The QoE Provisioning-Delivery-Hysteresis and Its Importance for Service Provisioning in the Future Internet

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***Abstract*—Quality of Experience (QoE) combines non-technical parameters such as user perception, experience and expectations with technical parameters such as application- and network-level Quality of Service (QoS). For service or network providers, it is important to understand the quantitative relationship between QoE and these technical parameters in order to manage the user-perceived quality. This paper investigates the different impacts of a) provisioning and b) delivery problems due to insufficient resources on QoE, leading to the QoE provisioning-delivery hysteresis (QoE-PDH). We demonstrate the QoE-PDH for Voice-over-IP, live video streaming, and web browsing based on existing measurement studies. The results clearly quantify the necessity to control quality, instead of suffering from uncontrollable impacts like packet loss caused by congestion. The implementation and the limitations of the QoE-PDH in the current Internet is shown using the example of Skype. Afterwards we discuss how these results can be used to enhance energy-efficient service provisioning and delivery in the Future Internet.**

I. Introduction

User satisfaction with application and service performance in communication networks has attracted increased attention during the recent years. A user of an Internet service may choose from a variety of service and network offers. From the user point of view, the perceived quality is an important criterion whether to stick to or whether to leave a provider. A typical trigger for the latter are recurring quality problems for a service. Quality of Experience (QoE) combines non-technical parameters such as user perception, experience and expectations with technical parameters such as application- and network-level Quality of Service (QoS).

For a service provider or network provider being responsible for the delivery of the service to the end-user, it is thus important to understand the relationship between user perception and performance characteristics of the service provisioning through networks. In [9], generic interdependencies between QoE and QoS were investigated and categorized, formulated through various differential equations yielding exponential or logarithmic QoE-QoS relationships. In the course of this work, it became apparent that the impact of provisioned resources (such as link capacity) on QoE differs substantially from the impact of failure in delivery due to congestion (leading to packet losses). It was observed on the example of web surfing traffic that a certain controlled reduction of the goodput of a connection, e.g. through traffic shaping, affected the QoE to a much lesser extent that the uncontrolled reduction through loss, making TCP react strongly and response times explode. This effect is referred to as *QoE provisioning-delivery hysteresis* (*QoE-PDH*) in [9]. The QoE-PDH discusses the different impacts of a) provisioning and b) success or failure in delivery on QoE.

In this paper, the QoE-PDH is shown for different measurement studies taken from literature. In particular, we quantify a) the impact of provisioning by reducing the required bandwidth consumption and b) the impact of congestion in terms of packet loss on the QoE for Voice-over-IP [3], [15], live video streaming [24], [25], and web browsing [9], [19]. The results clearly quantify the necessity to control quality, instead of suffering from uncontrollable impacts, and give an implementation guideline for network or service providers. The hysteresis provides a striking motivation for employing elastic adaptation mechanisms to available resources instead of suffering from uncontrolled data loss. For an optimized resource usage, necessary information has to be communicated between the application and the network and vice versa.

However, in the current Internet, information asymmetry [4] prevails due to the missing information exchange between network and service providers. Service providers do not know the network load and network providers do not know the service requirements, respectively. Thus, edge-based applications shift quality and network adaptation intelligence to the edge of the network and perform traffic management on application layer. A prominent example is the Skype application for Voice-over-IP (VoIP) and video conferencing. We discuss how Skype applies the QoE-PDH and tries to maximize the QoE on application layer by reacting to packet loss and bandwidth limitations. Although Skype is able to maintain a good QoE for its users, this edge-based intelligence may result in an unnecessarily increased resource consumption for the network provider due to the aforementioned information asymmetry.

Currently, different approaches are discussed how to overcome this information asymmetry. Prominent examples are oracle services offered by the ISP [1] or the concept of Economic Traffic Management (ETM) [7] as discussed in the SmoothIT project, while the ALTO IRTF discusses the deployment of such concepts in the Internet with respect to protocols and interfaces. The common denominator of these solutions is information exchange between the network provider and the service provider (or the application). Such an information exchange allows optimizing resource utilization with respect to the user perceived quality and the costs for network or service providers. For the use case of web browsing, we investigate the potential of the QoE-PDH to increase the number of supported users of the service and thus decrease the energy consumption per user.

The remainder of the paper is structured as follows. Section II gives a comprehensive background on existing works. In particular, notions describing the relationship between QoE and QoS to quantify the impact of provisioning and service delivery are introduced. Then, the QoE-PDH is explained formally. Section III presents different examples for the QoE-PDH by means of measurements conducted in our test laboratory or available in literature. It has to be noted that the paper revisits several studies from literature with respect to the QoE-PDH. Therefore, the related work cannot be summarized in a single section, but references to related work are given throughout the paper. Section IV discusses the information asymmetry in the current Internet and shows how edge-based applications try to overcome this issue. The potential gain of the hysteresis and the importance for service provisioning in the Future Internet is highlighted in Section V. To this end, we will discuss a QoE-based dimensioning of resources on the use case of energy savings for web browsing. We conclude the paper in Section VI.

II. Notions and Background

This section summarizes the differential equations presented in [9] and discusses the results with respect to related work.

A. Notions

In this subsection, we introduce a couple of notions of importance for the remainder of this work.

Subjective measures of QoE that grow with the degree of user satisfaction are called *satisfaction rating*. A typical example is the mean opinion score as measure for the overall quality of e.g., a web service [19].

Regarding the QoS measures, we need to distinguish between different sensitivities as follows:

- A *failure measure* $\bar{Q}oS_\mathrm{f}$ grows with degree of failures. Most QoS parameters are of this kind and related to packet delivery problems. Prominent examples are *loss ratios* L, jitter measures, reordering ratios or waiting times.
- A *success measure* QoS_s is the opposite of a failure measure; it grows with the degree of success with using a resource. Examples are availability measures, often given by the numbers of nines (e.g. four nines denote 99.99 % availability), or the *packet delivery ratio* $D = 1 - L$.
- A *resource measure* QoS_r is similar to the success measure in the sense that it grows as conditions improve. However, the reason for the improvement is rather found in an increased amount of resources than in better success in using the resources. A typical resource measure is the provisioned *throughput*.

We investigate the influence of two different kinds of quality degradation, that are

- *controlled quality degradation*, i.e. a controlled adaptation to a bottleneck capacity either through protocols like TCP, or content adaptation like codecs with lower bandwidth;
- *uncontrolled quality degradation*, i.e. an uncontrolled adaptation to a bottleneck capacity, typically resulting in packet loss.

We consider these impacts separately from each other in the following.

B. QoE Delivery – Impact of Uncontrollable Parameters

This subsection highlights the impact of $\bar{Q}oS_\mathrm{f}$ and QoS_s on the QoE with the help of the partial differential equations presented in [9]. The relationship between *satisfaction rating* and *failure measure* can be described as either exponential or logarithmic behavior:

$$QoE(\bar{Q}oS_\mathrm{f}) = \alpha + \beta \exp(-\gamma \bar{Q}oS_\mathrm{f})\,, \qquad (1)$$

$$QoE(\bar{Q}oS_\mathrm{f}) = \alpha - \beta \left|\log(\bar{Q}oS_\mathrm{f})\right|\,, \qquad (2)$$

where $\alpha \geq 0$, $\beta \geq 0$ and $\gamma \geq 0$. Although these coefficients are used in all formulae (1) to (5), they do not necessarily have the same value(s). Both functions are of convex nature and have similar shapes.For the sake of simplicity we will use the exponential relation between *satisfaction rating* and *failure measure* in the following. Nevertheless the results and discussions also apply for the logarithmic relationship.

The latter result can be extended to a relationship between *satisfaction rating* and *success measure*:

$$QoE(QoS_\mathrm{s}) = \alpha + \beta \exp(\gamma QoS_\mathrm{s})\,, \qquad (3)$$

indicating a relation between the packet delivery ratio and the user-perceived quality.

C. QoE Provisioning – Impact of Controllable Parameters

This subsection highlights the impact of QoS_r on the QoE, as investigated in [9]. Here, again an exponential and a logarithmic relationship were provided by resolving partial differential equations:

$$QoE(QoS_\mathrm{r}) = \alpha - \beta \exp(-\gamma QoS_\mathrm{r})\,, \qquad (4)$$

$$QoE(QoS_\mathrm{r}) = \alpha + \beta \left|\log(QoS_\mathrm{r})\right|\,. \qquad (5)$$

Both functions are of concave nature and have similar shapes. This behavior for providing better quality by increasing the required bandwidth was investiged by [18], [22], [24] for instance. We will use the logarithmic relationship between the *satisfaction rating* and the *resource measure* in the following. However, results and discussions also apply for the corresponding exponential relationship.

D. The QoE Provisioning-Delivery-Hysteresis

In this section, we will highlight the different impacts that provisioning and (lack of) success of packet delivery have on QoE. To this aim, we consider *goodput* Φ, that means the application perceived throughput, as joint parameter. Furthermore, the *goodput ratio* x is defined as the relative goodput as compared to an optimal value C for which the QoE is maximised, i.e. $x = \Phi/C$. For $x = 1$, the observed QoE is maximal and cannot be improved by higher goodput.

Goodput and goodput ratio can be affected by:

- controllable quality distortion through resource allocation $QoS_\mathrm{r} < C$, yielding $x = QoS_\mathrm{r}/C$;
- uncontrollable quality distortion through data loss $\bar{Q}oS_\mathrm{f}$, yielding $QoS_\mathrm{r} = 1 - \bar{Q}oS_\mathrm{f}$ and thus $x = QoS_\mathrm{s}/C = (1 - \bar{Q}oS_\mathrm{f})/C$.

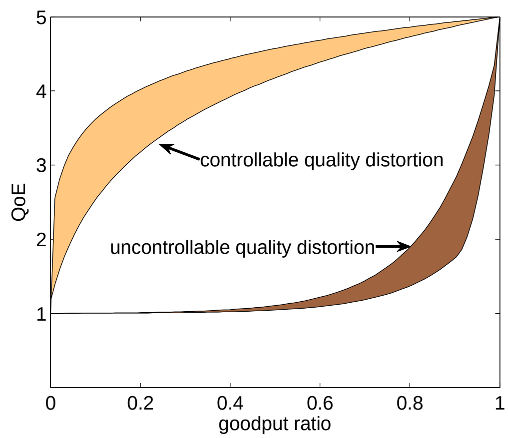

Fig. 1. Illustration of the QoE Provisoning-Delivery Hysteresis.

Figure 1 sketches the postulated hysteresis as a set of functions of the goodput ratio. While specific relationships between QoE and goodput ratio depend amongst others on application and context, we observe two fundamentally different areas. Controllable quality distortion allows for keeping the QoE rather high in view of considerable savings, i.e. goodput ratios much smaller than one. Significant decreases in QoE are observed for rather small goodput ratios. Uncontrollable quality distortion, however, yields a completely different behaviour. Small decreases in the goodput ratio imply large decreases in the QoE values, while that decrease flattens out at the lower edge of the QoE scale as the goodput ratio sinks. This implies that, in order to ensure good QoE, controlled actions are superior over problems that appear in an uncontrolled way.

III. Examples of the QoE Provisioning-Delivery Hysteresis

In this section we present examples for the QoE-PDH. The first example discusses the hysteresis for the cases of VoIP, the second example shows the relation for the case of web browsing, and the third for the case of live video streaming. The x-axis depicts always the goodput ratio as introduced in Section II-D.

A. The Case of Voice-over-IP

Mu et. al [15] consider the impact of packet loss on the voice quality as well as the bandwidth consumption and the maximum voice quality for different codecs or codec settings. For quantifying the user perceived quality, the authors use an utility value, the R score computed by means of the E-Model [10]. Further, they use the measurement results presented in [3] to discuss the impact of different codecs or codec settings with lower bandwidth requirements on the quality degradation. For

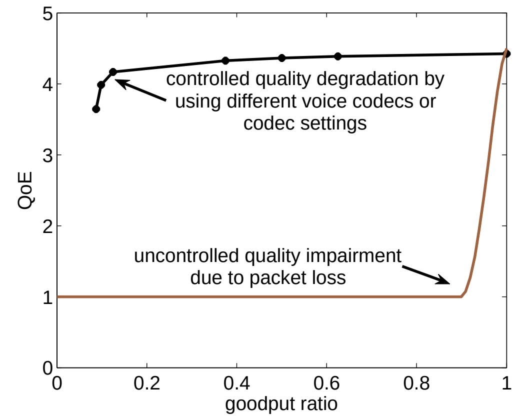

Fig. 2. Provisioning-Delivery Hysteresis for VoIP based on utility functions taken from [15].

our investigation we transformed the R values to MOS values according to [10]. Figure 2 shows the QoE in terms of MOS depending on the goodput ratio for both cases, a) the controlled quality degradation by using different voice codecs or codec settings and b) the uncontrolled quality impairment due to packet loss. First of all, the shape of the controlled quality degradation curve is of concave nature, whereas the shape of the packet loss curve is of convex nature, as discussed in Section II. Further, it can be seen, that the quality degradation due to lower bandwidth codecs or codec settings outperforms the impairments due to packet loss in terms of user perceived quality significantly. Thus, the QoE-PDH can be applied to VoIP.

B. The Case of Live Video Streaming

Next, we investigate the case of live video streaming as discussed in [23], [25]. For video delivery a controlled quality reduction can be achieved by reducing the resolution, frame rate or image quality, cf. [23], [24], whereas uncontrolled quality reduction is caused by packet loss [25]. The results discussed in the following, are taken from [25]. Here a lower video quality and thus a lower bandwidth consumption is achieved by reducing the resolution of the video. It should be noted, that the maximum MOS value, i.e. the best user quality for the video is $MOS_\mathrm{max} = 3.86$. Figure 3 illustrates the results for the performed measurements for different video clips, indicated by the different lightness of the curves. The dots represent the results of a single measurement experiment, while the solid lines represent the fitting functions according to [25]. The MOS values, depicted on the y-axis, denote the QoE as a function of the goodput ratio depicted on the x-axis. We can recognize two sets of curves, independent of the content of the three different video clips: (1) the upper, concave ones, emanating from variations of the resources, i.e. from a controlled quality degradation; (2) the lower, convex ones, emanating from goodput reduction due to losses, i.e. from an uncontrolled quality degradation. Starting from ideal conditions ($QoE = 3.86$ for maximal goodput) we consider five percent of goodput reduction, either through five percent packet loss or through five percent throughput reduction. While the QoE in case of a controlled throughput reduction is still high (≥ 3.5), the packet loss has significantly disturbed the video quality resulting in a low QoE (≤ 1.7). Further, a rather limited dependency on the content can be derived from the presented results. Similar results were reported for IPTV streaming by [22].

As we can see, a reduction of the quality in order to adapt the video bandwidth to the available network resources in terms of end-to-end bandwidth results in still a high QoE while the bandwidth consumption is significantly reduced. But as soon as packet loss appears, the video quality is lowered significantly, resulting in unacceptable service. Thus, the QoE-PDH is successfully demonstrated for video streaming.

C. The Case of Web Browsing

The last example investigates the QoE-PDH for HTTP/TCP-based web surfing as described in [9]. TCP is an elastic transport protocol which allows an adaptation to network congestion in two ways: (a) via increased round-trip times (RTT) delaying the delivery of acknowledgments or (b) via packet losses causing the reduction of TCP's sending window size. Both possibilities result in a reduction of the sending rate affecting the application-perceived throughput. Thus, the user-perceived response time is increased, resulting in a lower user satisfaction. However, both adaptation mechanisms are quite different; while option (a) results in a decent adaptation of the sending rate to the capacity of a loss-free bottleneck link, option (b) typically results in a heavy impact on the sending rate, when the sending window size is reduced. For both options, satisfaction rating functions are provided by [9] for $x \in [0,1]$ as follows:

$$QoE_r(x) = \max\{1, 5 + 1.5\ln(x)\}, \quad (6)$$
$$QoE_s(x) = \max\{1, 1.13 \cdot 10^{-8}\exp(19.91x)\}, \quad (7)$$

where QoE_r describes the rating concerning the loss-free adaptation to the bottleneck capacity and QoE_s describes the user rating in case of packet loss-based throughput adaptation.

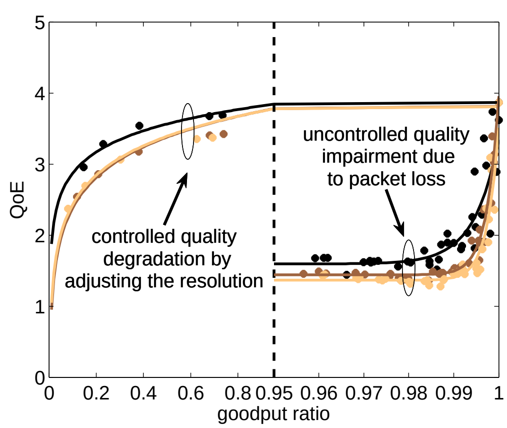

Fig. 3. Provisoning-Delivery Hysteresis for Video Streaming based on QoE measurements [23], [25].

The results for the user rating are illustrated in Figure 4 as functions of the goodput ratio on link level.

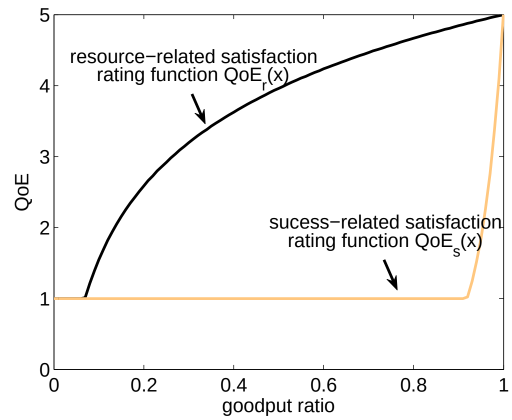

Fig. 4. Provisiong-Delivery-Hysteresis for web traffic based on QoE measurements [19].

Starting from ideal conditions ($QoE = 5$ for maximal goodput), we consider five percent of goodput reduction, either through five percent packet loss or through five percent throughput reduction. This yields $QoE_r(0.95) = 4.92$, i.e. still a very good user rating, as compared to $QoE_s(0.95) = 1.85$, i.e. a quite bad user rating. As we can see, a reduction of the bottleneck capacity allowing TCP to adapt to the changed conditions decently still yields a high QoE, although network resources are reduced. But as soon as significant loss appears, TCP reacts by lowering the throughput significantly. This has a strong impact on the user perceived quality resulting in a low QoE.

To summarize the results for the different examples in this section, we see that the QoE-PDH can be applied to different multimedia applications, like VoIP or video streaming, as well as for other interactive applications like web browsing. It came out that a controlled degradation of a resource outperforms uncontrolled degradation significantly in terms of user-perceived quality. In the next section, we will demonstrate how this general relationship is exploited by intelligent applications for maximizing the user perceived quality of their service.

IV. Implementation of the QoE-PDH in The Current Internet

In the current Internet, there exists an information asymmetry between network provider and the application or service provider, which we briefly emphasize in see Section IV-A. Then, we discuss how todays applications like Skype overcome this limitation in Section IV-B.

A. Information Asymmetry between Network and Application

The missing communication between network and service provider leads to an information asymmetry, illustrated in Figure 5. The service does not take the underlying physical infrastructure into account and the network does not know the requirements of the service. The information asymmetry

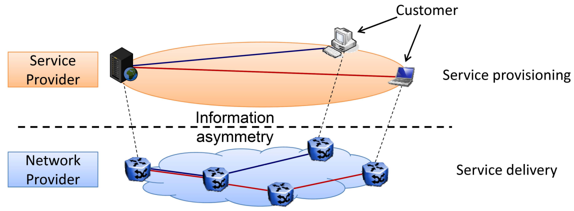

Fig. 5. Information asymmetry between service and network provider.

resulting from the lack of communication between overlay and underlay leads to an increase of provider costs and a decrease of end user's Quality of Experience.

For a video streaming service, the video streaming server could reduce the video bitrate, if there is a bottleneck within the network, in order to encounter congestion. This could be achieved by signaling the video streaming server *before* congestion occurs. Vice versa, if the application communicates its service requirements, e.g. in terms of average throughput, then the network provider could try to provision accordingly the service in the network.

Another prominent example currently discussed in literature is the information asymmetry emerging in P2P networks [1], [4], [17]. The overlay connections used by these networks are up to now generally network-agnostic and therefore wasteful with resources. For such a network it does not matter if the required data are downloaded from a peer located in the same domain or in the domain of another Internet Service Provider. However, the network provider would prefer communication with peers in his own domain since the usage of transit links between ISPs is costly in general.

Therefore, it is desired that the underlay provides some kind of information to the overlay application. The aim is to support traffic management of the overlay application and to prevent any negative effects on both parties caused by the information asymmetry, i.e. increased costs and reduced QoE. In any case, any information exchange must be able to lead to a "win-win" scenario for all parties involved. The prioritization is the result of an economic decision function which takes into account both requirements: reduction of provider costs and improvement on users' QoE.

B. Implementation of the QoE-PDH by Skype

The information asymmetry of current Internet streaming multimedia applications is inherently caused by the underlying protocol stack. These applications face the problem that their predominant transport protocol UDP does not take any feedback from the network into account. Consequently, any quality control and adaptation has to be applied by the application itself at the edge of the network. The network providers have to cope with the fact that these edge-based applications dynamically determine the amount of consumed bandwidth. In particular, applications such as Skype which is mainly used for VoIP or video conferencing do their own network quality measurements and react to quality changes in order to keep their users satisfied. In other words, edge-based applications perform QoE management and traffic control on application layer to resolve the information asymmetry in the current Internet.

Skype is a proprietary application which is based on P2P technology. It offers rapid access to a large base of users, seamless service operation across different types of networks (wireline and wireless) with an acceptable voice quality, as well as a distributed and cost-efficient operation of a new service. The good voice quality of the Skype service is achieved by appropriate voice codecs, such as iSAC and iLBC, as well as by adapting the traffic rate of the sender to the current conditions in the network which are described by classical end-to-end QoS parameters, like packet loss or jitter. However, the end-to-end QoE perceived by the user is the essential criterion for the subscriber of a service. In the following, we show measurement results for Skype VoIP as well as for Skype video conferencing. In both studies, it is revealed that Skype does QoE management and implicitly applies the QoE-PDH.

1) Skype VoIP Telephony: In [2], [12], a detailed analysis of Skype traffic is provided. It is shown that Skype distinguishes and reacts differently to packet losses and network congestion. However, since there is currently *no cooperation between service and network provider*, there is no information available at the application layer about the reason for the lost packets, i.e. lossy links or congestion. As a consequence, the application itself has to decide about the underlying network problem.

In case of lossy links, controlled quality degradation, e.g. using codecs with less bandwidth demands, may not be useful, since packets get lost randomly independent of the used voice codec. Thus, in order to overcome random packet losses, forward error correction mechanisms (FEC) are applied. An adequate and simple mechanism for VoIP is to replicate the voice datagrams. [13] shows that the duplication of voice packets for the iLBC codec improves the voice quality from a bad QoE (MOS value 2.29) to a good QoE (MOS value 3.63). However, this means that the bandwidth consumption is also doubled to achieve the better QoE. This is exactly what Skype does.

Figure 6 shows the reaction of the Skype software on packet loss, cf. [12], [13]. Every 30 ms, a UDP packet is sent from user A to user B (with a measured standard deviation of 6.65 ms). The measured packet loss ratio on the right y-axis denotes how many packet got lost, whereby we used the average for a time window of 6 s. On the left y-axis, Skype's bandwith consumption is plotted in kbps. First the Skype call is established between the users with no packet loss. After 5 minutes the packet loss probability is increased about 5% every two minutes, until the packet loss probability reaches 30%. The time interval of two minutes was chosen to ensure that Skype reacts to changes in the network [12]. As we can see in Figure 6, Skype reacts on the experienced QoE degradation in terms of packet loss by increasing bandwidth. This means that Skype sends now redundant information within every voice packet while experiencing packet loss in order to maintain the QoE. However, as a certain threshold is exceeded (here: about 20% packet loss), the bandwidth is lower than in the beginning. This indicates a change in the used voice codec. In other words, Skype assumes congestion in the network and applies the QoE-PDH by using voice codecs with less bandwidth requirements.

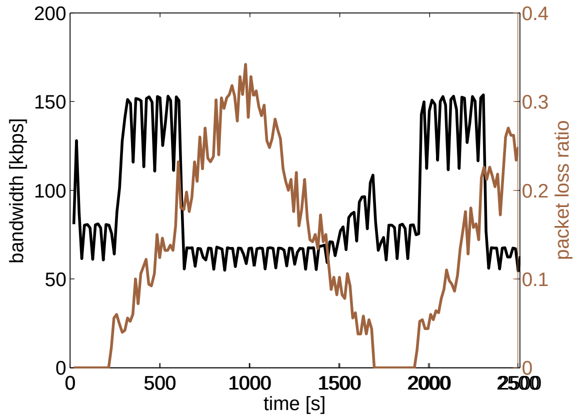

Fig. 6. Bandwidth adaptation by Skype as measured in [12], [13].

As soon as the packet loss probability is decreased again and falls below a certain threshold, the sender rate is again adapted by doubling the bandwidth consumption.

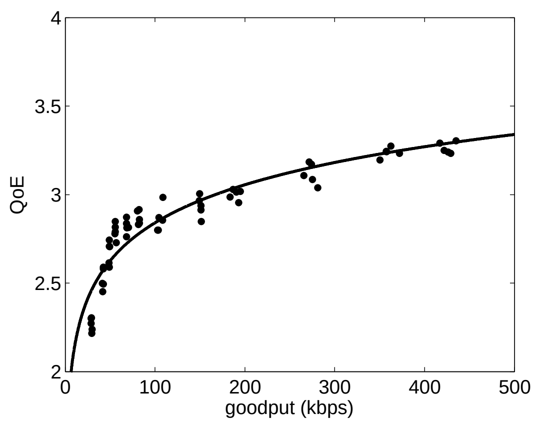

Fig. 7. QoE provisioning by Skype for videoconferencing.

2) Skype Video Conferencing: The responsiveness of Skype video conferencing to bandwidth variations was reported in [5]. The authors changed the network capacity during video calls and captured the reaction of Skype, which adopted the required bandwidth, similar to the findings for VoIP in Section IV-B1. In order to enhance their investigation with respect to quantifiying the user perceived quality we set up a similar experiment. Further, we captured the video stream at the destination with SkypeCap [14] and compared the source video with the captured video clip using the SSIM [21] implementation provided by the MSU tool [11]. The results of SSIM were mapped to MOS values with the mapping function presented in [6].

The results of the investigation are depicted in Figure 7. The x-axis denotes the average goodput ratio of the skype video call, whereas the y-axis denotes the MOS value. We observe the typical convex QoE provisioning relationship versus rising goodput as discribed in Section II. It can be seen that Skype adopts the quality of the video stream and also the required bandwidth in order to react to bottleneck capacity. This means that Skype implements the QoE-PDH in order maximize the QoE of its customers.

3) Limitations of the Skype Approach: As we have seen, Skype compensates the missing network information on service level by performing network measurements and thus estimating the current state of the network. Thus, it is able to adopt to the network either by changing the codec or codec paramters, or appending additional redundacy to compensate packet loss. If congestion is the reason for packet loss, the increased bandwidth consumption by Skype has two effects. First, the increased UDP traffic pushes away well-behaving traffic, e.g. TCP traffic, resulting in an increased traffic share for the selfish Skype application. Thus, Skype is able to deliver still a good QoE to its customers, while the performance of other applications is reduced due to packet loss and unfairness. Second, if it is not possible to push away other traffic, i.e. to be the winner in the congestion battle, an increased bandwidth consumption due to FEC worsens the congestion situation. In this case, Skype applies the QoE-PDH and performs quality degradation by using different codecs or codec settings for the voice and video transmission, respectively. However, the service for Skype and the other customers could be enhanced significantly by providing network information for the Skype service. Based upon this information, the application could determine the congestion state and adopt codecs and codec parameters. This would allow an appropriate customization of the service for the current network state.

V. Application of QoE-PDH for Service Provisioning in the Future Internet

For the future Internet, several possibilities introducing communication between the network and service provider to overcome this information asymmetry are currently being discussed, such as Economic Traffic Management [7] or oracle services [1] to mention two examples. In this section, we want to highlight the potential gain and the importance for service provisioning in the Future Internet. To this end, we will discuss a QoE-based dimensioning of resources, such that the costs for providers can be reduced while the users still experience a good quality. In particular, the hysteresis presented above can be applied to energy saving considerations. For that we discuss the use case web browsing as presented in Section III. Due to the similar QoE-PDH shapes of the other use cases the investigations are similar and can be applied in the same manner.

Let us define the resource consumption in the case of optimal QoE as r. We assume r to be constant over time, which does not allow for multiplexing gains [8]. Thus, the resource consumption of N homogeneous users amounts to Nr, and the maximal number of users that can be supported by a capacity C is given by

$$N_{\max}^{\text{excl}} = \left\lfloor \frac{C}{r} \right\rfloor . \tag{8}$$

Energy savings can be reached in two different ways:

1) By downscaling the energy consumption as a function of the actually used capacity $N r$ [16], [20], e.g. through rate scaling;
2) By "squeezing" additional traffic onto the link ($N > N_{\max}^{\text{excl}}$), leaving us with a relative share per customer of

$$x = \frac{C}{N\, r}\,. \tag{9}$$

Both ways could be combined, e.g. by reducing the capacity to

$$C^{-} = N\, x\, r\,. \tag{10}$$

Let us first (in Figure 8) consider the QoE, expressed in Mean Opinion Scores (MOS), as functions of N for different ratios of capacity C and the resource need of a single user r in order to maximise the MOS. We focus on the web example shown before, in which the obtainable throughput $x\, r$ determines the response time as a key QoE parameter.

Obviously, as long as N stays below C/r ($x \geq 1$), the MOS is maximised, but starts dropping as N grows ($x < 1$), with decreasing gradient as both N and C/r are growing. This is due to the logarithmic shape of the upper *provisioning* branch of the hysteresis. It practically means that a good quality (MOS $= 4$) can still be reached for approximately $2\, N_{\max}^{\text{excl}}$, which is illustrated by the admission control boundary for good quality in Figure 8. The latter is also seen from Figure 9 that shows the number of users N as a function of capacity C/r for different MOS values. The lower the MOS, the steeper the raise. We roughly observe a doubling of N when the MOS sinks from "excellent" (5) to "good" (4), and another doubling when the MOS sinks to the acceptability threshold (3).

The reduction of the MOS in a controlled way (by decreasing the assigned capacity per user to a share $x < 1$) allocates a *gain*

$$G = \frac{N r}{C} = \frac{1}{x}\,, \tag{11}$$

which in case of the logarithmic upper curve of the hysteresis

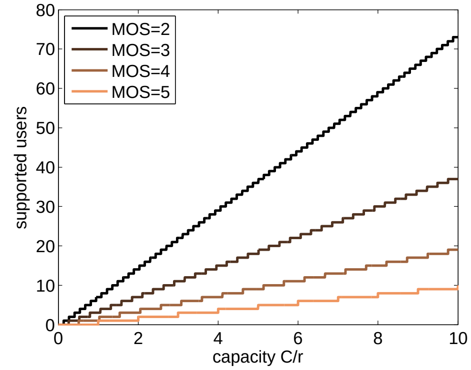

Fig. 9. Number of supported users as a function of the MOS value for different capacities C/r

MOS $= \alpha + \beta \ln(x)$ according to (6) reads

$$\begin{aligned} G &= \exp\left(\frac{\alpha - \text{MOS}}{\beta}\right) \\ &= \exp\left(\frac{10 - 2\text{MOS}}{3}\right)\,. \end{aligned} \tag{12}$$

On the other hand, an uncontrolled way of sharing the capacity that would imply a loss ratio $L = 1 - x$ and MOS $= \alpha + \beta \exp(\gamma(1 - l))$ according to (7) yields a gain of

$$\begin{aligned} G &= \frac{1}{1 - L} \\ &= \frac{\gamma}{\ln(\text{MOS} - \alpha) - \ln(\beta)} \\ &= \frac{19.9}{\ln(\text{MOS}) + 18.3}\,. \end{aligned} \tag{13}$$

Considering that $\ln(\text{MOS}) \in [1.1, 1.6]$ for $MOS \geq 3$, it is obvious that $G \simeq 1$. In other words, riding the lower *delivery* branch of the hysteresis cannot yield any gain. Figure 10 illustrates the gain curves belonging to the two branches.

The considerations above reveal a potential for energy savings: Obviously, it is possible to increase the gain and thus decrease the energy consumption per user significantly at

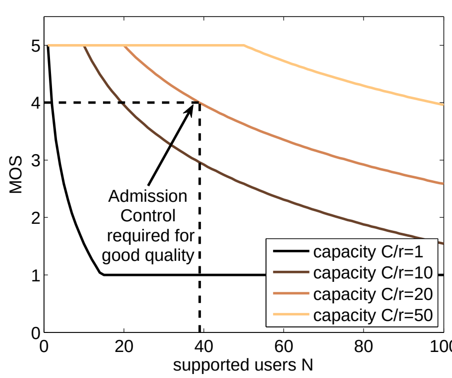

Fig. 8. User perceived quality as a function of the supported number of users for different provided capacities

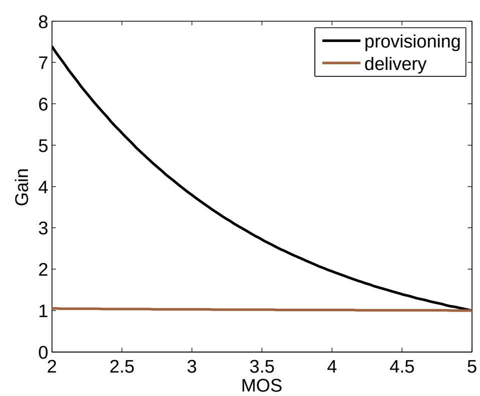

Fig. 10. Gain curves of service provisioning and service delivery in case of web browsing

a quite moderate expense in terms of QoE. Indeed, a doubling of the number of users lowers the MOS by approximately one step, which is due to the logarithmic nature of the underlying QoE-QoS relationship. However, this gain can be allocated if and only if the throughput per connection is reduced in a way that no delivery issues such as loss and extraordinary delay (jitter) arise.

VI. Conclusions and Outlook

The QoE provisioning-delivery hysteresis (QoE-PDH) highlights the different impacts of a) provisioning and b) success or failure of packet delivery on QoE. It is shown that the difference between both cases is tremendous. On one hand, a slight reduction of provisioning goes hardly unnoticed: A controlled adaptation to a bottleneck capacity either through protocols like TCP or content adaptation through using some scalable video codec is hardly perceived by the end-user in terms of QoE. On the other hand, uncontrolled resource degradation in the same order of magnitude causes unacceptable QoE: An uncontrolled adaptation to a bottleneck capacity, typically through packet loss, is strongly perceived by the end-user. Resource allocation that tries to squeeze too many uncoordinated requests on filled-up resources adventures the QoE of everyone using that resource.

The observations of this QoE hysteresis effect teaches us to try to make applications as elastic as possible in order to avoid delivery problems. It is definitely recommended to ride the upper curve of the hysteresis in a controlled way instead of getting cast onto the lower curve due to bad network conditions. Thus, the QoE-PDH helps to optimize the usage of existing network resources to maximize the overall QoE in relation to boundary conditions such as energy consumption.

We also discussed the impact of the information asymmetry between network and service providers and showed how the Skype application overcomes this asymmetry. It applies the QoE-PDH and reacts accordingly to packet loss or congestion in the networks, however in a selfish way. We summarized the limitations of this approach and motivated the need of communication between network and service providers as suggested by management concepts like ETM. Our results clearly showed the potential gain of such an approach for reducing the energy consumption per user in particular and for future service provisioning in general.

Future work will address further quantifications of different hystereses, e.g. for different voice or video codecs and response time issues. We will also examine the simultaneous impact of resource management measures and delivery issues on the hysteresis.

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