Quality of Experience-Related Differential Equations and Provisioning-Delivery Hysteresis

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***Abstract*—Churn of revenue-generating and dissatisfied users has become a major point of concern for service providers and network operators. As services rely on interconnecting networks, service performance and thus user satisfaction depend on network performance. Consequently, it is of outmost importance to understand the relationships between user perception, captured by quantitative Quality of Experience (QoE) parameters, and network performance, described by Quality of Service (QoS) parameters. This paper provides insights into fundamental relationships between QoE and QoS, formulated as partial differential equations describing changes in QoE with respect to specific QoS parameters. A set of illustrating examples is given. Furthermore, the different impacts of provisioning and degree of success or failure of delivery on QoE are discussed, leading to QoE provisioning-delivery hysteresis. This hysteresis provides a striking motivation for employing elastic adaptation mechanisms to available resources instead of suffering from uncontrolled data loss.**

I. INTRODUCTION

In times of fierce competition, the users' strong position in the ever-growing market of services on one hand and limited resources on the other hand keeps increasing providers', operators' and researchers' interest in performance issues. The user has moved into the center of the interest, as she is finally generating revenue for providers (and operators). If user perception of a service is besmirched and a competing serviced seems to offer better priceworthiness, the user churns, which means loss of revenue for the overgiven provider. The latter finds itself heckled between the users' economic power on the one hand and cost, capacity and environmental limitations on the other hand. It is thus of outmost importance to understand the relationship between user perception and performance characteristics of the service provisioning through networks. As services rely on interconnecting networks, service performance and thus user satisfaction depend on network performance [1]. Network performance is thus one of the ultimate enablers or disablers of user perception and readiness to pay for a service.

Originally, the concept of *Quality of Service* (QoS) was to characterise the "degree of satisfaction of a user of the service" [2]. Later on, the provisioning of QoS became business of the network, trying to integrate or differentiate between traffic streams as integral part of services, typically targeting to provide them with "better-than-best-effort" service. QoS parameters nowadays relate to the network's transport capabilities. In the meantime, the notion of *Quality of Experience* (QoE) arised, which according to [3] may be defined as "overall acceptability of an application or service as perceived subjectively by the end-user". The main difference between QoE and QoS is the focus, namely user versus network. However, end-to-end QoS is an important enabler for QoE. This motivates the need for investigating relationships between user-oriented QoE and network-oriented QoS parameters. In particular, it is of interest to gain insight into the principle ways in which QoS parameters affect the quantitative parts of QoE, e.g. ratings on a linear scale given by user themselves or on behalf of users by an algorithm.

Given this background, this paper presents a fundamental and systematic investigation of relationships between QoE and QoS. It builds upon recently discovered differential equations [4]–[6] that motivate the frequently observed appearance of "natural" functions, i.e. exponentials and logarithms [1], [4], [7], [8]. So far, describing QoE by differential equations is still in its infancy, and also, a systematic catalogisation of so-far known differential equations is missing. This paper aims at closing that gap. Doing so, it takes into account different natures of QoE and QoS parameters. The quantitative rating related to QoE considered in this paper can be related to the degree of user *satisfaction* [4], [8] of *dissatisfaction* [7], while QoS can be given as measure for *failure* [1], [4], *success* or *resources* [7]. It will be shown that these different interpretations of measures have a major impact on the shape and understanding of the fundamental relationsips. In particular, for elastic applications, the impact of resources (such as link capacity) on QoE differs substantially from the impact of success or failures in packet delivery (such as losses). Our quantification of this difference helps to gain a deepened understanding of the potential that elasticity of network traffic has for users and providers, and in which way this elasticity can be employed to find a good balance between user satisfaction and network usage.

The remainder of the paper is structured as follows. Section II introduces a set of key notions to be used throughout the paper. Section III contains a catalogue of differential equations, expressing fundamental relationships between QoE and QoS, and Section IV illustrates these basic forms by published examples. Section V demonstrates the important difference between the impacts of resources and failures on QoE for elastic traffic. Section VI concludes the paper and presents future work.

II. NOTIONS

In this section, we introduce a couple of notions of importance for the remainder of the paper. Regarding the QoE rating, we distinguish between

- *Satisfaction rating* QoE that grows with the degree of user satisfaction, e.g. mean opinion scores about the overall quality of the web service [1];
- *Dissatisfaction rating* $\bar{Q}oE$ that grows with the degree of user dissatisfaction, e.g. the ratio of web browsing users canceling a web session due to a bad overall quality [7].

Both QoE-related ratings are obtained either by observing or asking the user (typically on a linear scale between 1 = worst and 5 = best, cf. [1], [9]), by an algorithm on behalf of the user (e.g. the Perceptual Evaluation of Speech Quality, PESQ [10], subsequently transformed into Mean Opinion Scores, MOS [9], [11]), or by measuring user reactions such as e.g. abandonning sessions [7] or varying the session volume [1].

Regarding the QoS measures, we distinguish

- *Failure measure* $\bar{Q}oS_\mathrm{f}$ that grows with degree of failures or problems. Most QoS parameters are of this kind and related to packet delivery problems. Prominent examples are *loss ratios* L, jitter measures and reordering ratios [5]. We will even include waiting times [1], [8];
- *Success measure* QoS_s that grows with the degree of success with using a resource. Examples are availability measures – often given in the numbers of nines (e.g. four nines means 99.99 % availability) [12], [13] – or the *packet success ratio*
  $$S = 1 - L\,, \tag{1}$$
  which is a rather uncommon measure so far, but will be helpful in our study;
- *Resource measure* QoS_r that grows with the provided resources, e.g. the provisioned or the yielded *goodput* or *throughput* [1], [7].

The QoS measures are obtained from measurements, and the need for their distinction is motivated by the different cases contained in the next section.

III. BASIC DIFFERENTIAL EQUATIONS

In this section, we review two kinds of differential equations that are underlying exponential and logarithmic relationships between QoE and QoS. The next section will contain some illustrative examples. In order to express the fact that QoE depends on many non- and technical parameters, partial differentiations (∂) are used, and the parameter on which QoE depends is explicitly given as an argument of the corresponding function.

In the sequel, we assume $\alpha \geq 0$, $\beta \geq 0$ and $\gamma \geq 0$; although these coefficients are used in all formulae, they do not necessarily have the same value(s). To limit the QoE-result to the correct area, corresponding max/min operators might need to be employed. Denote $QoE^\star$ as the corrected value reflecting satisfaction, we arrive at

$$QoE^\star = \min\{\max\{QoE, QoE_\mathrm{min}\}, QoE_\mathrm{max}\}. \tag{2}$$

A corresponding relationship applies for the dissatisfaction rating ($\bar{Q}oE$). For the sake of readability, we do not explicitly mention the corrected value $QoE^\star$ for the QoE–QoS relationships in the remainder of the paper.

A. Exponential relationships

Consider the following relationship between *satisfaction* rating and *failure measure* [4], [6]:

$$\frac{\partial QoE}{\partial \bar{Q}oS_\mathrm{f}} = -\gamma(QoE - \alpha)\,. \tag{3}$$

Its solution is of the form

$$QoE(\bar{Q}oS_\mathrm{f}) = \alpha + \beta\exp(-\gamma\bar{Q}oS_\mathrm{f})\,. \tag{4}$$

It starts at $\alpha + \beta$ in the optimal case of no failure and tends asymptotically towards α as the disturbance grows.

Equation (3) communicates that the decline of the QoE value with respect to QoS failure is a function of the current level of QoE. This means that when the QoE is high, a certain additional QoS disturbance has much more effect than if the QoE is already quite low.

Replacing $\bar{Q}oS_\mathrm{f}$ by $QoS_\mathrm{s} \sim -\bar{Q}oS_\mathrm{f}$ leads to a relationship between *satisfaction rating* and *success measure*:

$$QoE(QoS_\mathrm{s}) = \alpha + \beta\exp(\gamma QoS_\mathrm{s})\,, \tag{5}$$

which is the solution of

$$\frac{\partial QoE}{\partial QoS_\mathrm{s}} = \gamma(QoE - \alpha)\,. \tag{6}$$

Here, we face a curve whose gradient is proportial to the attained level of satisfaction.

A second type of relationships relates *dissatisfaction rating* and the *resource measure* [6]:

$$\frac{\partial \bar{Q}oE}{\partial QoS_\mathrm{r}} = -\gamma(\bar{Q}oE - \alpha)\,, \tag{7}$$

which similarly to (6) yields

$$\bar{Q}oE(QoS_\mathrm{r}) = \alpha + \beta\exp(-\gamma QoS_\mathrm{r})\,, \tag{8}$$

where α denotes the asymptote for optimal conditions. Similarly to (3), the dissatisfaction decresases with respect to the QoS improvement due to increased resources in proportion to the current rating.

Replacing $\bar{Q}oE$ by $QoE \sim -\bar{Q}oE$ leads to a relationship between satisfaction rating and resource measure:

$$QoE(QoS_\mathrm{r}) = \alpha - \beta\exp(-\gamma QoS_\mathrm{r})\,, \tag{9}$$

the solution to

$$\frac{\partial QoE}{\partial QoS_\mathrm{r}} = -\gamma(\alpha - \bar{Q}oE)\,, \tag{10}$$

The curve (9) is rising and approaches its asymptote α as the conditions get optimal.

B. Logarithmic relationships

Let us now consider a relationship between *satisfaction rating* and *failure measure* [8] of the type

$$\frac{\partial QoE}{\partial \bar{Q}oS_\mathrm{f}} = -\frac{\beta}{\bar{Q}oS_\mathrm{f}}\,, \tag{11}$$

which yields

$$QoE(\bar{Q}oS_\mathrm{f}) = \alpha - \beta \left|\log(\bar{Q}oS_\mathrm{f})\right| \,. \tag{12}$$

The notation of (11) with absolute value bars has been chosen to ensure the assumption $\beta > 0$ even for $\bar{Q}oS_\mathrm{f} < 1$. Obviously, the underlying differential equation (11) relates the change of the satisfaction to the reciprocal QoS failure, e.g. a waiting time [8]. Similarly to (4), the curve is falling, indicating a slower decrease of satisfaction as failures and discomfort grow.

The other logarithmic relationship of interest quantifies *satisfaction rating* as a function of the *resource measure*. From

$$\frac{\partial QoE}{\partial QoS_\mathrm{r}} = \frac{\beta}{QoS_\mathrm{r}}\,, \tag{13}$$

we arrive at

$$QoE(QoS_\mathrm{r}) = \alpha + \beta \left|\log(QoS_\mathrm{r})\right| \,. \tag{14}$$

Again, we observe that the growth of the rating is proportional to the reciprocal value of the QoS parameter itself instead of the QoE parameter as in the exponential cases described above. This means that the better the QoS, the smaller the effects of an additional improvement. The shape of the curve resembles that of (9).

IV. EXAMPLES

This section illustrates some relationships between the user-oriented QoE and the network-oriented QoS for two different service types, Voice-over-IP (VoIP) and web browsing, which are available in literature. In Section IV-A, the level of satisfaction QoE of a VoIP user is formulated in dependence of the level of disturbance $\bar{Q}oS_\mathrm{f}$. In particular, we consider the impact of random packet losses as well as the impact of re-ordering on packets on the voice quality by means of the PESQ algorithm whose results are mapped to mean opinion scores according to [11]. In contrast to the UDP-based transport of data, Section IV-B considers elastic web traffic transmitted via HTTP/TCP and reconsiders the results from [1], [6]–[8] under the view point of QoE and QoS. To be more precise, the functional relationships between i) QoE (MOS) and $\bar{Q}oS_\mathrm{f}$ (session time), $\bar{Q}oS_\mathrm{f}$ (loss ratio), as well as QoS_r (goodput); and ii) $\bar{Q}oE$ (cancellation rate) and QoS_r (bandwidth) are depicted.

A. VoIP

For VoIP, exponential relationships are seen in [5], [6]. For the quantification of the QoE, the Perceptual Evaluation of Speech Quality (PESQ) method is used which is described in ITU-T P.862 [10]. The resulting PESQ value is mapped into a subjective MOS value according to ITU-T P.862.1 [11]. As 'failure' QoS parameter $\bar{Q}oS_\mathrm{f}$, the packet loss ratio L and the type$_\mathrm{p}$ reordered ratio are considered.

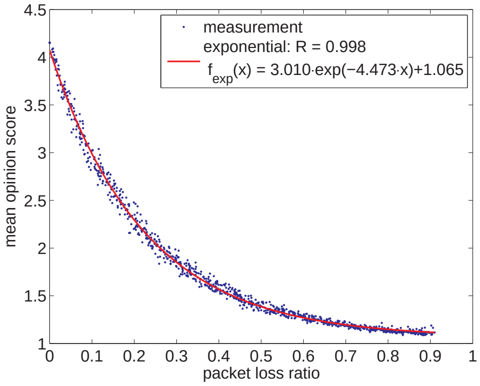

Fig. 1. Measurement results and obtained mapping function between packet loss ratio and QoE for the iLBC codec.

- packet loss ratio $\bar{Q}oS_\mathrm{f} = L$:
  $QoE(L) = 1.065 + 3.010 \exp(-4.473 L/\%)$;
- type$_\mathrm{p}$ reordered ratio $\bar{Q}oS_\mathrm{f} = p$:
  $QoE(p) = 1.411 + 2.482 \exp(-10.453 p/\%)$.

The relationship $QoE(L)$ is illustrated in Figure 1, which shows a good match (correlation coefficient $R = 0.998$) between the measurement results and the exponential function $QoE(L)$. According to [14], the exponential function $QoE(p)$ matches again well the measurement results with a correlation coefficient of $R = 0.993$.

B. Web browsing

Regarding interactive traffic, the functional relationship between QoE and QoS is examined for web browsing based on three different examples. In the first example, the dependency between mean opinion score (QoE) and weighted session time ($\bar{Q}oS_\mathrm{f}$) is analysed. It turns out that both logarithmic [8] and exponential [6] models are available for the same dataset. The second example is the only one which considers the dissatisfaction rating $\bar{Q}oE$. In [7], the cancellation rate of web browsing sessions in dependence of the bandwidth of a user is modelled with a logarithmic function, while in [6] an exponential relationship is derived using the same dataset. The third example [1] investigates the impact of bandwidth and loss ratio on the mean opinion scores of the users which are described via a logarithmic function and an exponential function, respectively.

1) Mean opinion scores QoE vs. weighted session time $\bar{Q}oS_\mathrm{f}$: The ITU-T Rec. G.1030 [8] applies perceptual models to gauge user satisfaction for web-browsing applications. As QoS parameter response and download times were used which were measured in the network or calculated from the HTTP transaction times. In the laboratory experiments, the response and download times were manipulated and the users were asked to evaluate the perceived quality according to the five-point MOS scale. The web session consisted of three steps, reflecting a typical search-for-information situation involving

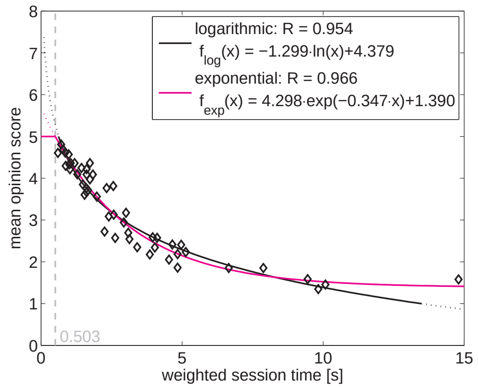

Fig. 2. Measurement results for web browsing according to ITU-T Rec. G.1030 [8] and comparison of logarithmic and exponential model.

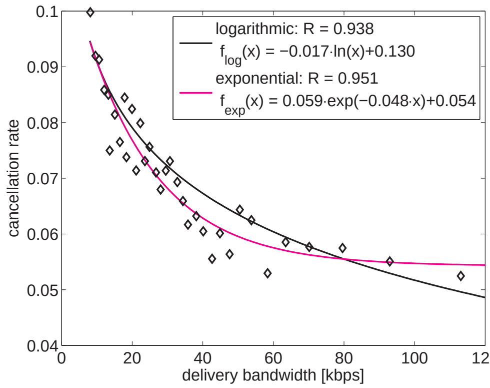

Fig. 3. Measurement results for web browsing taken from Khirman and Henriksen [7] and comparison of logarithmic and exponential model.

(a) requesting a search page; (b) typing and submitting a query; and (c) retrieving the results. As a result of [8], it was found out that for some network settings, the coefficient of correlation between session time and MOS is too low. Therefore, the model was extended and the weighted session time was used as $\bar{Q}oS_{\mathrm{f}}$ parameter. The weighting factors of the different request and response phases for (a)-(c) are calculated such that correlation between the weighted session time and the MOS is maximized.

In [8], the relationship between MOS $QoE(T)$ and weighted session time $\bar{Q}oS_{\mathrm{f}} = T$ is described with a logarithmic function, while in [6] an exponential relationship is identified on the same measurement results:

- logarithmic model [8]:
  $QoE(T) = 4.379 - 1.299 \log(T/\mathrm{s})$;
- exponential model [6]:
  $QoE(T) = 1.390 + 4.298 \exp(-0.347T/\mathrm{s})$.

Both relationships are illustrated in Figure 2, where the exponential relationship slightly outperforms the logarithmic one wrt. correlation coefficient R. Each point in Figure 2 represents the result of a single experiment which is the MOS for the weighted session time observed in this experiment.

2) *Cancellation rate $\bar{Q}oE$ vs. bandwidth QoS_{r}:* The second example stems from [7] and considers the impact of bandwidth $QoS = R$ on the cancellation rate $\bar{Q}oE$. A passive network-attached sniffing device is used that collected packets traveling across a specific network link. Afterwards, reverse engineering to the captured packets is applied in order to get information about the states of TCP connections and to extract details of the application layer transactions. The data collector was installed in a commercial ISP network with public Internet access.

The cancellation rate of HTTP objects depending on the delivery bandwidth of that object are analysed for low range delivery bandwidth up to 120 kbps, since the majority of users had dial-up connections at that time. In order to determine if an object is canceled, the object size advertised by the server and the actual size of the delivered object are compared. Both logarithmic and exponential types of relationships between the cancellation rate $\bar{Q}oE(R)$ and the delivery bandwidth $QoS_{\mathrm{r}} = R$ are available:

- logarithmic model [7]:
  $\bar{Q}oE(R) = 0.130 - 0.017 \log(R/\mathrm{kbps})$;
- exponential model [6]:
  $\bar{Q}oE(R) = 0.054 + 0.059 \exp(-0.048R/\mathrm{kbps})$.

Every point in Figure 3 represents the average cancellation rate for a bin of 7,461 objects with a similiar delivery bandwidth. It can be seen again that the exponential relationship slightly outperforms the logarithmic one.

3) *Mean opinion scores QoE vs. goodput QoS_{r} and loss ratio $\bar{Q}oS_{\mathrm{f}}$ respectively:* A third example [1] considers the impact of (a) the goodput $QoS_{\mathrm{r}} = R$ which is defined here as throughput on application layer and (b) the loss ratio $\bar{Q}oS_{\mathrm{f}} = L$. Thus, the QoE is modelled regarding a resource measure and a failure measure, respectively. In the study [1], experiments were performed in a laboratory environment in which random packet losses were introduced into the network. For the experiments, the actual loss ratio and the goodput on application layer were measured. In addition, the users were asked to provide their subjective responses abouth the service on the MOS scale from 5 to 1. The following relationships have been found:

- goodput $QoS_{\mathrm{r}} = R$ on QoE:
  $QoE(R) = 1.15 + 1.50 \ln(R/\mathrm{Mbps})$;
- loss ratio $\bar{Q}oS_{\mathrm{f}} = L$ on QoE:
  $QoE(L) = 5.50 \exp(-0.2L/\%)$,

according to [1]. Figure 4 illustrates the QoE in terms of MOS for web traffic depending on the goodput R and the loss ratio L, respectively. In particular, for any point (L, R), the user rating is equal, i.e. $QoE(L) = QoE(R)$, which is indicated by the color of the curve. This allows to derive a relationship between the loss ratio and the goodput which lead to the same user experience, i.e. the same QoE value. It holds $R(L) = -5 \ln\left(\frac{23}{110} + \frac{3}{11} \ln(L)\right)$. These particular relationships between QoE and QoS will be used in the next section to discuss the QoE hysteresis.

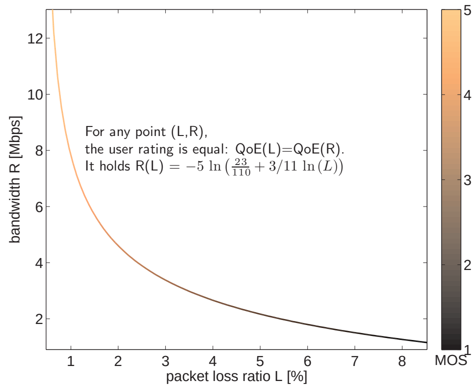

Fig. 4. QoE in terms of MOS for web traffic depending on goodput R and loss ratio L according to [1], respectively.

V. QoE PROVISIONING-DELIVERY HYSTERESIS

In this section, we compare the impact of provisioning (14) with the impact of problems (5) on QoE satisfaction rating. We consider the case of an interactive service, namely HTTP/TCP-based web surfing. TCP-based applications are said to be elastic, as they can adapt to network congestion in two ways: (a) via increased round-trip times (RTT), delaying the delivery of acknowledgements; (b) via losses, causing TCP to reduce the window size. Both measures reduce TCP's sending rate and thus decrease the application-perceived throughput R. This increases the user-perceived response time, which in turn decreases the satisfaction rating. However, while option (a) allows for a potentially decent adaptation of the sending speed to the capacity of a loss-free bottleneck, option (b) typically results in a quite heavy impact when TCP starts reacting to losses and reduces the window size so that response times explode. Reference [1] provides a set of formulae quantifying the impact of loss on response times and application-perceived throughput, respectively.

Define the resource-related satisfaction rating function

$$QoE_r(x) = \alpha_r + \beta_r \left|\ln(x)\right| \tag{15}$$

according to (14), and the success-related satisfaction rating function

$$QoE_s(x) = \alpha_s + \beta_s \exp(\gamma_s x) \tag{16}$$

according to (5). Choosing a common parameter x as combined *relative resource and success parameter* makes both QoE formulae comparable in x. We define the matching between x and the actual QoS-parameter (throughput R for QoE_r and success rate S for QoE_s) such that $QoE_r(1) = QoE_s(1) \equiv QoE_{\max}$ and that $x = 0$ for $R = 0$ and $S = 0$, which leads us to

$$x = \left\{ \begin{array}{ll} R \exp\left(\frac{\alpha_r - QoE_{\max}}{\beta_r}\right) & \text{for } QoE_r \\ \frac{S}{\gamma_s} \ln\left(\frac{QoE_{\max} - \alpha_s}{\beta_s}\right) & \text{for } QoE_s \end{array} \right\} . \tag{17}$$

We observe that both functions rise monotonically in x, where $QoE_r'(x) > 0$; $QoE_r''(x) < 0$; $QoE_r'''(x) > 0$ (concave) and $QoE_s'(x) > 0$; $QoE_s''(x) > 0$; $QoE_s'''(x) > 0$ (convex). However, due to the above properties of the derivates, we can conclude

$$QoE_r(x) \geq QoE_s(x) \text{ for } x \in [\varepsilon, 1] , \tag{18}$$

where $\varepsilon < 1$ denotes the intersection point $QoE_r(\varepsilon) = QoE_s(\varepsilon)$. Equation (18) expresses that, for sufficiently large x, the resource-related satisfaction rating is found above the success-related satisfaction rating, an effect which we henceforth call *QoE provisioning-delivery hysteresis*. It implies that starting from optimal QoE conditions ($x = 1$), a reduction of provisioning to a share $x < 1$ means better QoE than a reduction of success to the same value x. In practice, this means that it is *better to reduce provisioning e.g. by 5 %, for instance through traffic shaping or flow control, than to face those 5 % throughput reduction as uncontrolled loss because of overload*.

We illustrate the QoE hysteresis in Figure 5 based on the numerical example from section IV-B. After a variable transformation onto $x \in [0, 1]$ as described, the corresponding formulae for resource-related and success-related satisfaction rating functions read as follows:

$$\begin{aligned} QoE^{\star}{}_r(x) &= \min\{5 + 1.5\ln(x), 5\} ; && (19) \\ QoE^{\star}{}_s(x) &= \max\{1, 1.13 \cdot 10^{-8} \exp(19.91\, x)\} , && (20) \end{aligned}$$

which are plotted in Figure 5. Starting from ideal conditions ($QoE = 5$ for $x = 1$), we consider five procent of reduction in either provisioning or success. The value $QoE_r(0.95) = 4.92$ communicates hardly any loss of perceived quality when provisioning is reduced; however, $QoE_s(0.95) = 1.85$ points at quite bad perceived quality.

Obviously, the strength of *elastic* traffic, protocols and applications is to adapt throughput carefully to the conditions, while still yielding quite high QoE most of the time. TCP is actually offering this graceful degradation feature, as it adapts to reduced capacities via delayed acknowledgements. But as soon as significant loss appears, which is some kind of forced network-level throughput reduction, TCP reacts and lowers the application-perceived throughput significantly. Thus, a small

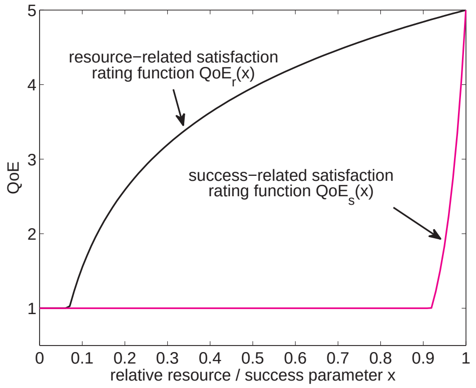

Fig. 5. Numerical example for the QoE hysteresis.

but uncontrolled change of the success parameter S might entail a quite large change of user satisfaction. On the other hand, if a graceful reduction of the provisioning R was possible, it would help to still keep the QoE high as long as losses can be avoided.

The latter insights also apply to *streaming* services. The transport protocol UDP is not elastic by itself, and losses, jitter and reordering have quite strong impacts on perceived quality, cf. Section IV-A. Capacity mismatches in the sense that the provisioned bandwidth drops below the bandwidth required by the stream will make the QoE drop quickly in a way that resembles to the lower hysteresis branch QoE_s in the example above. The solution to this dilemma is to make the application's generation of traffic elastic in the way that application settings are changed (e.g., reducing colour depth, number of frames per second, etc.), cf. [15], [16]. By carefully adapting the application's settings to the conditions in the network, a behaviour qualitatively similar to that of the upper hysteresis branch QoE_r is expected. The quantification of these considerations is planned for future work.

VI. CONCLUSIONS AND OUTLOOK

Motivated by the need for insights into systematic relationships between quantitative QoE and QoS parameters, we have presented a catalogue of partial differential equations, relating (dis-)satisfaction QoE ratings with failure-, success- and resource-related QoS measures. One set of differential equations expresses the partial differentiation of a QoE parameter with respect to the QoS measure of interest as a function of the current level of the QoE, which can be considered as a user-centric approach and leads to an exponential relationship between QoE and QoS. In contrary, the other set of differential equations expresses that partial differentation as function of the reciprocal QoS value, which can be considered as network-centric approach and yields a logarithmic relationship between QoE and QoS. Despite of the different approaches, similar shapes of the resulting QoE curves as function of the QoS can be observed. This is amongst others illustrated by a set of examples, as found in the literature.

We finally turned our attention to the different impacts of resources and success/failure of delivery on QoE. It was quantified how an elastic application (such as TCP-based surfing) makes the user react upon a reduction of capacity by some percent on one hand, and upon some percent uncontrolled loss on the other hand. The difference between two cases were found to be hair-raising in the sense that a slight reduction of provisioning goes hardly unnoticed, while loss in the same order of magnitude causes TCP throughput to drop and thus response times to grow beyond feasibility. Observation 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 than to get cast onto the lower curve because of bad network conditions. This strategy applies definitely even for streaming multimedia traffic, which is currently also deployed successfully by video portals (e.g. YouTube) in the Internet by means of TCP-based progressive downloads instead of UDP-based streaming.

Future work will amongst other deepen the analysis of the presented differential equations, which involves the investigation of the interpretability of their parameters α, β and γ. Also, the joint dependencies of quantitative QoE parameters on a whole set of QoS will need to be addressed beyond the so-far studied partial differentiation with respect to one single QoS parameter at a time. Furthermore, links towards queuing theory as well as to control theory will be established. In particular, the found dependencies taking into account QoE hysteresis for QoE control mechanisms for e.g. video streaming.

VII. ACKNOWLEDGEMENTS

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