prices *after* observing the capacity is justified by Shetty et al. in [55] by the "scale of the required initial investments". ISP's investments are longer-term investments in infrastructure and thus harder to adjust in contrast with the prices which are in reality relatively easy to adjust. We investigate three methods how an ISP can determine the access prices, and follow the PMP approach (cf. Section 4.1). First, the ISP could maximize its revenue and sets the access prices accordingly. Second, we investigate the case if user utility is maximized. Third, social welfare maximization (i.e., maximizing Equation (4.20)), where an independent regulator sets ζ. Due to the increased complexity of this approach compared to PMP no analytical results for the optimal access prices could be calculated. This issue undergoes numerical analyzes instead.
Aware of the access prices the users set their QoE expectations Φ. In QoS priced PARQUE a regulator or the ISP itself must choose a Mapping I method, e.g., α-sensitive. Gathering all these information the classification on the QoS and QoE level can occur and revenue and utility calculated.

4.4 QoE priced PARQUE

Based on the QoS priced PARQUE from Section 4.3 we now investigate a different approach what we call *QoE priced PARQUE*. We propose an advanced model, which is dedicated to the optimisation of the mapping and pricing issue. Price discrimination in this approach is based on quality as perceived by the end user (i.e., QoE), as proposed by e.g., [47]. Here an ISP directly sets the prices p_γ for the QoE classes $\gamma \in \{l, h\}$. Therefore the effort of the required mapping process can be reduced compared to QoS priced PARQUE (cf. Section 4.3).

In this section we describe the big picture of this advanced approach (cf. Figure 4.17). Our concept consists of the following building blocks. Three blocks (i.e., *demand*, *user* and *regulator*) remain unchanged compared to QoS priced PARQUE, described in Section 4.3.

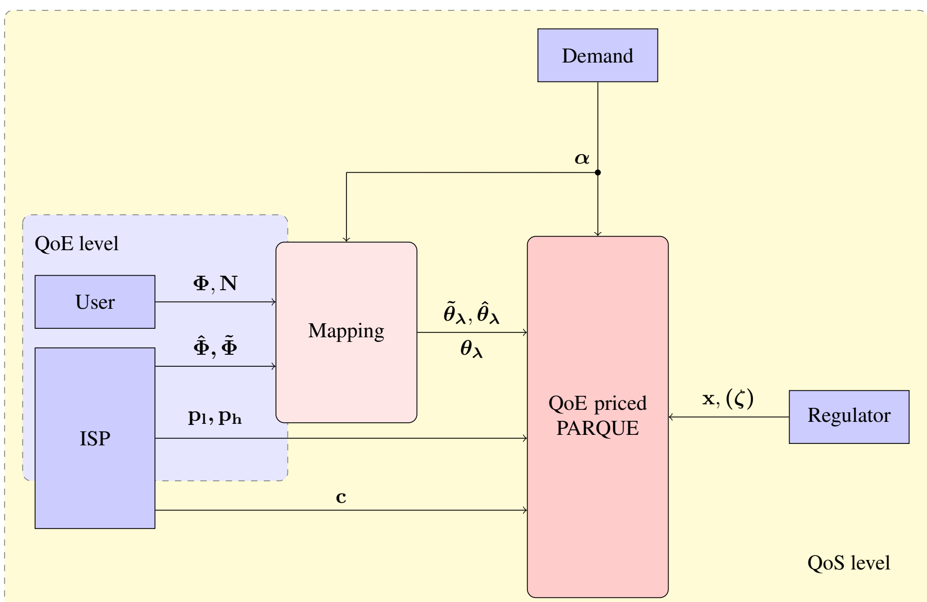


Figure 4.17: The big picture of QoE priced PARQUE

Demand side distinguishes between two types of applications denoted by $\lambda \in \{web, video\}$. The fraction of video applications is modelled by α, where $\alpha \in [0, 1]$. Each, from a total of N **User** is characterized by its QoE expectation Φ. In the considered time interval each user contributes with only one packet to the total Internet traffic. An independent **Regulator** sets x, representing the fraction of the total capacity c allocated to the premium segment, where $x \in [0,1]$. The monopolistic **ISP** first invests in capacity c and then sets the QoE based prices p_γ, where $\gamma \in \{l,h\}$ and additionally sets the threshold values $\tilde{\Phi}$ and $\hat{\Phi}$ for the QoE classification. As the classification process occurs still on QoS level a **Mapping** is required. In QoE priced PARQUE only a functional mapping from QoE to QoS is needed. Gathering all the informations on the QoS level applications can be allocated in one of the two QoS classes $i \in \{1,2\}$ according the users' requirements. Analysing the network we pay our attention to the monopolistic ISP revenue and the user utility. In Subsection 4.4.1 QoE priced PARQUE is depicted in more detail and especially differences to QoS priced PARQUE are indicated.

4.4.1 Environment

This subsection discusses the *classification process* in QoE priced PARQUE and shows how the *revenue* can be calculated, if flat rate prices for QoE levels are adopted. To this end we investigate the *user utility*.

The environment is very similar to QoS priced PARQUE. While applications are classified on the QoS level, price discrimination is based on the users' QoE expectations.

Classification

From a total of N user, each user is categorized by his QoE expectations Φ in a QoE class $\gamma \in \{l,h\}$ regarding two threshold values, i.e., $\hat{\Phi}$ and $\tilde{\Phi}$. Equation (4.29) from Section 4.3 is still valid in QoE priced PARQUE. This model differs from QoS priced PARQUE that the ISP directly sets this threshold values (i.e., $\hat{\Phi}$ and $\tilde{\Phi}$) as well as the corresponding prices p_γ for standard and premium QoE class, $\gamma \in \{l,h\}$.
The classification on the QoS level is equal as in QoS priced PARQUE from Section 4.3. The threshold values are mapped to application specific QoS values, i.e., $\tilde{\Phi} \multimap \tilde{\theta}_\lambda$ and $\hat{\Phi} \multimap \hat{\theta}_\lambda$ for $\lambda \in \{web, video\}$. Also the users' QoE expectation Φ is mapped to a corresponding QoS expectation θ_λ according their application types $\lambda \in \{web, video\}$. Then QoS classification is done according to Equation (4.31) and Equation (4.32).
After the QoE classification we can calculate the ISP revenue, discussed next.

Revenue

User with a certain Φ so that $\tilde{\Phi} \leq \Phi \leq \hat{\Phi}$, hence $\gamma = l$ pay the price p_l for the standard QoE class. A user pays the premium fee p_h, if $\gamma = h$ and $\Phi > \hat{\Phi}$ respectively. The ISP revenue in QoE priced PARQUE is given by Equation (4.43).

$$R = \sum_{\gamma \in \{l,h\}} z_\gamma \cdot p_\gamma \tag{4.43}$$

The term z_γ is the sum of all user in the QoE class $\gamma \in \{l, h\}$ and p_γ represents the price for the QoE class.
In the following part we discuss the end user utility in QoE priced PARQUE.

User Utility

The users' utility U_Φ in QoE priced PARQUE can be expressed by Equation (4.44). The term γ in $\theta_\lambda(\gamma)$ denotes that only user within the QoE class γ pay the according fee p_γ, where $\gamma \in \{l, h\}$. Note that although the prices p_γ are for a certain QoE level, they are with support to $[0, 1]$ to ensure that the term $(\theta_\lambda(\gamma) - p_\gamma)$ is positive in the utility expression.

$$U_\Phi = (\theta_\lambda(\gamma) - p_\gamma)\, I(\underbrace{q_i - \theta_\lambda}_{=\beta}) \tag{4.44}$$

$$where \quad I(\beta) = \begin{cases} 1 & \text{if } \beta \geq 0 \\ 0 & \text{if } \beta < 0 \end{cases}$$

The term q_i represents the quality in the QoS class $i \in \{1, 2\}$ and models the user's quality satisfaction as 1 if quality q_i is higher than the QoS expectation θ_λ, or 0 else.

4.5 Comparison and Conclusions

This work has analyzed the following three different quality pricing approaches: First *classic PMP* based on a model from [53] was introduced in detail (cf. Section 4.1) as it provides a common framework for both PARQUE versions. In Section 4.3 we introduced *QoS priced PARQUE* as a novel approach to deal with the increasing Internet demand. Based on QoS priced PARQUE, but with some key differences in the pricing we introduced *QoE priced PARQUE* in Section 4.4. This section provides a comparison between this three approaches on the following dimensions: In (a) we survey the underlying concept, (b) shows how user are characterized and (c) gives an overview on the pricing methods. (d) explains the role of the different applications in each approach and in (e) we survey the different classification processes. The mapping is illustrated in (f) and finally (g) explains whether congestion weighting is necessary or not.

(a) **Concept Setup**:
The basic idea for both PARQUE approaches is to achieve – similarly to PMP [39, 53] – a QoS differentiation as a side effect of the ISP's pricing decisions. PARQUE differs from PMP by centering pricing decisions on QoE considerations. The novel PARQUE approaches differ from each other from the pricing aspect as per particular given below in (c). A detailed description of PMP can be found in Section 2.5. QoS priced PARQUE is a novel approach, where similar to PMP the pricing has an impact on QoS and prices are set for certain QoS parameters. Additionally QoE plays a key role and a resulting application differentiation improves QoS classification. Although, QoE priced PARQUE is similar to QoS priced PARQUE, it is a different approach where an ISP sets prices for QoE classes instead of QoS. Table 4.1 gives an overview of the underlying concept of both PARQUE versions.

QoS priced PARQUE	*QoE priced PARQUE*
• pricing has impact on QoS • QoE influences in user classification • includes application differentiation • prices set for QoS	• similar to QoS priced PARQUE pricing has an impact on QoS • prices set for QoE

Table 4.1: Conceptual setup of both PARQUE approaches

(b) **User Characterization**:

In PMP – according to [53] – each user is characterized by his QoS expectation θ, while in PARQUE each user is characterized by a QoE value Φ instead. The variable θ coincides the user's willingness to pay for adopting the service i and the quality perception of service $i \in \{1, 2\}$. Hence, the latter part can be seen as the quality required for the most quality-intensive application utilized by the end-user. θ is a random variable uniformly distributed with support to $[0, 1]$, which represents a commonly used user preference in such context [3, 53, 59]. For the PARQUE approaches we assume the users' QoE expectation to be equally distributed in the interval $[1.4, 4]$ representing MOS values. Table 4.2 quickly reviews the user characterizations used in the different approaches.

conventional PMP	*QoS priced PARQUE*	*QoE priced PARQUE*
• $\theta \sim U(0, 1)$ • represents QoS expectations • coincides the user's willingness to pay	• $\Phi \sim U(1.4, 4)$ • represents QoE expectations	• $\Phi \sim U(1.4, 4)$ • represents QoE expectations

Table 4.2: User characterization

(c) **Pricing**:

Pricing composes an essential part in all three approaches. In general, a user pays a price per considered unit time for the access to the Internet. Hence Gibbens et al. in [22] speak of *subscription-based* rather than usage-based prices, where for the latter case prices would be dependent upon data volume transmitted.

In PMP and QoS priced PARQUE the monopolistic ISP sets access prices p_i for each QoS class, in our two class case $i \in \{1, 2\}$, but QoS priced PARQUE differs from PMP that price discrimination is based on quality as perceived by the end-user as suggested e.g., in [47] rather than QoS. Therefore, a mapping is needed as discussed below in (f). On the contrary, in the advanced PARQUE version – QoE priced PARQUE – an ISP directly sets prices p_γ for both considered QoE classes $\gamma \in \{l, h\}$. Table 4.3 surveys the pricing issue.

	conventional PMP	*QoS priced PARQUE*	*QoE priced PARQUE*
ISP sets	prices p_i for QoS classes $i \in \{1, 2\}$	prices p_i as in PMP	directly prices p_γ for QoE classes $\gamma = \{l, h\}$
price discrimination	on QoS level	on QoE level	on QoE level

Table 4.3: Pricing

(d) **Applications**:

Generally we distinguish between *web* application representing low quality requirements and *video* – as quality-intensive applications – denoted by λ, where $\lambda \in \{web, video\}$. While in PMP the application type has no influence on the classification process, we introduce in both PARQUE approaches an application based QoS differentiation. Therefore, because the application type directly influences the outcome of the mapping QoE to QoS (cf. (f) mapping) and the user classification (cf. (e) user classification) is still based on the QoS level, it has an impact on the classification process. Table 4.4 summarizes the impact of the different applications in the considered approaches.

conventional PMP	*QoS priced PARQUE*	*QoE priced PARQUE*
no influence on the classification nor user utility	applications influence QoS *classification*	
	two different application types $\lambda \in \{web, video\}$	

Table 4.4: The influence of application types

(e) **User Classification**:

In all approaches we consider a network with two QoS classes $i \in \{1, 2\}$, where actual classification occurs between this two QoS segments according the users' type θ. While in PMP the classification is done considering two common thresholds $\tilde{\theta}$ and $\hat{\theta}$ (i.e., independent of the application type). We classify in both PARQUE approaches according to application specific limiting values, denoted by the term λ, i.e., $\tilde{\theta}_\lambda$ and $\hat{\theta}_\lambda$ for $\lambda \in \{web, video\}$.

Additionally in PARQUE a second classification is done on the QoE level for price discrimination. Table 4.5 summarizes the classification process.

	conventional PMP	*QoS priced PARQUE*	*QoE priced PARQUE*
decision basis	θ	Φ	Φ
Assignment of QoS level	in class $i \in \{1,2\}$ according access prices p_i	in class $i \in \{1,2\}$ according to application specific thresholds $\hat{\theta}_\lambda$, $\tilde{\theta}_\lambda$	in class $i \in \{1,2\}$ according to application specific thresholds $\hat{\theta}_\lambda$, $\tilde{\theta}_\lambda$
Assignment of QoE level	none	in class $\gamma \in \{l,h\}$ according to mapped p_i (cf. Mapping I) for price discrimination	in class $\gamma \in \{l,h\}$ according to thresholds $\hat{\Phi}$, $\tilde{\Phi}$ directly for price discrimination

Table 4.5: The user classification process

(f) **Mapping**:

Mapping plays a key role in PARQUE and is done utilizing the findings of [21, 65]. See Section 4.2 for a detailed overview on the mapping issue. For QoS priced PARQUE a mapping in two steps is necessary, i.e., Mapping I and Mapping II. While Mapping I transforms the ISP's prices p_i to QoE levels (cf. Definition 2), Mapping II QoE expectations to QoS level for classification (cf. Definition 3). In QoE priced PARQUE only an application specific transformation from QoE to QoS is needed. Table 4.6 briefly surveys the mapping issue.

	conventional PMP	*QoS priced PARQUE*	*QoE priced PARQUE*
Mapping I	not required	$p_1 \multimap \tilde{\Phi}$, $p_2 \multimap \hat{\Phi}$	not required[2]
Mapping II[1]	not required	$\Phi \,\bullet\!\!-\!\!\circ\, \theta_\lambda$ $\tilde{\Phi} \,\bullet\!\!-\!\!\circ\, \tilde{\theta}_\lambda$, $\hat{\Phi} \,\bullet\!\!-\!\!\circ\, \hat{\theta}_\lambda$	$\Phi \,\bullet\!\!-\!\!\circ\, \theta_\lambda$ $\tilde{\Phi} \,\bullet\!\!-\!\!\circ\, \tilde{\theta}_\lambda$, $\hat{\Phi} \,\bullet\!\!-\!\!\circ\, \hat{\theta}_\lambda$

Table 4.6: The mapping issue

(g) **Congestion Weighting**:

A congestion weighting was introduced in Section 4.3 to transform congestion in a packet loss metric. This is necessary to connect the packet loss based mapping in both PARQUE approaches with the congestion of the class. A mapping describes the relationship between QoE and packet loss [21, 65]. Table 4.7 gives an overview on this issue.

[1]Note that Mapping II is referred as only Mapping in QoE priced PARQUE.

[2]The threshold values $\hat{\Phi}$ and $\tilde{\Phi}$ are directly set by the ISP in QoE priced PARQUE.

conventional PMP	*QoS priced PARQUE*	*QoE priced PARQUE*
not needed	*essential*	*essential*

Table 4.7: Congestion weighting

Although congestion weighting is not necessary in PMP, it is used to provide comparable results with PARQUE.

This Chapter introduced PMP as proposed by [53] and based on that – but with essential changes outlined in this section – two novel approaches under the common name PARQUE. These PARQUE approaches slightly differ from each other from the pricing point of view. The following Chapter 5 presents our results and compares the discussed approaches for the two service class scenario in the presence of a regulator.

Chapter 5

Results

Contents

In this chapter we present analytical and predominantly numerical results for each concept introduced in Chapter 4. Explicitly, the findings of the *conventional PMP* model are presented in Section 5.1. Thereafter, Section 5.2 surveys the core results of the *QoS priced PARQUE* model, while Section 5.3 outlines our findings for *QoE priced PARQUE*. Finally, in Section 5.4 we summarize our findings and infer a series of conclusions.

We analyze a scenario of a non-neutral network (cf. Section 2.3), where a monopolistic ISP provides two QoS classes. Similarly to [51] the presence of a regulating authority mitigates the transition from single to two service classes. We focus on finding ISP's optimal pricing strategy, i.e., access prices, under certain network restraints caused by the regulator. This is investigated in relationship to the ISP's revenue R and the accumulative user utility U in the equilibria of the game. The analysis is undertaken with the help of MATLAB[1].

5.1 Conventional Paris Metro Pricing

This section briefly surveys the results from Shetty et. al in [53–55] before we present our core findings.

[1] `http://www.mathworks.de/products/matlab/index.html`

In [53] a game theoretic model is presented, investigating welfare effects and distributional consequences if QoS provision is adopted. This model provides the basis for this work's approaches, but Shetty et al. in [53] concentrate on the influence of the costs for capacity τ in the unregulated case and for three different regulators. While the ISP's incentive is to maximize revenue the regulator's objective is utility and social welfare maximization. Shetty et al. proceed in two actions. First, they derive the optimal choice of capacity $c(x)$ by solving the ISP profit Π w.r.t. c for fixed x and τ. Then profit and user surplus can be calculated. Second, they calculate the optimal fraction of capacity for the premium class, denoted by x regarding the ISP or the regulators objectives. While Shetty et al. in [53] provide the results for x as a function of capacity cost τ, in [55] and [54] results consider multiple competing ISPs. Results show that the more the regulator cares about the users' welfare, the lower is the fraction x, i.e., the bigger is the standard quality class. Although, a transition to two service classes increases user welfare (but decreases with competition), there remains a percentage of users which have to face a surplus loss (i.e., utility loss), whether a regulator is present or not [54]. It can be shown that for a single service class the optimal price (maximizing revenue) is $p = \frac{1}{2}$ [54].

This work investigates on the optimal access prices, and the corresponding actual user utility and ISP revenue in a stressed network – analytically and numerically. For this purpose, we assume the ISP provides a certain network capacity c while the percental share of premium traffic x is set by a regulator (e.g. according to [53]). Then for any arbitrary combination of x and c we can analytically determine the optimal access prices $p_1^\dagger(c, x)$ and $p_2^\dagger(c, x)$ from revenue maximization following Equation (4.15) and Equation (4.16). We also analyze the optimal prices $p_1^\star(c, x, \zeta)$ and $p_2^\star(c, x, \zeta)$ for social welfare maximization (cf. Equations (4.21-4.22)), where ζ denotes the influence of utility on the social welfare. Thus we investigate a network, where an independent regulator influences the ISP's setting of the access prices. At this point we would like to note that the revenue calculation — as applied in our analysis -– is fully agnostic to capacity costs τ. Profit calculations in contrast would subject to τ, but are intentionally left out of focus in this work.

In our numerical analysis, each user is characterized by the random variable θ with support to $[0, 1]$. Without loss of generality, but for the sake of simplicity we set the capacity $c = 1$. We consider a total number of $N = 100$ potential costumers. We vary x in the interval $[0.1, 0.9]$, by intentionally excluding $x = 0$ and $x = 1$ in order to intentionally eliminate one service class cases, i.e., all two service classes are inspected. After the ISP sets his prices

p_i for class $i \in \{1, 2\}$ we classify the user according their willingness to pay θ. For the numerical analysis we linearly increase the access prices p_1 and p_2 with step size $\Delta = 0.05$ in the interval $[0.1, 1]$. After the users have been classified according their θ, the quality q_i in each class and the corresponding utility U can be determined (cf. Equation (4.5)). We calculate the ISP's actual revenue R according to Equation (4.8) and the social welfare according Equation (4.20). For each fraction of capacity x we calculate revenue, utility and social welfare for the whole set of access prices $p_i \in \{1, 2\}$, thereafter we find the maxima (i.e., $\max_{p_i}\{R\}$, $\max_{p_i}\{U\}$ or $\max_{p_i}\{SW\}$) and the corresponding access prices (i.e., the ISP's optimal choices) – this is referred to as numerical analysis. This process is repeated $n = 200$ times to alleviate statistic spikes at manageable calculation effort. Although, the congestion weighting function (introduced in Subsection 4.3.2) in PMP is not necessary it is used to achieve comparable results. Table 5.1 provides an overview of the settings for the numerical analysis.

x	θ	N	p_1	p_2	Δ	c	n
$[0.1, 0.9]$	$\theta \sim U(0, 1)$	100	$[0.1, 1]$	$[0.1, 1]$	0.05	1	200

Table 5.1: Settings for numerical analysis of PMP

Below, Figures 5.1(a)-5.1(c) summarize the numerical results along with the analytical results of this model – if available. Let p_i overline (i.e., $\overline{p_i}$) denote the calculated mean value of a set of n access prices p_i. Figure 5.1(a) depicts the optimal access prices $\overline{p_i^\dagger}$ for class $i \in \{1, 2\}$ from revenue maximization. In Figure 5.1(b) we show the optimal prices $\overline{p_i^\ddagger}$ from utility maximization. Figure 5.1(c) illustrates the optimal prices $\overline{p_i^\star}$ from pure social welfare maximization (i.e., $\zeta = 1$). The values in tabular form can be found in Appendix A Tables A.1-A.3. Under the presence of a regulator a fraction $x > 0.5$ might not be permitted, but is presented for providing a comprehensive theoretical view. The results from revenue maximization hardly change with fraction x (cf. Figure 5.1(a)) and else it is noticeable that an access price for the standard class $p_1^\dagger \approx 0.4$ seems rather high. For the case of equally distributed user this implies that about 40% of the total number of users N in this scenario do not have access to the Internet. This may conflict with strong global Internet traffic growth rates and intentions of providing Internet access to everyone. For [37] it is a matter of fairness to offer at least one channel at a widely affordable level. This concept might be achieved by maximizing the user utility resulting in a very low access price to the standard class $p_1^\ddagger$ and a rather high for the premium class $p_2^\ddagger$ respectively (cf. Figure 5.1(b)). With increasing fraction x access price $p_1^\ddagger$ increases while $p_2^\ddagger$decreases. This

can be easily explained by congestion: If the capacity of the premium segment is low (e.g., $x = 0.1$) then a very low access price to standard class (i.e., p_1) together with a high entry fee for class 2 ensure that most customers stay in class 1 with higher capacity and thus reduce congestion in both classes. While, if the premium capacity increases (i.e. x grows) the access price p_2 decreases to target more user.
In Table 5.2 the maximal achieved revenues denoted by R_{max} and in Table 5.3 maximal achieved user utility denoted by U_{max} for various x are shown together with the corresponding optimal prices. Note that R_{max} and U_{max} are arithmetic mean values. It can be

x	$\overline{p_1^\dagger}$	$\overline{p_2^\dagger}$	R_{max}
0.1	0.336	0.684	*30.950*
0.2	0.342	0.688	32.700
0.3	0.341	0.678	34.650
0.4	0.336	0.684	31.650
0.5	0.338	0.679	**35.900**
0.6	0.344	0.684	34.500
0.7	0.332	0.682	37.100
0.8	0.332	0.671	34.800
0.9	0.340	0.681	*30.950*

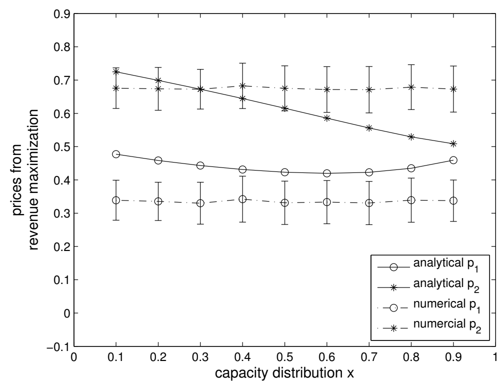
Table 5.2: Maximum Revenue

x	$\overline{p_1^\ddagger}$	$\overline{p_2^\ddagger}$	U_{max}
0.1	0.047	0.815	**27.736**
0.2	0.064	0.763	23.610
0.3	0.126	0.737	19.027
0.4	0.163	0.682	16.485
0.5	0.198	0.631	15.789
0.6	0.194	0.538	*14.755*
0.7	0.201	0.463	17.161
0.8	0.219	0.387	18.708
0.9	0.214	0.305	20.703

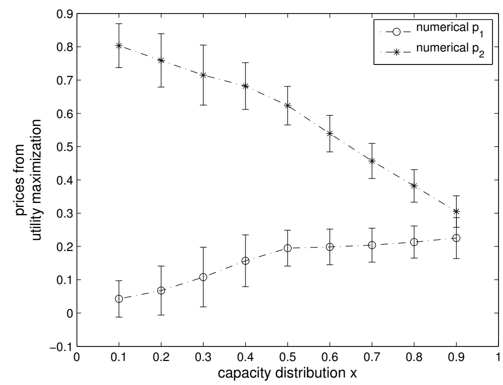
Table 5.3: Maximum Utility

seen from Tables 5.2-5.3 that for $x = 0.5$, where the ISP's revenue is at its maximum the user utility is low. The results indicate that there is a trade-off between revenue and user utility. As a possible solution – to find optimal prices with which an adequate revenue can be gained together with a satisfying user utility – we suggest social welfare maximization. The findings for the optimal prices $p_i^\star$ from social welfare maximization are depicted in Figure 5.1(c). It can be seen that in the case of pure social welfare maximization the utility part outweighs. Therefore we suggest to introduce ζ to regulate the influence of the utility on social welfare. In Table A.3 we list the optimal prices for $\zeta = 1$ and $\zeta = 0.5$.

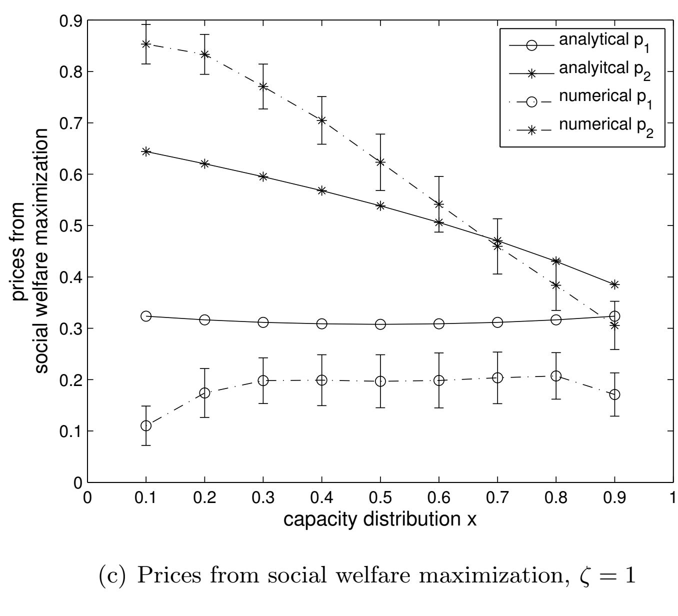
The strong deviation from analytical and numerical results (cf. Figure 5.1(a) and Figure 5.1(c)) is noticeable but can be explained the following: (i) in our numerical model a congestion weighting function (cf. Section 4.3) is used which has a strong influence on the quality q_i in class $i \in \{1, 2\}$ and thus on user utility. This congestion weighting is not considered in the analytical calculation. (ii) while for the analytical calculations an ideal uniform distribution is assumed, the distribution is slightly distorted in the numerical case due to the limitation of end users to a total number of N. We try to alleviate the impact of statistical spikes by repeating the analysis n times and the determination of arithmetic mean values. (iii) our numerical analysis considers the initial classification process only, i.e., users adopt a service according their θ values and do not change their decisions thereafter (e.g., do not drop service if they receive bad quality). (iv) while for analytical calculations according to [53] we set $U_\theta = (\theta - p_i)$ to solve the integral given in Equation (4.4), in our numerical analysis we determine the user utility by including the actual quality q_i in the step function $I(q_i - \theta)$ (cf. Equation (4.5)). To summarize, although (i)-(iii) limit the feasibility of the findings achieved by the numerical analysis, mainly because of (iv) we argue that the optimal access prices p_i numerically determined may provide more viable results.



(a) Prices from revenue maximization



(b) Prices from Utility maximization



(c) Prices from social welfare maximization, $\zeta = 1$

Figure 5.1: Prices from analytical and numerical calculation, at capacity $c = 1$, $N = 100$ User and $n = 200$ runs

Finally, Figure 5.2 shows the dimensional plot of the revenue and the user utility for the case $x = 0.2$ for various access prices p_i, where $i \in \{1, 2\}$. This figure illustrates the trade-off between revenue and utility as discussed above. Note that results where $p_1 \geq p_2$ are not plausible. Shetty et al. in [53] formulate a more stringent condition given in Theorem 4.6, i.e. $p_1(c, x) < \frac{1}{2}$ and $p_2(c, x) > \frac{1}{2}$. Figure 5.2 underlines that for PMP maximizing social welfare with respect to ζ might provide a possibility to find robust access prices.

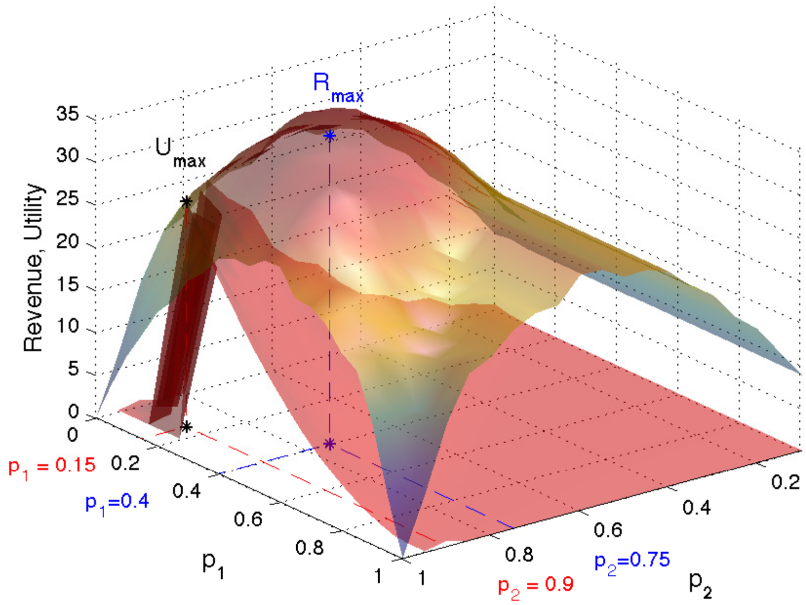


Figure 5.2: Dimensional plot of revenue and utility for $x = 0.2$

This section briefly surveyed the findings of the PMP model based on [53], the results serve in the following sections as a rule for our novel approaches.

5.2 QoS priced PARQUE

In this section, we present our findings for the QoS priced PARQUE approach. First, we describe the numerical analysis and the corresponding settings. Then, as a start we illustrate the classification before we present our findings regarding user utility and ISP revenue. Finally, we show the optimal access prices p_i for various maximizations and we illustrate the influence of three different Mapping I methods on the resulting access prices.

Similar to PMP (cf. Section 5.1), we analyze a monopolistic ISP providing two service classes $i \in \{1, 2\}$. We evaluate three different pricing strategies: While in a first approach the ISP maximizes his *revenue* and sets the access prices p_i accordingly, we investigate in a second and third approach how prices change if a regulator maximizes *user utility* or *social welfare* instead. We generate a random value Φ for each user characterizing his QoE expectations in MOS values, where Φ is in the interval $[1.4, 4]$. We model a total of $N = 100$ user, where each user participates with one packet per considered time slot to the total amount of traffic. For numerical analysis we increase the access prices p_i with the incrementation factor Δ, where $i \in \{1, 2\}$. The considered capacity is fixed to $c = 1$. We model a stressed network, where full congestion is observed when all users are consuming services via this link.

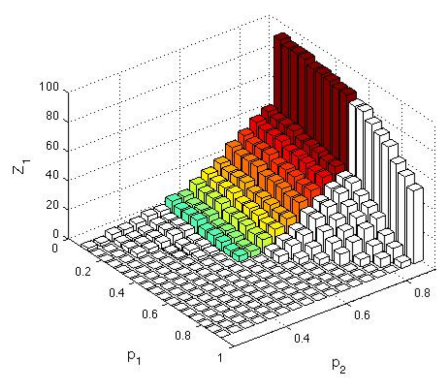
The determination of the access prices p_i is done in the following procedure. First, we assume that a monopolistic ISP invests in capacity c in the awareness of the regulator's choice variable x. This first step could be achieved according to the results of [53] for an optimal fraction x. In this game we hold the capacity c constant and variate x in the interval $[0.1, 0.9]$. Then we generate Φ randomly and classify the user in the QoE classes $\gamma \in \{l, h\}$ accordingly. For this classification the Mapping I is needed (cf. Definition 2). We investigate three different Mapping I procedures – mean, linear and α-sensitive Mapping I– as explained in Subsection 4.3.1.1. In the next step, Mapping II transforms Φ to QoS level according their application types $\lambda \in \{web, video\}$ (cf. Definition 3) and a classification in QoS classes $i \in \{1, 2\}$ can occur. Then we can calculate the ISP revenue according Equation (4.40) and user utility (cf. Equation (4.38)). We run this procedure n times for various α and determine the mean values for the access prices p_i where either revenue, utility or social welfare is maximum. $n = 50$ is a compromise between calculation complexity and elimination of statistical spikes. The variable α denotes the fraction of *video* application types from a total of N applications. We increase α in our analysis with support to $[0, 1]$. Table 5.4 summarizes the settings for the numerical analysis.

At first we present our results for α-sensitve Mapping I starting with the allocation of user

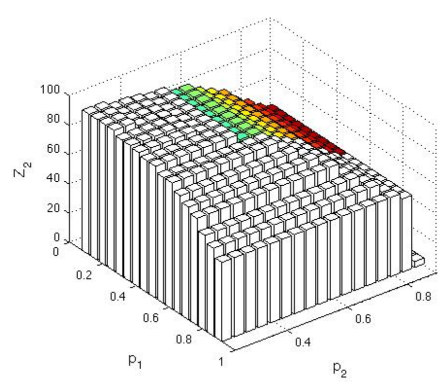
x	Φ	N	p_1	p_2	Δ	c	λ	α	n	Mapping I
$[0.1, 0.9]$	$\Phi \sim U(1.4, 4)$	100	$[0.1, 1]$	$[0.1, 1]$	0.05	1	$\{web, video\}$	$[0, 1]$	50	$mean$ $linear$ $\alpha - sensitive$

Table 5.4: Settings for numerical analysis of QoS priced PARQUE

(i.e., application) in Figures 5.3(a)-5.3(b). Figure 5.3(a) shows the dimensional plot for the applications z_1 in QoS class 1, while Figure 5.3(b) depicts the allocation of z_2 for various access prices p_i. It can be seen that the access price for the standard class p_1 compared to the access prices for premium level has a minor impact on the user allocation. As in conventional PMP the area where $p_1 > p_2$ provides no feasible results. As for PMP (cf. Section 5.1) the access prices must satisfy Theorem 4.6.
For any fixed capacity c and fraction of capacity x the conditions $p_1 < \frac{1}{2}$ and $p_2 > \frac{1}{2}$ must be given [53]. In Figures 5.3(a)-5.3(b) this condition can be deduced, considering that quality of a class i is strongly depending on the amount of applications (i.e congestion) in class $i \in \{1, 2\}$. Thus, to achieve a proper quality in class $i = 2$ the access price p_2 must be accordingly high, then the amount of usages in z_2 is low and quality q_2 high (cf. Figure 5.3(b)). Note that in QoS priced PARQUE the amount of participants in the QoE classes $\gamma \in \{l, h\}$ and the amount of QoS classes $i \in \{1, 2\}$ coincide. To change this behavior is dedicated to future work on this issue. Figures 5.3(a)-5.3(b) give no information on the distribution of the application types within the classes i.



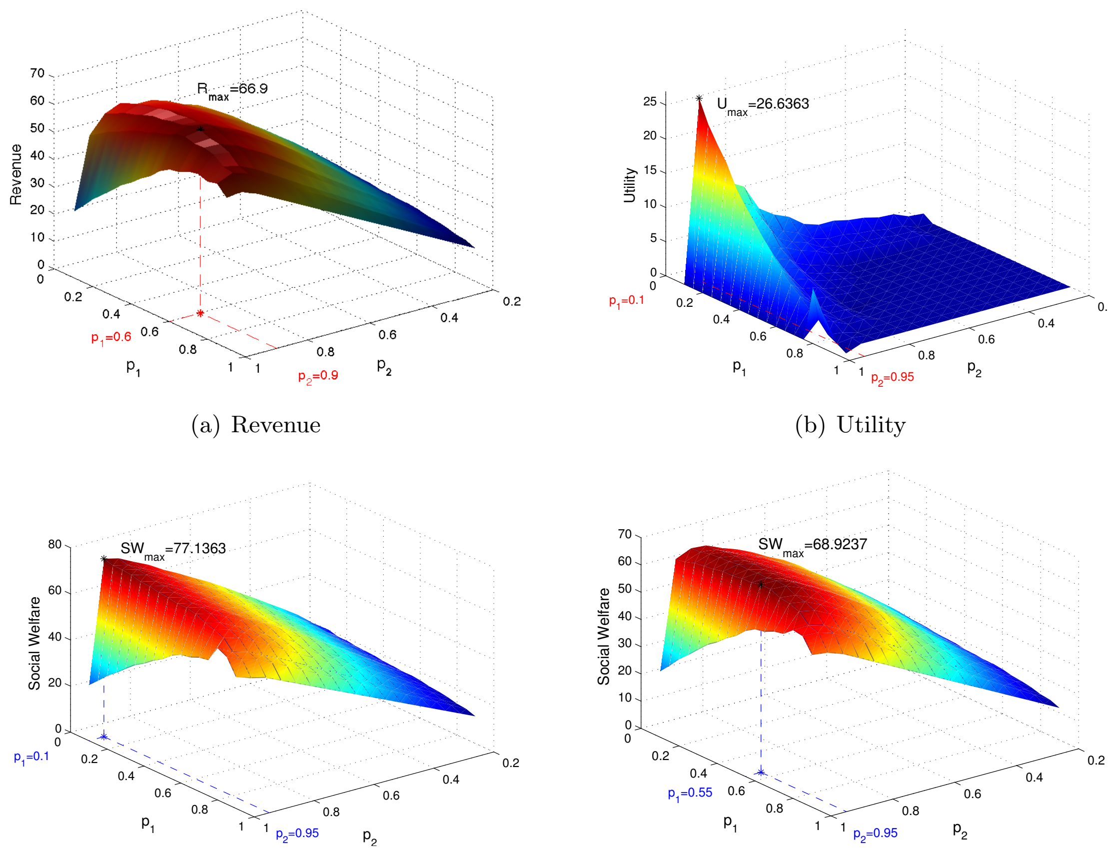
(a) Application z_1 in class 1



(b) Application z_2 in class 2

Figure 5.3: Distribution of applications z_i in the QoS classes $i \in \{1, 2\}$ for α-sensitive Mapping I, where $\alpha = 0.3$, $x = 0.2$ and $N = 100$ user

Figures 5.4(a)-5.4(d) provide an dimensional overview on the revenue, utility and social welfare for $x = 0.2$ and $\alpha = 0.3$ for a random distribution of Φ. Figure 5.4(a) depicts the revenue and the optimal prices p_i for the maximum revenue denoted by R_{max}. Figure 5.4(b) illustrates the surface plot for the utility and the corresponding optimal prices p_i. Results indicate that there exists a trade-off between user utility and ISP revenue, i.e., the highest revenue does not imply the highest utility or vice versa. Therefore, we suggest social welfare maximization for the pricefinding as depicted in Figures 5.4(c)-5.4(d). According to Equation (4.20) by the variable ζ the influence of the utility on the social welfare can be influenced. In Figure 5.4(c) the utility has the maximum impact (i.e., $\zeta = 1$), while in Figure 5.4(d) the revenue part influences the prices ($\zeta = 0.5$). We suggest that a regulator might set ζ to achieve robust prices where both sides (i.e., ISP and user) are satisfied.



(a) Revenue

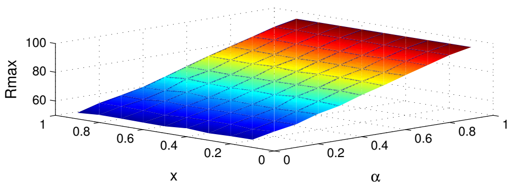
(b) Utility

(c) Social welfare $\zeta = 1.0$

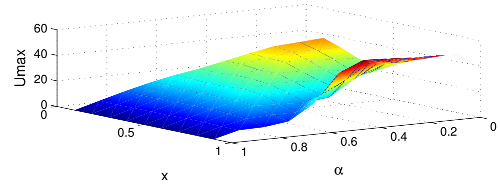
(d) Social welfare $\zeta = 0.5$

Figure 5.4: Overview for α-sensitive Mapping I, where $\alpha = 0.3$ and $x = 0.2$

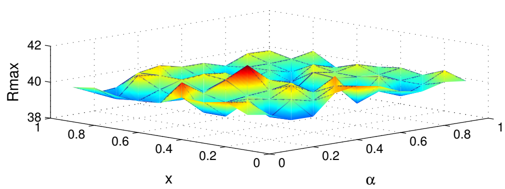
In the next analysis block we concentrate on the maximum possible values for revenue and user utility for certain access prices p_i for various x and α values, in Figures 5.5(a)-5.5(d) we give an overview. While Figures 5.5(a)-5.5(b) represent α-sensitive Mapping I, Figures 5.5(c)-5.5(d) represent linear Mapping I. As depicted in Figure 5.5(a) the revenue grows with an increasing α value (i.e., amount of video applications), while the utility decreases (cf. Figure 5.5(b)). By adopting the QoS priced PARQUE approach higher revenues can be achieved compared to conventional PMP (cf. Section 5.1). A possible reason that utility seems rather low (cf. Figure 5.5(b)) – compared to PMP – might be that through the application specific mapping (i.e., Mapping II) the users QoS the user quality requirements may be transformed to higher QoS levels.



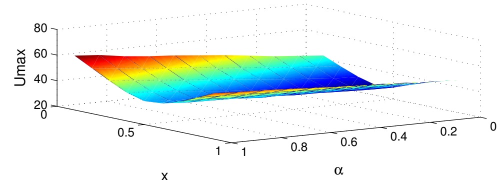
(a) Maximum Revenue



(b) Maximum Utility



(c) Maximum Revenue



(d) Maximum Utility

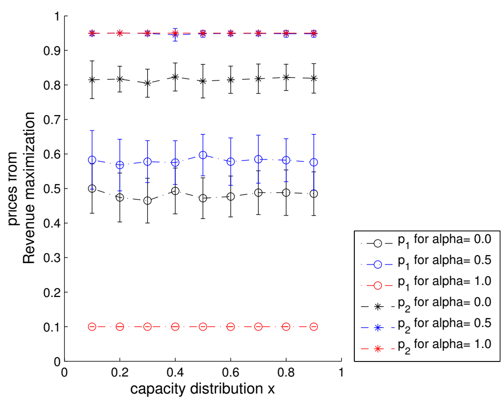
Figure 5.5: Maximum achievable Revenue R_{max} and Utility U_{max} using (a-b) α-sensitive Mapping I and (c-d) linear Mapping I

In Figure 5.5(c) the maximum revenue R_{max} is depicted for linear Mapping I, where R_{max} remains approximately constant for various x and α values. While the revenue is lower as for α-sensitive Mapping I, the user utility (cf. Figure 5.5(d)) remains clearly above the maximum value from Figure 5.5(b) and thus from the utility point of view is the preferable approach. The analysis showed that the worst results are achieved with a mean Mapping I, especially for low values of α the utility sinks drastically. For this reason, no further efforts are made in investigating this method for Mapping I.

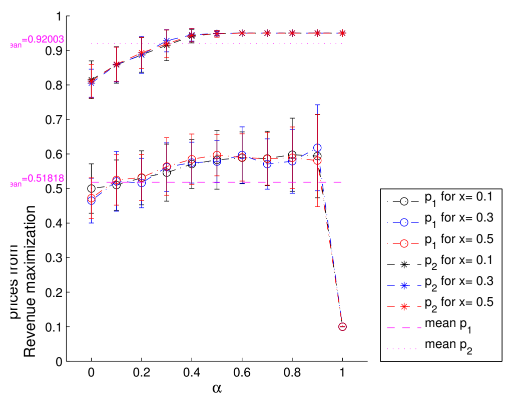
The corresponding optimal **access prices** p_i from revenue maximization can be found in Figures 5.6(a)-5.6(b). It can be seen that the prices are not sensitive to variations in x (cf. Figure 5.6(a)) but vary depending on the fraction α (cf. Figure 5.6(b)). In Figure 5.6(b)) a runaway value for access price p_1 can be seen at $\alpha = 1$, which limits the applicability for α-sensitive Mapping I at high video demand. $\alpha = 1$ implies that the Mapping I is done utilizing the QoE-QoS mapping curve for video (cf. Figure 4.8), which is characterized by a gently incline over a wide area and a very steep growth at the end (i.e., $\theta \approx 0.9$). Subsequently, the access prices p_1 and p_2 out of the interval $[0, 0.85]$ are mapped to equal

QoE representations of ≈ 1.37. The whole approach is based on price discrimination to provide different QoS levels in the standard and premium class, which is not given in this case. Hence, Mapping I does not provide robust pricing if the traffic is dominated by video applications (i.e., α tend to 1). The same effect can be experienced for social welfare maximization (cf. Figure A.3(b)).

Results for linear Mapping I can be found in Appendix A in Figures A.1(a)-A.1(b). The optimal prices from utility maximization are very sensitive for x and α and thus can not be utilized for a robust pricing mechanism and additionally are economically challenging. By integrating the user utility in the pricefinding, social welfare is again maximized. We provide results for the optimal prices from social welfare maximization for α-sensitive and linear Mapping I in Appendix A Figures A.3(a)-A.2(b) for $\zeta = 1$ and $\zeta = 0.5$.



(a) prices vs. x



(b) prices vs. α

Figure 5.6: Prices from revenue maximization using α-sensitive Mapping I, $n = 50$ runs

Finally, we want to demonstrate the influence of the chosen Mapping I variant on the optimal access prices. In Figure 5.7 we depict the optimal access price p_1 for all considered Mapping I methods over x for social welfare maximization by exemplary. This illustrates that Mapping I is the key part of QoS priced PARQUE to investigate on, hence for facilitating real world adoption more research on this mapping is needed.

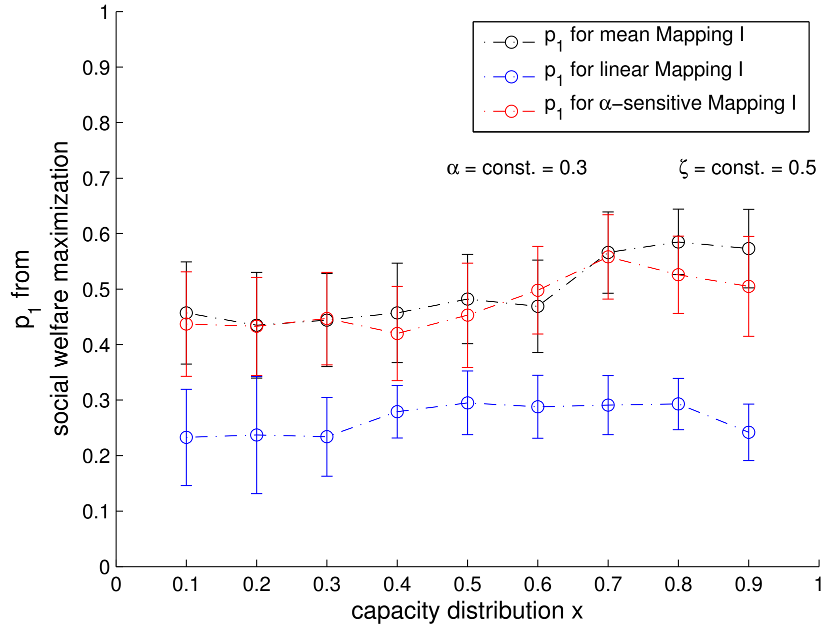


Figure 5.7: Influence of Mapping I on the price p_1 by example, $\zeta = 0.5$, $\alpha = 0.3$

5.3 QoE priced PARQUE

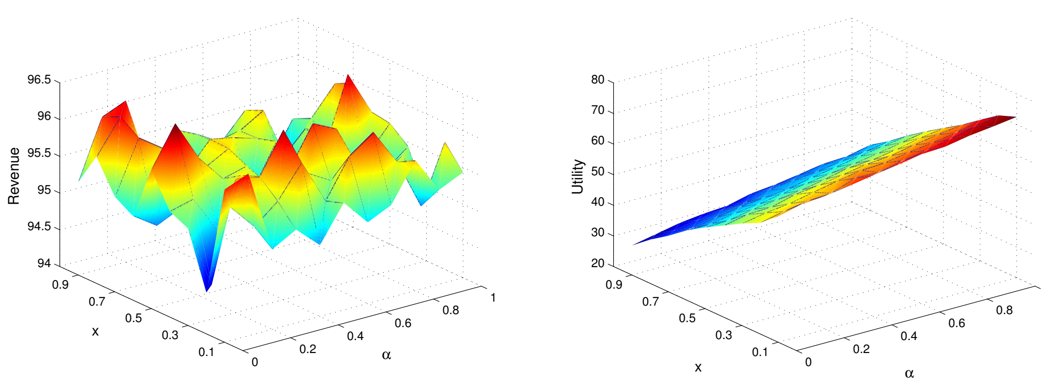
This section surveys our key findings analyzing the QoE priced PARQUE approach introduced in Section 4.4. First, we explain our proceedings and settings for the simulation. Thereafter, we show our results for the ISP's access prices.

As before, our intention is to perform a numerical analysis in order to gain the ISP's optimal choices for the access prices regarding three different maximization methods (cf. Section 4.1). Price discrimination occurs based on QoE expectations according to the thresholds $\tilde{\Phi}$ and $\hat{\Phi}$. In contrast to Section 5.2, the monopolistic ISP directly sets both thresholds and the according prices p_γ for the QoE classes $\gamma \in \{l, h\}$, while the users applications are still categorized in QoS classes as before. Now, we iterate the threshold values (i.e., $\tilde{\Phi}$ and $\hat{\Phi}$) and the prices p_γ according Table 5.5. Both, thresholds and prices are increased linearly with step size $\Delta = 0.1$. Note that the thresholds are given in MOS values in the interval $[1.4, 4]$, while the prices are still set in the interval $[0, 1]$ to allow the comparison with the other approaches. After the mapping process according to the ISP's pricing decisions the user classification can occur as explained in Section 5.3. Gathering this informations, revenue (cf. Equation (4.43)) and user utility according to Equation (4.44) can be determined. Our aim is to find the prices (i.e., p_γ) and thresholds (i.e., $\tilde{\Phi}$ and $\hat{\Phi}$), where revenue, user utility or social welfare is maximal. This calculations were repeated $n = 20$ times and therefore our findings represent arithmetic mean values and the standard derivation is denoted by σ.

x	Φ	N	p_l	p_h	$\tilde{\Phi}$	$\hat{\Phi}$	Δ	c	λ	α	n
$[0.1, 0.9]$	$\Phi \sim U(1.4, 4)$	100	$[0, 0.9]$	$[0.5, 1]$	$[1.5, 3]$	$[1.9, 4.5]$	0.1	1	$\{web, video\}$	$[0, 1]$	20

Table 5.5: Settings for numerical analysis of QoE priced PARQUE

As a starting point, the maximum ISP revenue R_{max} is depicted in Figure 5.8(a) and the maximum user utility U_{max} is presented in Figure 5.8(b) for various x and α. Note that R_{max} and U_{max} represent arithmetic mean values. Our findings indicate that we gain maximum revenue if the threshold values are set at the lower bound (i.e., $\tilde{\Phi} = 1.5$ and $\hat{\Phi} = 1.9$) and the highest possible price levels are used (i.e., $p_l = 0.9$ and $p_h = 1.0$). Thus, we can observe the highest possible revenues achievable in this model as participation at the considered time slot is very high (due to low thresholds) and prices are exclusive. At the same time, the results from revenue maximization imply very bad user utilities as (a) prices are high and (b) the quality is highly degraded (cf. Equation (4.3)). The low quality is obviously a consequence of the high congestion of the link. The maximum revenue changes only slightly with varying x or α and remains at ≈ 95.5, i.e., the revenue maximization is agnostic to demand characteristics or capacity decisions.



(a) Maximum revenue R_{max}

(b) Maximum user utility U_{max}

Figure 5.8: Maximum (a) revenue and (b) user utility values in QoE priced PARQUE

On the other hand, the maximum user utility U_{max} is very sensitive to capacity decisions and decreases with increasing fraction of capacity dedicated to the premium class x (cf.

Figure 5.8(b)). While the maximum revenue R_{max} stays rather uninfluenced by a changing fraction of video applications α as discussed above, the user utility is growing with increasing α value (i.e., increasing video demand). As in Section 5.2, the growing utility can be explained due to increasing application-specific QoS values θ_λ. This values directly influence the price sensitivity part for the user utility (cf. Equation (4.44)). From our analysis the optimal ISP's decisions to maximize user utility are: A price for the standard QoE class of $p_l = 0.0$ and $p_h = 0.5$ for the premium segment respectively. A price $p_l = 0$ implies that the basic service is provided for free, while for the fee for premium segment are $p_h = 0.5$. Little surprising, with these settings very low revenues can be gained. While the threshold value for the standard QoE class $\tilde{\Phi}$ is constant at ≈ 2.14, the threshold value between standard and premium QoE class $\hat{\Phi}$ has a strong dependency on x as depicted in Figure 5.9. The higher the fraction of the premium capacity x the lower is the threshold value, which ensures that congestion remains moderate in both classes. Hence, we have to face a trade-off between maximizing user utility and maximum revenue. The findings for U_{max} represent the highest achievable results for the user utility in a PARQUE model.

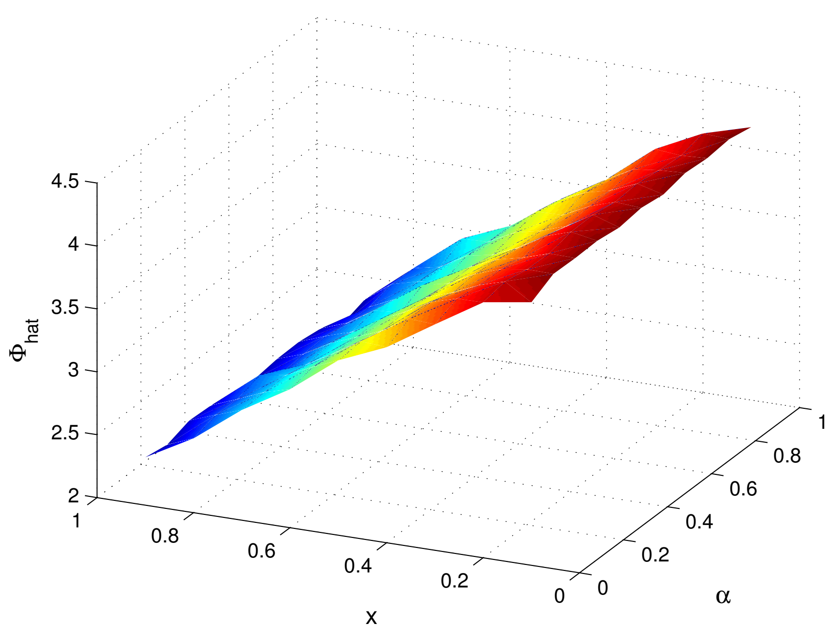


Figure 5.9: Threshold value $\hat{\Phi}$ for maximizing user utility

In QoS priced PARQUE (cf. Section 5.2) we try to alleviate the trade-off between utility and ISP revenue by maximizing social welfare. Our findings for QoE priced PARQUE indicate that the revenue outweighs the utility for any ζ from the interval $[0, 1]$, where ζ

characterizes the influence of user utility on the social welfare (cf. Equation (4.20)) and thus does not offer a possibility to obtain feasible ISP's settings. In order to mitigate the revenue part, the social welfare might be calculated with a value of ζ exceeding one to support the utility part. The influence, where $\zeta > 1$ on the social welfare and the corresponding optimal ISP's settings is dedicated to further work on this issue.

Considering the case of a monopolistic ISP who provides two QoS classes – adopting a QoE based application classification method, can increase the user utility and ISP's revenue. Although our findings do not provide a method for a robust pricing, we have shown the theoretical maximum possible revenue and user utility for both PARQUE models.

5.4 Conclusion

This chapter surveys the findings of three models where an ISP provisions QoS differentiation under regulation. We investigate a conventional PMP approach (cf. Section 4.1) and two novel models (cf. Section 4.3 and Section 4.4), which integrate QoE to the user classification and for price discrimination. We numerically analyze the pricing models with the focus on the ISP's optimal settings regarding its incentives and social objectives, i.e., we determine the ISP's revenue and the user utility. To this end we provide a detailed comparison of conventional PMP and QoS priced PARQUE.

We have introduced a regulating tool – similar to [53] – to mitigate effects due to transition to two service classes by fixing the fraction x of capacity dedicated to the premium QoS channel. We argue that ISP should make their pricing decisions by maximizing social welfare (cf. Equation (4.20)) instead of solely maximizing revenue. An independent regulator's objective might be to set the term ζ, which controls the influence of user utility of the social welfare. For a ζ value close to 1 the utility is fully included in the social welfare, while $\zeta = 0$ implies pure revenue maximization. Summarizing the regulator's role: First, he alleviates the political economic constraints regarding the Net Neutrality issue (cf. Section 2.3). The findings of Shetty et al. in [55] indicate that – by applying this regulating tool – the transition to two service classes is socially desirable, although it inflicts in some fractions to the current network users. Second, the regulator affects the pricefinding to increase social welfare. And third, for the QoS priced model a regulator might choose a proper Mapping I method (i.e., either α-sensitive or linear Mapping I).

While in [55] a robust pricing for the PMP model is given, the pricefinding in PARQUE is more challenging. Nevertheless, our results for *QoS priced PARQUE* indicate that, for the case of a monopolistic ISP in terms of revenue, price discrimination among QoE values is more favorable (cf. Section 5.2). We showed that the Mapping I process (cf. Definition 2) has a major impact on the outcome of this approach.

In Section 5.2 we paid our attention to the effects on social welfare if either *α-sensitive* or *linear Mapping I* is used. In the first case – α-sensitive Mapping I – very high revenues can be achieved at the costs of low to maximum moderate user utility. While, for applying linear Mapping I a constant revenue can be achieved and user utility remains continuously higher than for conventional PMP (cf. Section 5.1 and Section 5.2). To further investigate Mapping I is dedicated to future work on this issue.

Although we have not gained feasible results from *QoE priced PARQUE* – the findings (i.e., maximum utility U_{max} and maximum revenue R_{max}) can be interpreted as the maximum achievable values adopting a PARQUE model (only if prices for QoE class p_γ are within the same interval as the QoS access prices p_i, $\gamma \in \{l, h\}$, $i \in \{1, 2\}$). Therefore, results provide a good theoretical basis for comparison and evaluation of QoS priced PARQUE.

Finally we summarize the QoS priced PARQUE approach by providing a comparison with the conventional PMP model by exemplary (cf. Table 5.6). The access prices are fixed to $p_1 = 0.4$ and $p_2 = 0.8$, which depict approximately the analytical results from revenue maximization in PMP (cf. Figure 5.1(a)).

Mapping I	Settings	PMP $\overline{R}$	PMP $\overline{U}$	PMP $\overline{z}$	QoS priced PARQUE $\overline{R}$	QoS priced PARQUE $\overline{U}$	QoS priced PARQUE $\overline{z}$
α-sensitive	$x = 0.3$, $\alpha = 0.3$	32.184	9.668	60.180	61.740	13.202	90.430
	$x = 0.2$, $\alpha = 0.5$	32.228	8.481	60.630	67.056	7.572	93.090
	$x = 0.2$, $\alpha = 1.0$	32.040	8.437	60.380	**80.000**	3.521	**100.000**
linear	$x = 0.3$, $\alpha = 0.3$	32.184	9.668	60.180	39.100	20.882	66.470
	$x = 0.2$, $\alpha = 0.5$	32.228	8.481	60.630	38.608	18.448	65.340
	$x = 0.2$, $\alpha = 1.0$	32.040	8.437	60.380	38.760	**21.661**	65.620

Table 5.6: Comparison of PMP and QoS priced PARQUE, where $p_1 = 0.4$, $p_2 = 0.8$

We consider a total number of users $N = 100$ and we investigate three different scenarios:

First, the fraction of the premium channel is set to $x = 0.3$ and is equal to the fraction of video applications $\alpha = 0.3$. Second, we decrease x and increase α, i.e., $x = 0.2$, $\alpha = 0.5$. Third, α is even further increased to its maximum 1.0, while $x = 0.2$ remains constant. The analysis for QoS priced PARQUE is done utilizing *α-senstive* and *linear Mapping I*. The given results in Table 5.6 represent arithmetic mean values from a total of $n = 100$ runs, where $\overline{R}$ is the mean of the ISP's revenue and $\overline{U}$ the user utility. The term $\overline{z}$ denotes the total number of users adopting either standard or premium service, hence $z = \sum_{i\in\{1,2\}} z_i$. Table 5.6 emphasizes that – independent of the used Mapping I method – QoS priced PARQUE is economically desirable compared to conventional PMP. The revenue growth follows from a strong user participation if price discrimination is based on QoE, i.e., the total number of users denoted by $\overline{z}$ in both classes $i \in \{1, 2\}$ is higher in PARQUE. Considering that in our model quality is strongly depending on congestion and quality has a heavy impact on user utility, the social benefits from adopting QoS priced PARQUE can be seen (cf. Table 5.6). As already mentioned above, surprisingly the best results concerning the user utility are gained with linear Mapping I.

Chapter 6

Conclusions

To recapitulate briefly, the aim of this work is to analyze if integrating Quality of Experience (QoE) in the pricing mechanism is beneficial. Section 6.1 summarizes and depicts the key findings. Thereafter Section 6.2 gives an outlook on how the models could be further improved.

6.1 Summary and Key Findings

This work proposes an approach facing the problems stated in Section 1.2. In general, Internet demand is growing and the number of quality-sensitive real-time applications is increasing in importance (cf. Section 1.1). QoS differentiation has been widely recognised as a possible way to respond to this issue, although no such services are currently offered in the Internet. This could be driven by various demand and supply side considerations summarized by [55]. This work targets many of these issues: First, we try to alleviate the threat of the ongoing Net Neutrality debate (cf. Section 2.3) by applying a regulating tool – similarly to [53]. Second, we investigate robust pricing for QoS or either QoE. Third, we analyze a "primitive" mechanism based on Paris Metro Pricing (PMP) (cf. Section 2.5) which could be implemented with relatively low initial investment[1].

In particular, we formulate a model for conventional PMP (cf. Section 4.1), which is enhanced in two subsequent advanced models — *QoS priced PARQUE* (cf. Section 4.3) and *QoE priced PARQUE* (cf. Section 4.3). While, in QoS priced PARQUE the ISP's price and quality decisions are still made upon QoS values, QoE priced PARQUE is a step ahead and sets prices directly on the QoE level. Section 4.5 provides a summary of the key differences of these approaches. We integrate demand considerations to our novel models

[1]High upfront costs make only primitive QoS mechanism feasible [55].

by distinguishing two different kind of Internet applications – web surfing for lower QoS requirements and video representing sensitive QoS applications respectively – defined by the fraction α (cf. Definition 1). Whereas in the PMP approach QoE (cf. Section 2.2) does neither influence the model functioning in terms of price strategies nor in terms of user classifications, in PARQUE QoE plays a substantial role. Indicated by our findings, we argue that price discrimination should be based on the users' QoE expectations and traffic should be classified by application specific QoS representations (i.e., QoE needs to be related to QoS values). In Section 4.2 we introduce a method to transform QoS to QoE and vice versa, i.e., the mapping. Thus, this mapping is responsible to transform QoS requirements into MOS values and relies on the following assumptions:

- We define packet loss as our QoS metric (cf. Section 4.2.1), which has been chosen as packet loss will still be a concern in the future when links perceive a higher aggregate number of flows [64]. Buffering time-sensitive traffic, as a way to decrease packet loss, might not be an adequate solution as it increases the delay.
- The relationship between packet loss and QoE is expressed according to findings from [21, 65].
- The packet loss is limited to a certain maximum value $p_{loss,max}$, which is inferred from the QoE saturation levels at higher (cf. Assumption 1, p. 34).
- QoS is the difference between the highest possible QoS level given by 1 and the actual packet loss, i.e., $QoS = 1 - p_{loss}$ (cf. Assumption 2, Equation (4.25)).
- QoS is rescaled to match the interval $[0, 1]$, i.e., $p_{loss,max}$ is set to 0.

Mapping is utilized in both PARQUE approaches and depicts the core process. There are several other assumptions concerning market and traffic we make that might be viewed as limitations of our models:

- We use the common assumption that each user's QoS requirement (denoted by θ) is a equally distributed in the interval $[0, 1]$. This is adopted for the users' QoE expectations (denoted by Φ) in PARQUE but on the MOS scale. (cf. Section 4.5 Item (b)).
- As applied in [53], we assume that the users' willingness to pay and QoS expectation coincide (cf. Equation (4.3)). For a more general description these might differ from each other and should be defined separately.
- A one link assumption is applied, considering only a certain time slot, where each user contributes equally and with only one packet to the total amount of traffic, i.e., constant packet size.

- We assume that QoS depends linearly on packet loss, although our models meter the congestion. Therefore, we introduce a congestion weighting function to link congestion to the packet loss metric as utilized in the mapping process. (cf. Section 4.3, Equation (4.35)).

Furthermore, a standard definition of the user utility as in [53] is used (cf. Equation 4.3), where the surplus is given as the difference between the willingness to pay and the price. Following the approach from [53], the actual quality of the link is not included in the surplus. This implies that a user who adopts a network service for receiving e-mail traffic only, gains no extra utility from the fact that the available quality permits him to receive video applications.

In the following paragraphs, we summarize the key findings resulting from our evaluation in Chapter 5.
[53] showed that the proposed regulatory tool makes the transition to a two-service class network viable and thus enervates the constraints of Net Neutrality for their PMP model. By adopting this tool to our models and because in PARQUE even higher user utility values at simultaneously increased user participation can be attained, we argue that for PARQUE the transition to two service classes is desirable without explicitly considering the single-service class case. Therefore, mechanism with a traffic classification centered on QoE (i.e., PARQUE) might provide an impulse to rethink the ongoing Net Neutrality debate as our findings (cf. Section 5.4) indicate an increase in social welfare. Hence, traffic management and application differentiation (cf. Section 2.4) as a way to deal with the growing demand, but conflicting the NN in the sense its understood today, may become accepted by NN advocates if classification decisions are based on QoE.
The increase of social welfare in QoS priced PARQUE can be explained by the following findings:
Our analysis indicates that independent of the used Mapping I mechanism – i.e., α-sensitive or linear Mapping I – the ISP's revenue are permanently higher compared to conventional PMP at the same price level (cf. Table 5.6).

- *Price discrimination based on QoE increases the ISP revenue.*

The growth of revenues is a side-effect of an increase in users adopting the services. While in PMP approximately 40% do not attend any service, in QoS priced PARQUE utilizing α-sensitive Mapping I over 90% adopt either standard or premium class (cf. Table 5.6). Another part influencing social welfare is the user utility, our analysis pointed out that utility is increased when PARQUE is adopted.

- *Integrating QoE aspects in traffic classification enhances the overall user utility.*

Our findings indicate that for a comparable number of attending users the user utility can be doubled (cf. Table 5.6 for PMP and QoS priced PARQUE with linear Mapping I). However, to provide robust pricing for Qos priced PARQUE is challenging and highlighted the necessity for further advancements, e.g., changing demand scenarios require adopting the optimal prices (cf. Figure 5.6(b)). Especially the Mapping I methods complicate the analysis. While, for α-sensitive Mapping I high revenues can be achieved the advantage of linear Mapping I is the growth of user utility.

6.2 Outlook

Further work in this area may encompasses several aspects, outlined as following:
In Section 5.2 and Section 6.1 the impact of the different *Mapping I* methods was illustrated. As the Mapping I influences the threshold values and hence revenue and utility – more investigations are necessary to provide a better understanding.
There is also a high relevance of extending our monopolistic model for the duopoly or even oligopoly case in order to capture influences from competition.
To be able to effectively integrate QoE facets to Internet pricing mechanism, a *functional mapping* between QoS and QoE is needed. Hence, further efforts on this issue are necessary.
In our PARQUE models a *congestion weighting* is integrated, which principal task is to transform congestion in a packet loss based metric to be thereafter used in the mapping process (cf. Subsection 4.3.2.1). To the best of my knowledge, there exists no data describing this relationship, hence user trials should be encouraged to gain proper expressions.
Less attention has been paid on the costs for capacity as [53] has a detailed look on this issue for PMP. Nevertheless, costs play an important role and are dedicated to future work.

We focus our analysis on the two-class scenario only. In fact, there might be another possibility to enhance PARQUE. In PARQUE we differ video traffic, representing QoS-sensitive and insensitive web traffic. We suggest to investigate the sub-division of the total capacity in four classes, i.e., we end up with a standard and premium class for each application type and thereafter a mechanism similar to PARQUE classifies accordingly. The four-class case is outside the scope of this thesis, although this might be a focus of future work in this field.

List of Acronyms

AP	Application Provider
BE	Best Effort
CoS	Class of Service
CP	Content Provider
DiffServ	Differentiated Services
EU	European Union
FAN	Flow Aware Networking
FCC	Federal Communications Commission
FTP	File Transfer Protocol
FTW	Telecommunications Research Center Vienna
HTML	Hyper Text Markup Language
HW	Hardware
IntServ	Integrated Services
IP	Internet Protocol
IPv4	Internet Protocol Version 4
ISP	Internet Service Provider
MOS	Mean Opinion Score
MTTF	Mean Time to Failure
NN	Net Neutrality
NSP	Network Service Provider
OSI	Open System Interconnection
P2P	Peer to Peer
PARQUE	Pricing and Regulating Quality of Experience
PMP	Paris Metro Pricing
QoE	Quality of Experience

QoS .... Quality of Service
SLA .... Service Level Agreement
SW .... Software
TCP .... Transmission Control Protocol
VoIP .... Voice Over IP

List of Symbols

Δ .... Increment for numerical calculations
α .... Fraction of video applications
γ .... QoE class $\gamma \in \{l, h\}$
$\hat{\Phi}$ .... Threshold MOS value between standard and premium QoE class
$\hat{\theta}_\lambda$ .... Application specific threshold value btw. standard and premium QoS class
λ .... Application type $\lambda \in \{web, video\}$
Π .... ISP profit
τ .... Unit costs per unit capacity
θ .... User characterisation on QoS level
θ_λ .... Application specific QoS perception
$\tilde{\Phi}$ .... Threshold MOS value for standard QoE class
$\tilde{\theta}_\lambda$ .... Application specific threshold value for standard QoS class
c_1 .... Capacity of the standard class
c_2 .... Capacity of the premium class
i .... QoS class $i \in \{1, 2\}$
K .... Congestion parameter
MSS .... Maximum segment size
N .... Total number of user
n .... Number of runs for numerical calculations
p .... Packet loss probability
p_i .... Access price for QoS class i
p_{loss} .... Packet loss
q .... Quality of service
R .... ISP revenue
RTT .... Round trip delay
S .... Social surplus

SW .... Social welfare
T .... Throughput
U_θ .... User surplus, user utility
$w(K_i)$ .... Congestion weighting function
x .... Regulator's choice variable for capacity distribution between QoS classes
z .... Amount of application

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Appendix A

Additional Results

In the Appendix additional results from our analysis are shown to achieve a more comprehensive view on the models.

Paris Metro Pricing

The following tables (cf. Table A.1-A.3) list the optimal prices p_i for revenue, utility and social welfare maximization, for various x and for each class $i \in \{1, 2\}$.

x	Revenue maximization numerical $p_1^\dagger$	$p_2^\dagger$	analytical $p_1^\dagger$	$p_2^\dagger$
0.1	0.336	0.684	0.477	0.725
0.2	0.342	0.688	0.459	0.699
0.3	0.341	0.678	0.443	0.672
0.4	0.336	0.684	0.431	0.644
0.5	0.338	0.679	0.423	0.615
0.6	0.344	0.684	0.420	0.586
0.7	0.332	0.682	0.423	0.556
0.8	0.332	0.671	0.435	0.529
0.9	0.340	0.681	0.459	0.509

Table A.1: Optimal access prices $p_i^\dagger$

x	Utility maximization numerical $p_1^\ddagger$	$p_2^\ddagger$
0.1	0.047	0.815
0.2	0.064	0.763
0.3	0.126	0.737
0.4	0.163	0.682
0.5	0.198	0.631
0.6	0.194	0.538
0.7	0.201	0.463
0.8	0.219	0.387
0.9	0.214	0.305

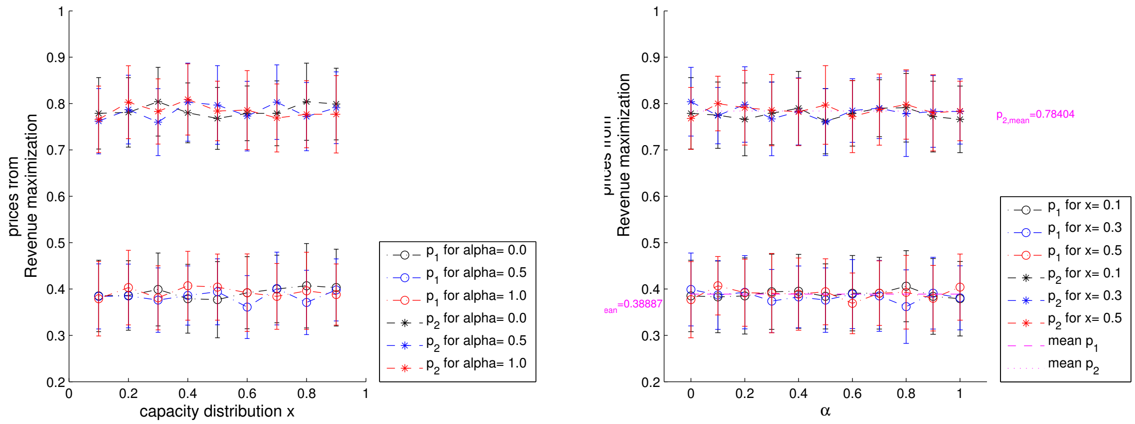
Table A.2: Optimal access prices $p_i^\ddagger$

	Social welfare maximization					
	numerical				analytical	
	$\zeta = 0.5$		$\zeta = 1$		$\zeta = 1$	
x	$p_1^\star$	$p_2^\star$	$p_1^\star$	$p_2^\star$	$p_1^\star$	$p_2^\star$
0.1	0.270	0.755	0.109	0.860	0.324	0.644
0.2	0.265	0.768	0.181	0.840	0.316	0.620
0.3	0.275	0.767	0.197	0.779	0.312	0.595
0.4	0.263	0.711	0.193	0.694	0.309	0.568
0.5	0.245	0.651	0.201	0.632	0.308	0.538
0.6	0.251	0.582	0.193	0.540	0.309	0.506
0.7	0.257	0.523	0.201	0.464	0.312	0.470
0.8	0.263	0.501	0.212	0.390	0.316	0.430
0.9	0.255	0.521	0.175	0.305	0.324	0.385

Table A.3: Optimal access prices $p_i^\star$

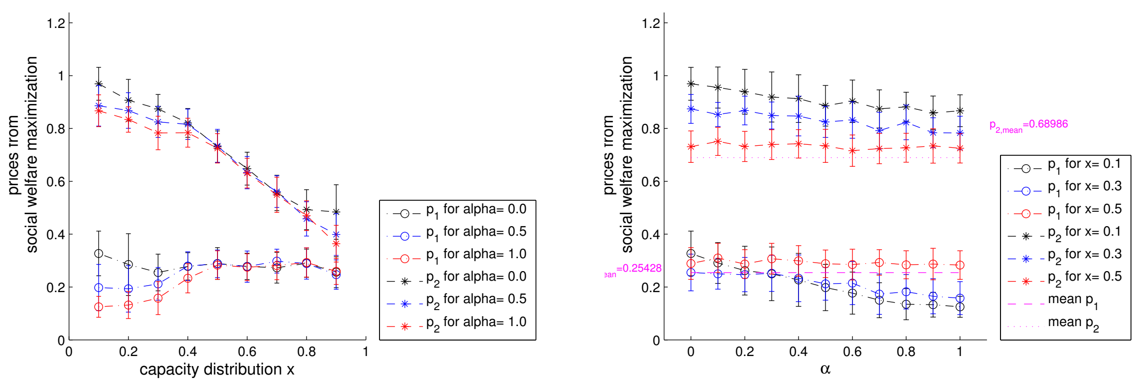
QoS priced PARQUE

This section provides an additional extract of our findings. Figures A.1-A.2 illustrate *linear- Mapping I*. Where Figures A.1 depict the optimal prices for revenue maximization for various x and α, and Figures A.2 depict the case of social welfare maximization. To this end, we depict results for social welfare maximization utilizing *α-sensitive Mapping I*. Figure A.3(b) shows the social welfare maximization for various α, where $\zeta = 0.5$, while in Figure A.3(c) the case for $\zeta = 1$ is depicted. It can be seen that the stronger impact of utility in the latter case shifts the access price for the standard class towards its minimum.



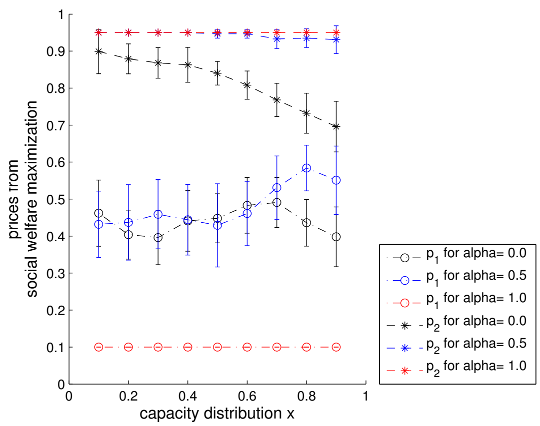
(a) prices vs. x (b) prices vs. α

Figure A.1: Prices from revenue maximization using linear Mapping I, $n = 50$ runs

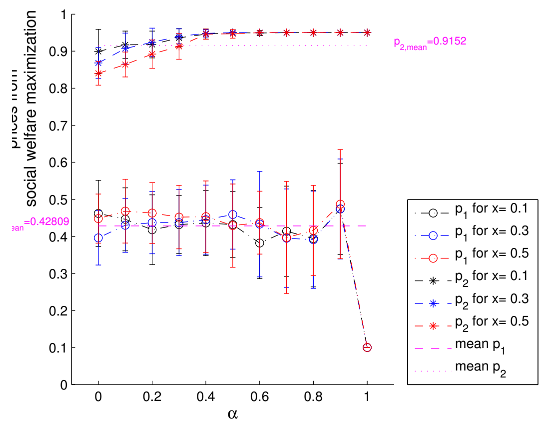


(a) prices vs. x (b) prices vs. α

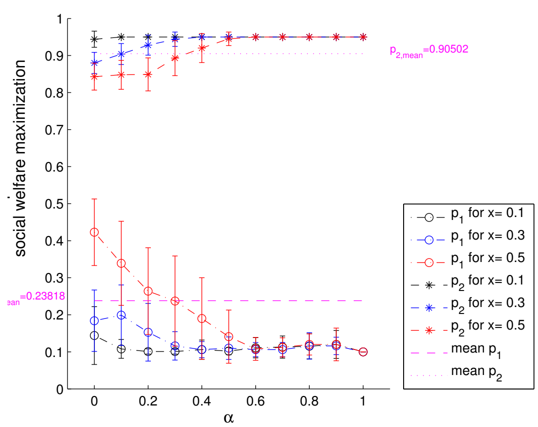
Figure A.2: Prices from social welfare maximization using linear Mapping I, for $\zeta = 1.0$, and $n = 50$ runs



(a) prices vs. x



(b) prices vs. α, $\zeta = 0.5$



(c) prices vs. α, $\zeta = 1.0$

Figure A.3: Prices from social welfare maximization using α-sensitive Mapping I, for $\zeta = 0.5$ and $\zeta = 1.0$ respectively and $n = 50$ runs