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A Generic Quantitative Relationship to Assess Interdependency of QoE and QoS

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Abstract

Researchers as well as network providers are increasingly interested in understanding how a network user's experience changes in relation to different quality of service (QoS) parameters, with many attempts being made to identify the general relationship between quality of experience (QoE) and QoS. Several relations in different function forms have been proposed. There are instances when this variety of proposed functions potentially results in one problem having completely dissimilar solutions at the same time. The question then is which function form is the one that can better explain this relationship. In this paper, three major existing quantitative relationships between QoE and QoS are investigated. After conducting a comprehensive comparative analysis between them, a new definition of QoE-QoS dependency appears. It then results in identifying a new mutual relationship between QoE and QoS. The newly proposed relationship improves the deficiency of previous QoE-QoS relationships along with solving the problem of diversity of simultaneous solutions for one problem.

Keywords: QoE, QoE assessment, QoS, QoE-QoS relationship

1. Introduction

Due to the rapidly expanding Internet and computer network technology, service and network providers can now offer their customers a multitude of appealing services. User satisfaction has priority on their list of strategic goals since survival in today's highly competitive market depends on the user [1]. Besides, with the advent of real time services, which are highly sensitive to any quality disturbance [2], users will get irritated and possibly leave a service as soon as they experience quality degradation. Therefore, it seems necessary To manage and promote how users perceive network service quality by defining a relationship that shows how QoE changes with variations in QoS parameters. So far, a QoE-

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QoS relation has been often proposed in papers, some of which mainly examine QoE-QoS dependency in a specific network service while others attempt to create a common answer regardless of service type. [3-6] provide adequate examples of a proposed QoE-QoS relation for a particular service kind. In [3], a statistic technique called “Discriminate Analysis” was utilized to develop multimedia streaming service QoE. Focus was on identifying a network bandwidth threshold below which dissatisfaction with network service quality could be experienced by users. The dependency between QoE and network bandwidth was expressed as a quantitative relationship. Further work concentrating on specific service sorts was carried out by Hyun Jong et al. [4] who proposed a solution to improve the QoE image of IPTV services relative to various QoS parameters at the network layer. In [5], an objective quality evaluation for noise-reduced voice in hands-free oral communication environments has been proposed which is applicable to both full-reference and non-reference quality evaluation methods. Against existing conventional solutions, the overall quality estimation in this approach can be achieved from estimation of speech and noise quality, separately. Another research focusing on audio QoE in multimedia streaming services was conducted by Noritsugu et al. [6] on the basis of quality degradation caused by coding and packet loss of an audio stream. A subjective listening test was performed in order to consider the impact of some contributing factors in audio quality on user perception. Authors then use the test result to propose an objective parametric packet-layer estimation model which results in an equation to calculate Degradation Mean Opinion Score (DMOS). Their calculation is verified by achieving high correlation between subjective and objective estimated DMOS. In [7], a dynamic multimedia quality adjustment mechanism have been proposed in order to improve the quality of multimedia services delivered to the end user. A holistic view toward multimedia quality makes the proposed solution to take a wide variety of contributing factors into account in order to provide an acceptable level of multimedia service quality for the end users. Then, Liang et al. [8] attempted to reduce video distortion in video streaming services with minimizing network congestions over multi-channel multi-radio multi-hop wireless networks. The authors’ method to formulate their problem along with their proposed solution can be adopted by researches in the field of relationship between QoE and QoS.

In addition to the above mentioned works, there exist two solution groups attempting to define a general relationship between QoE and QoS, regardless of network service type. The first group comprises relations derived from the psychophysics laws, for example, a logarithmic relationship between QoE and QoS derived from the well known psychological Weber-Fechner Law (WFL) [9]. It shows how human perception can change relative to physical stimulus changes resulting in a certain perception. The authors in [9] claim that the QoE-QoS relationship is of logarithmic nature. Their findings are validated experimentally, where speech quality is considered as a function of varied bit rate and packet loss in voice communication. Khirman and Henriksen [10] also view the QoE-QoS relation as logarithmic. Their numerical relationship was tested by service cancellation rate as a function of network bandwidth. They also calculated how strong their formula is, using goodness-of-fit indexes. The proposed equation is in agreement with nearly 93% of results, on average. Another example of psychophysics-based relation between QoE and QoS is presented in [11]. It shows how a power function can explain user experience changes in relation to the QoS parameter fluctuations. The proposed relation is then tested by indicating how packet loss affects QoE in a video streaming service. Then, [12-15] are classified as the perception-centric group, and are founded on the IQX-hypothesis which postulates that QoE variations are associated to the current user quality perception levels. This definition results in an exponential QoE-QoS relationship. This exponential equation was tested in three scenarios, and then matched to data obtained from various test bed experiments. Goodness-of-fit indexes illustrated how well the exponential equation can convey the relationship between QoE and QoS.

This paper aims to compare the two general groups of relationships between QoE and QoS, as well as explore which one better reflects QoE changes due to QoS fluctuations. Besides, a generic quantitative relationship between QoE and QoS in a complete differential form of the function will be proposed and evaluated. The results show the proposed relationship in this paper can better explain the interdependency of QoE and QoS, compared with existing numerical relationships. In other words, this research makes an attempt to illustrate quantitatively how QoE and QoS interact mutually. Three major existing quantitative relationships between QoE and QoS are investigated. After conducting a comparative analysis among them, a new definition of QoE-QoS dependency appears. It then results in identifying a new mutual quantitative relationship between QoE and QoS.

The remainder of the paper is organized as follows. The Weber-Fechner Law and Steven's Power Law, two psychophysics laws, as well as the IQX hypothesis are reviewed in Section 2. Section 3 focuses on the three general relations used and previously discussed in Section 2, to develop a relationship between QoE and QoS. Depending on how they define QoE as a function of QoS parameters, grouping will fall into stimulus-centric and perception-centric relations. Next, the groups are compared to learn more about potential capabilities, while power, logarithmic, and exponential form relationships between QoE and QoS are expanded on and discussed in terms of stimulus-centric and perception-centric relations. Section 4 illustrates our test bed and explains the process of data collection. Methodology and experiment results analysis follow along with how and how well the relations given in the sections before fit the gathered data. Section 5 explains and evaluates the new relationship proposed by this research work. A comparison will be conducted between the proposed relationship and those which were categorized as stimulus-centric and perception-centric in section 3. Finally, Section 6 concludes this paper with a discussion of the results and potential future work.

2. Psychophysics Laws and IQX Hypothesis

2.1 Stevens' Power Law

In 1957, American psychophysicist Stanley Smith Stevens introduced a simple but powerful law which explains how magnifying human perception changes with the strength of a physical stimulus [16]. This law can be stated in the following formula:

$$P(S) = K.S^{b} \tag{1}$$

where P represents human perception as a function of stimulus intensity (S); K is a constant and depends on the conditions of measurement environment; and exponent b, which is an important part of the formula, can indicate the type of stimulus and in fact, plays the role of stimulus identifier and at the same time defines the curvature of the power function. We can employ the method of least squares [17] to find K and b. The power form of (1) helps cover almost every continuum of perception based on the stimulus magnitude in a known range. **Fig. 1** better illustrates Stevens' Power Law capability in that a power function can cover a wide range of relationships between perception magnitude and stimulus intensity. Different exponent values result in various curves which may go upward concavely or downward. Clearly, the function produces three different shapes for three different stimulus types. The first curve (the solid black curve) demonstrates human perception growth according to muscle force as a stimulus, where the exponent is 1.7. It also illustrates the situation in which perception magnitude increases faster than stimulus intensity, meaning that if a potential amount of force on human muscles increases, the force perceived is higher than what it really is. The second graph (the dashed blue line), which is almost a straight line, depicts how humans can perceive changes in visual length. The measured exponent here is almost 1.0 and stimulus intensity speed growth and perception magnitude are almost the same. In other words, humans can see objects as far as they really are, not closer or further than their real distance. The third curve (the dotted red curve) demonstrates human perception as a function of smell with the exponent of 0.6. Here, perception magnitude rises slower than stimulus intensity. For example, humans cannot strongly recognize the increasing odor of something like garlic when the amount of odor in the air exceeds a certain limit. If we consider QoE as human perception and QoS as stimulus which affect that perception, then (1) can show a power relation between QoE and QoS.

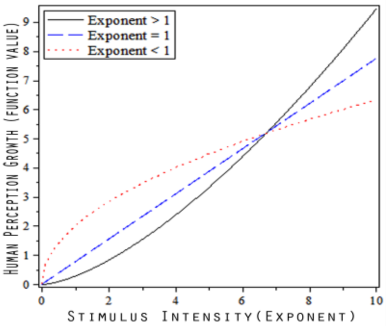

Fig. 1. Three different stimuli intensities (exponent values) result in three different range of human perception changes

2.2 Weber-Fechner Law

Ernst Heinrich Weber was a German psychologist who conducted some studies on human perception based on various physical stimuli. His study results were published as a law known as Weber's law which claims that the just noticeable differences (JND) between stimuli are related to their magnitudes [18]. The law's formula can be expressed as:

$$\Delta R = K.R \tag{2}$$

where R demonstrates stimulus magnitude, ΔR is JND, and K is a constant which can be determined in relation to the experimental environment.

Gustav Theodor Fechner was another German psychologist who later worked on Weber's law. He came up with a new elaborate interpretation of Weber's law and expressed it as a differential equation between strength of a physical stimulus and the magnitude of human perception [19]. This relationship can be described as:

$$dP = K.\frac{dS}{S} \tag{3}$$

where dP is the change in perception, dS is the change in stimulus magnitude, S is stimulus threshold below which humans cannot perceive anything from stimulus magnitude changes, and K is a constant and can be determined experimentally. If we integrate both sides of (3), then we reach:

$$P = k.\ln S + C \tag{4}$$

In (4), C appears as the constant of integration. If we put $P = 0$ then we find the C value. Substituting the value of C in (4) results in a logarithmic equation between stimulus magnitude and its perceived intensity. This equation is:

$$P = K.\ln \frac{S}{S_0} \tag{5}$$

Here, S_0 plays the role of S in (3). Again, it is possible to consider QoE as the perception and QoS as the stimulus. Thus, we would have a logarithmic equation explaining the general relationship between QoE and QoS.

2.3 IQX Hypothesis

The IQX Hypothesis [12] states that QoE is a function of n different factors, one of which is QoS parameters. Thus, it centers on QoE as a function of QoS parameters, implying that QoS parameters as packet loss or delay can affect the user's overall perception of service quality. This is shown as:

$$QoE = f(QoS) \tag{6}$$

The authors in [12] also agree that QoE fluctuates according to its current level. Assuming this, then QoE changes with respect to the QoS changes seen in the form of a partial differential equation as:

$$\frac{\delta QoE}{\delta QoS} = -\beta.(QoE - \gamma) \tag{7}$$

Solving (7) produces a possible relationship between QoE and QoS as an exponential equation form, as:

$$QoE = \alpha.e^{-\beta.QoS} + \gamma \tag{8}$$

In (8), α , β , and γ are three non-negative parameters that may vary among experiments. By using appropriate statistical techniques however, they can be estimated by an adequate confidence level for each experiment.

3. Perception-Centric versus Stimulus-Centric Relations

The equations derived from psychophysics have a stimulus-centric view regarding changes in human perception, or they postulate that the perception changes relative to stimulus changes. If this assumption extends to the QoE-QoS relation, it can be stated that QoE may change as QoS parameters change. On the other hand, the IQX hypothesis presumes that QoE change related to QoS is a current QoE level function. In fact, the QoE-QoS relationship is seen from the perception point of view. This section provides comparisons of existing power, logarithmic and exponential relations between QoE and QoS, and Table 1 includes a summary of the equations.

Table 1. Perception-centric & Stimulus-centric relations

	Name	Trend	Relation	Form
Adopted from Psychophysics	Stevens' Power Law	Stimulus-centric	$QoE = K.QoS^b$	Power
	Weber-Fechner Law	Stimulus-centric	$QoE = k.\ln(QoS)$	Logarithmic
Adopted from a Hypothesis	IQX	Perception-centric	$QoE = \alpha.e^{-\beta.QoS} + \gamma$	Exponential

3.1 Power vs. Logarithmic Forms of Relation

As seen in Table 1, there are three different relations in three different forms (power, logarithmic, and exponential) which express the possible general relationship between QoE and QoS. Before proceeding to the test bed results and using them to analyze the above formulas, these three relations should be first investigated. The first equation shows a power relation between QoE and QoS. The relation's power form implies that for different QoS parameters, the growth of perceived quality magnitude may experience various speeds. For clarification, Fig.1 in the previous section presents three different curves for three different stimuli. For the muscle force as a physical stimulus, the exponent is 1.7 meaning that when a person receives some force on their muscle, the amount of contraction experienced in the muscle increases faster than the force actually received. For visual length, the stimulus intensity rate is approximately equal to the increase in perception. In the case of smell where the exponent $b = 0.6$ there is an observed decreasing rate of perception as stimulus magnitude increases. This is a noticeable flexibility of power function which can be used in the field of QoE and QoS relationship. As we may know, different network services are sensitive to different types of QoS parameters, and these parameters affect QoE in various ways. This phenomenon can be covered very well by power function and to discuss this issue making some changes in the power equation is necessary. From Table 1 we have:

$$QoE = K.QoS^{b} \tag{9}$$

In terms of logarithm, (9) becomes:

$$\log QoE = logK.logQoS^{b} \text{잽}\Rightarrow og\,\mathrm{QoE} = \mathrm{b}.\log\mathrm{QoS} + \log\mathrm{K} \tag{10}$$

because K is a constant, $\log K$ will be a constant too and does not greatly influence (10). Therefore, it is temporarily omitted and the following is obtained:

$$\log\mathrm{QoE} = \mathrm{b}.\log\mathrm{QoS} \tag{11}$$

The power relation between QoE and QoS in (9) becomes a logarithmic function in (11). Exponent b in the power function which determined the curve's shape plays the role of function slope in (11), and determines the logarithmic lines' slopes. **Fig. 2** shows these changes in graphs.

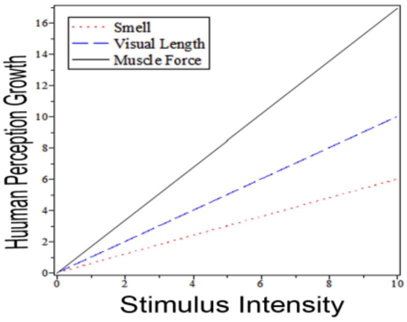

Fig. 2. Power function in logarithm form

The power relation between QoE and QoS changes to a logarithmic function. Now, the question is what difference there is between the below relation, presented in (12), and the logarithmic relation in **Table 1**. In other words, what is the difference between Steven's Power Law and the Weber-Fechner law when explaining the QoE/QoS relationship? To answer this question, attention should first be given to the logarithmic relation between QoE and QoS adopted from the Weber-Fechner law. Referring to the second row in **Table 1**:

$$QoE = K.\ln(QoS) \tag{12}$$

In (12), when QoS is multiplied by a constant amount, QoE increases approximately in an additive manner by a constant number. For example, if QoS becomes 4 times stronger than its initial value then QoE will have 2 added. In (11), however, both sides of the equation change in a constant manner. In other words, constant changes in the QoS amount will lead to a constant percentage of changes in QoE. In fact, the main difference between power and logarithmic forms is the magnitude of impact that QoS changes have on the QoE changes. Although there are researchers who believe that the power form is more realistic than the logarithmic form, more investigation is needed to confirm their statements in the field of QoE/QoS relationship [17, 20].

3.2 Logarithmic vs. exponential forms of relation

The equations derived from psychophysics have a stimulus-centric view regarding changes in human perception, or they postulate that the perception changes relative to stimulus changes. If this assumption extends to the QoE-QoS relation, it can be stated that QoE may change as QoS parameters change. On the other hand, the IQX hypothesis presumes that QoE change related to QoS is a current QoE level function. In fact, the QoE-QoS relationship is seen from the perception point of view.

This section provides comparisons of existing exponential and logarithmic relations between QoE and QoS, and **Table 1** includes a summary of the equations. First, the inverse function definition needs to be taken into account. If there is a function, f, let $D_{f=}$ set X be the domain of f, while R_f= set Y is its range. f is called invertible if another function like g exists, where D_g= set Y and R_g= set X with the condition:

$$f(x) = y \Leftrightarrow g(y) = x \tag{13}$$

Any existing function like $g(y)$ is unique for each $f(x)$. $g(y)$ is considered an inverse function of $f(x)$, represented by f^{-1}. According to fundamental mathematics, a natural (Neperian) logarithm is the inverse function of an exponential function which can be written as:

$$\forall y > 0 : f(x) = e^x \Rightarrow f^{-1}(e^x) = \ln(y) \tag{14}$$

This result shows an interesting correlation with the QoE-QoS relationships, in that a stimulus-centric relation of logarithmic form here is the inverse function of a perception-centric relation of exponential form. In other words, the existing magnitude of QoS parameters dictates the QoE quantity in the stimulus-centric method. However, in the perception-centric solution, the existing perception intensity comprises the relationship between QoE and QoS. A second look at (3) and (7) can be used for clarification, and (3) can be re-written in terms of QoE-QoS as:

$$dQoE = k.\frac{dQoS}{QoS} \tag{15}$$

Both (3) and (15) are differential equations. In order to comprehend how proportional QoE and QoS are toward each other, the following equation is generated:

$$from(15): k.dQoS = QoS.dxdQoE \Rightarrow dQoS \propto QoS.dQoE \tag{16}$$

According to (7) and logically similar to (16), the equation obtained is:

$$dQoE \propto QoE.dQoS \tag{17}$$

By comparing (16) and (17) it is obvious that in the QoE-QoS relationship, the stimulus-centric relation (as a logarithmic function) is the inverse of a perception-centric relation (expressed as an exponential function). This is because the stimulus-centric method (in logarithmic form of function) approaches the QoE-QoS relationship from a stimulus perspective while the perception-centric solution shifts toward the QoE-QoS relationship from a perception perspective. It is now worth mentioning why a perception-centric solution appears as an exponential function. A simple mathematical calculation may show that when function changes are proportional to their current value, that function’s form can be exponential. This is also seen in the nature of perception-centric methods which assume that QoE changes are related to existing levels of QoE.

In line with the discussion so far, arithmetic changes of QoS parameters in the logarithmic function result in QoE geometric changes. In the exponential type, regular QoS parameter changes can result in proportional QoE increase or decrease because in the exponential form, the dependent variable (QoE) varies relative to independent variable (QoS) changes in addition to the current QoE level having a crucial role in the QoE changes. **Fig. 3** illustrates perception changes (QoE) due to stimulus (QoS parameters) according to three relations with different function forms.

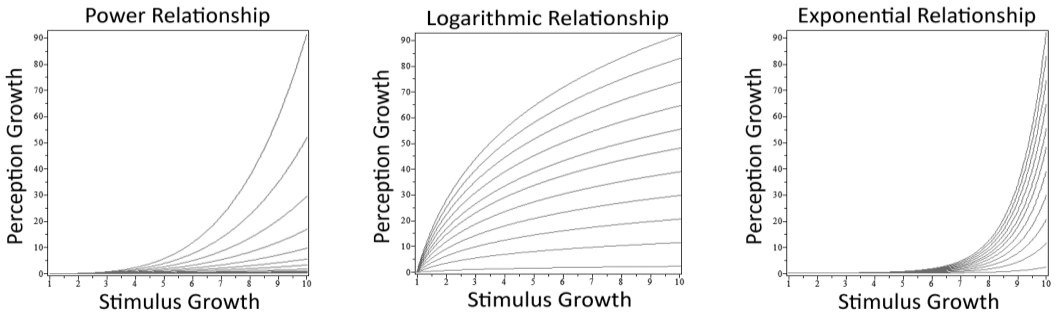

Fig.3. Perception and stimulus growth in stimulus-centric and perception-centric relations

4. Experiments and Results

This section presents the test bed configuration, and also explains how data was collected from the test bed. End-to-end measurements were performed in order to observe which type of relation (stimulus-centric or perception-centric) and which function forms (power, logarithmic, or exponential) can better explain the effects that QoS parameters have on user-perceived quality. Finally, a discussion will reflect an analysis of the collected data and results. The test bed architecture, its components, and how they are connected are explained in section 4.1. After that, three different scenarios have been performed to consider how QoS parameters can affect QoE. Conducted experiments are discussed in detail in sections 4.2, 4.3, and 4.4. In each experiment, traffic between client and server has been shaped with a traffic shaper. Both subjective and objective measurement standards are employed to realize how different QoS parameters can affect delivered quality by the end user. Finally, statistical methods are used to elicit required information out of the collected data.

4.1 Test bed Configuration and Measurement Framework

The test bed in **Fig. 4** helps illustrate how QoS parameters affect user experience. It comprises a server, a client, and a Linux traffic shaper [21]. All devices are connected to each other via a Fast Ethernet switch. A 10Mbps link has been used to connect each device to the switch. A “Route Add” command on the client and server sides delineates a specified path between them, and traffic must pass through the traffic shaper while transmitting through the Fast Ethernet switch. Traffic shaper generates and distributes required QoS parameters throughout the test bed based on a normal distribution function. Three different experiments were conducted in the test bed, and they were only chosen as candidates to aid in the investigation on whether relations presented in **Table 1** are capable of assessing QoE in different services and with various types of QoS parameters. In the first scenario, the relations introduced in **Table 1** were tested to show how they can assess video streaming QoE according to packet loss. Secondly, the impact of delay was considered on a VoIP service QoE. Finally, the impact that the available bandwidth has on web browsing quality was investigated. In each scenario, curve estimation and non linear regression technique is used to estimate the parameters of each relation. Goodness-of-fit measures are used to test which relation and what function form can better explain the interdependency of QoE and QoS. This comparison is accompanied by diagrams and tables. Then, a statistical test is performed to ensure that the results obtained from the test bed experiments can be extended to other potential samples or even a population. This section concludes with a discussion on the achieved results.

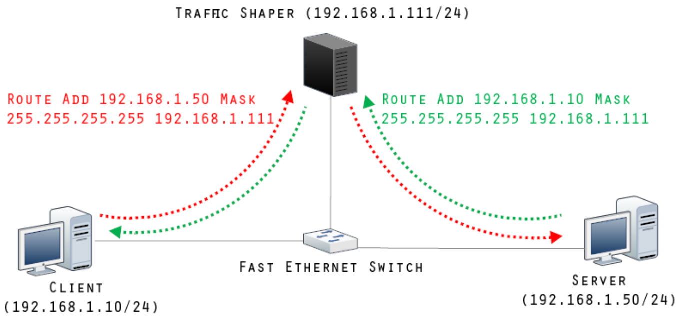

Fig. 4. Test bed configuration

4.2 Video Streaming Quality affected by Packet Loss

This section illustrates how packet loss can affect the quality of a video streaming service perceived by the end user. In this experiment, a Video LAN media player [22] streams a 2.3 MB video with MPEG-4 video codec over UDP and IP in the network. Processed video is captured on the client side to be compared with the original video later. A peak signal to noise ratio algorithm (PNSR) [23] was used to objectively evaluate perceived quality of the delivered video. The PNSR results are then converted to MOS which ranges from 1 to 5 [24]. The starting point is 0% loss intensity, which then increases by 1% increments until it reaches 10% packet loss in the network. 10% loss intensity is the limit, because from that level on, user perceived quality decreases in such a way that may lead to giving up the service. The experiment was repeated at each step forty times. At the end, sample size was 440. According to Krejcie and Morgan [25], when experiment population size is not definite, sample sizes greater than 380 can be considered reliable for any further analysis. Here, the arithmetic mean (average) of the collected data was chosen as representative of each group of loss intensities. **Fig. 5** includes the plot between average video streaming QoE in MOS terms and nominal loss intensities in percent. For better understanding the changes in the range of collected data, the averages are shown with upper and lower standard deviations.

Curve estimation (**Fig. 6**) indicates how three different equations in three different forms of function can fit the data collected from the test bed. It also expresses how each function can explain QoE changes in connection with packet loss, while **table 2** demonstrates these as formulas. To realize how strong and accurate the relations in **table 2** are, goodness of fit indexes and mean squared error (MSE) is employed. All of them yield a high match while coefficient of correlation (r) and coefficient of determination (R^2) both are close to 1. On the other hand, MSE for each equation is close to zero. Thus, it is clear that all above mentioned indexes show an almost ideal match for our proposed equation. However, the perception-centric relation with exponential form of function can better present the dependency of QoE and QoS.

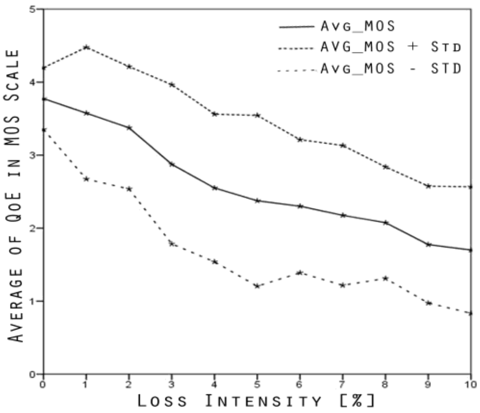

Fig. 5. Video streaming QoE (average ± standard deviation) as a function of Packet loss

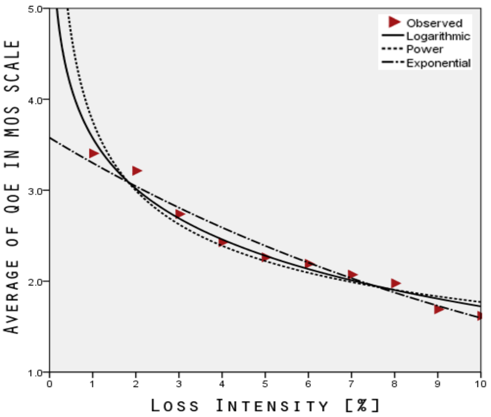

Fig. 6. Estimated non-linear regression curves for collected data in three different forms of function

Table 2 Estimated non-linear relations between video streaming QoE and packet loss with goodness of fit measures and the best fit in bold

Form of Function	Estimated Relation (Regression Model)	Goodness of Fit Measures		
		r	R^2	MSE
Power	$QoE = ?.803(QoS)^{-0.299}$	0.964	0.931	0.031
Logarithmic	$QoE = ? - .844$ 잴 $(QoS) + 3.753$	0.983	0.967	0.015
Exponential	$\mathbf{QoE = ?.810(e)^{-0.171(QoS)} + 1.243}$	**0.990**	**0.981**	**0.002**

4.3 VoIP Quality affected by Delay

In this section, different amounts of delay were tested to show how they can affect the quality of a VoIP service perceived by the end user. In this experiment, a client sends audio data to the server through a traffic shaper using UDP and IP. The audio data is a standard Windows Media Video (WAV) file with a length of 16 seconds, a rate of 8 kHz, and encoded with 16 bits per sample. SJPhone version 1.65.2637 [26] is an open source soft phone which is used to set up direct SIP (Session Initiation Protocol) calls with the G.711 codec between the client and the server. The received audio files were compared to the sent audio files. PESQ (Perceptual Evaluation of Speech Quality) described in ITU-T P.862 [27] was employed to calculate the perceived voice quality objectively. To map the obtained results to their counterpart subjective measures in terms of MOS, ITUT Recommendation ITU-T P.862.1 [28] was used. Moreover, a two-way delay was emulated to find out how delay can affect voice quality in each call. The starting point was 0ms delay, which then increased by 20ms increments until it reached 200ms packet loss in the network. 200ms loss intensity is the limit, because from that level on, user perceived quality decreases in such a way that may lead to users giving up the service. Besides, at that point, the collected data is statistically significant enough to be analyzed later. The experiment was repeated at each step forty times.

Here, the mean of the collected data was chosen as representative of each group of delays. **Fig. 7** includes the plot between average VoIP QoE in MOS terms and nominal delay in ms. To better understand the range of collected data, the averages are shown with upper and lower standard deviations. Curve estimation (**Fig. 8**) indicates how three different equations in three different function forms can fit the data collected from the test bed. It also expresses how each function can explain QoE changes in connection with delay, while **Table 3** demonstrates these as formulas. Again, goodness-of-fit measures were calculated in order to show how strongly each group of relations can predict the dependency between QoE and QoS. Also in this experiment, the perception-centric relation with an exponential function form can better explain the relationship between QoE and QoS.

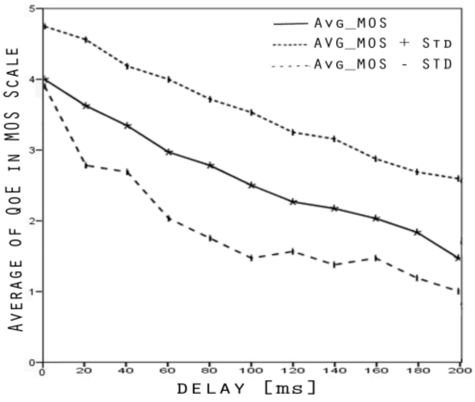

Fig. 7. VoIP QoE (average ± standard deviation) as a function of delay

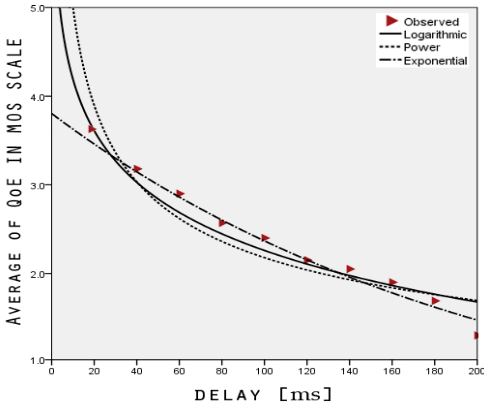

Fig. 8. Estimated non linear regression curves for collected data in three different forms of function

Table 3 Estimated non-linear relations between VoIP QoE and delay with goodness of fit measures and the best fit in bold

Form of Function	Estimated Relation (Regression Model)	Goodness of Fit Measures		
		r	R^2	MSE
Power	$QoE = ?.723(QoS)^{-0.338}$	0.905	0.819	0.017
Logarithmic	$QoE = ?- .963\text{잼}(QoS) + 6.739$	0.956	0.913	0.026
Exponential	$\boldsymbol{QoE = ?.712(e)^{-0.004(QoS)} + 0.793}$	**0.982**	**0.965**	**0.007**

4.4 Web Browsing Quality affected by Available Bandwidth

This section considers how available bandwidth in the network can affect user satisfaction while visiting a web page. The conducted experiment consists of a web page (transfers on HTTP) containing a 1.5MB image. The user on the client side attempts to download the image from the server. Because caching is disabled on the client machine, the user should download the image each time the experiment is repeated. Since all the traffic between client and server passes through a traffic shaper, it can limit the available bandwidth to the desired amount at each step in the experiment. Due to image size, the capability of the traffic shaper software and the statistical sample size needed, the starting point for bandwidth was 50Kbps, which then increased by 50Kbps increments until it reached 500Kbps bandwidth in the network. 500Kbps bandwidth is the limit, because from that level on, users will not face with any considerable difficulty during the downloading process. For each step, the experiment was repeated 40 times. During each experiment, users were asked to give their opinion (on MOS scale) regarding the amount of time they had to wait until the image downloaded completely. This subjective measurement was conducted in relation to the instructions stated in ITU-T Recommendation G.1030 [29]. Here, the mean of the collected data was chosen as representative of each bandwidth group. **Fig. 9** shows the plot between average web surfing QoE in MOS terms and available bandwidth in Kbps. For better understanding, the averages are accompanied by their upper and lower standard deviations. Curve estimation (**Fig. 10**) indicates how three different equations in three different function forms can fit the data collected from the test bed. It also expresses how each function can explain QoE changes in connection with bandwidth, while **Table 4** demonstrates these as formulas. Again, goodness-of-fit measures were calculated in order to show how strongly each group of relations can predict the dependency between QoE and QoS. In this experiment, the stimulus-centric relation with logarithmic function form can better explain the relationship between QoE and QoS.

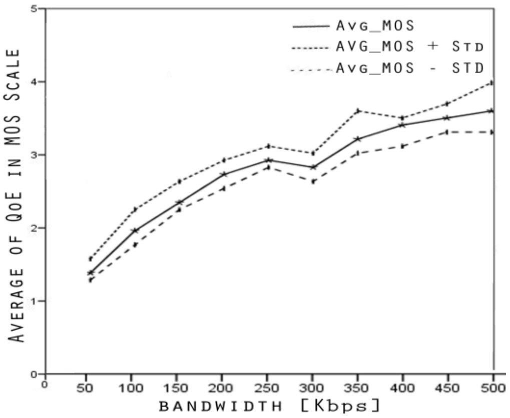

Fig. 9. Web browsing QoE (average ± standard deviation) as a function of bandwidth

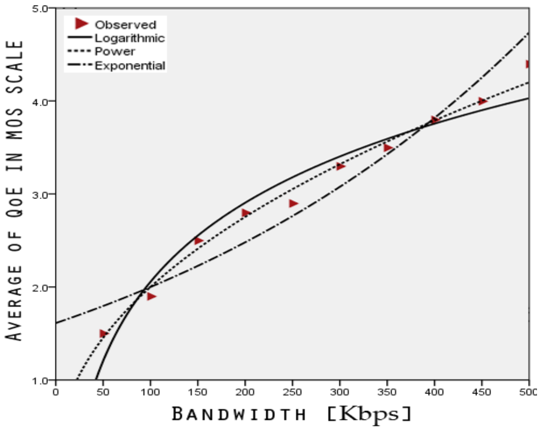

Fig. 10. Estimated non linear regression curves for collected data in three different forms of function

Table 4. Estimated non-linear relations between web browsing QoE and bandwidth with goodness of fit measures and the best fit in bold

Form of Function	Estimated Relation (Regression Model)	Goodness of Fit Measures		
		r	R^2	MSE
Power	$QoE = ?.281(QoS)^{0.435}$	0.977	0.954	0.008
logarithmic	$\mathbf{QoE = ?.005 잽 (QoS) - 2.689}$	**0.992**	**0.984**	**0.010**
Exponential	$QoE = ?.076(e)^{(QoS)} + 1.161$	0.923	0.851	0.019

4.5 Statistical test and validation

In order to make sure that the estimation strength of relations introduced in **Tables 2-4** does not change significantly from one sample to another, a two-tailed significance test was performed for the population's coefficient of correlation at the 0.5% significance level (equivalent to a 90% probability). In this test, it was checked whether the population's coefficient of correlation will still stay above 0.9 (equivalent to a probability of 90%). In other words, if the test can show that $r >= 0.9$ in the population, then we can claim that the relations in **Tables 2-4** can strongly explain QoE-QoS dependency in different samples (a population). To do so, the test's hypotheses need to be defined as follows:

$$\begin{cases} H_0 : r >= 0.9 (null - hypothesis) \\ H_1 : r < 0.9 (alternative - hypothesis) \end{cases} \tag{18}$$

The amount of statistics used in the statistical test are introduced by Fischer [30] and named Z. It can be calculated as:

$$Z = \frac{Z_r - E(Z_r)}{1 \big/ \sqrt{n-3}} \tag{19}$$

Where

$$Z_r = \frac{1}{2?}\ln\frac{1+r}{-r} \tag{20}$$

In (19), $E(Z_r)$ is the mean of Z_r, and n represents the sample size. In addition, Z has almost a normal distribution. In (20), r is the desired coefficient of correlation for the population. Different calculated Z s show that the population coefficient of correlation for each of the estimated relations is above 0.9. Simply put, all three forms of function in **Tables 2 - 4** can strongly explain the relationship between QoE and QoS in a statistical population too.

4.6 Test bed results and discussion

As considered in previous sections, both stimulus and perception-centric relations can assess QoE based on different QoS parameters. In all presented samples, the coefficient of correlation for three function forms is above 0.9, meaning that all of them can assess QoE based on QoS changes with 90% or higher accuracy. However, based on each sample condition, type of network service, contributing QoS factor, and type of measurement (subjective or objective) the explanatory strength of each relation differs slightly (below 8%). In all samples, power function could not fit the best. Although the last sample power function shows a rather high amount of r and R^2, in the other samples it is the weakest function to express the potential dependency of QoE and QoS. Another look at Section 3 reveals that the relations in power form consider changes of QoE as a ratio of QoS changes, while the logarithmic and exponential function forms define QoE changes as differences of QoS changes. This is why Steven's Power Law, as opposed to the Weber-Fechner Law and IQX Hypothesis, led us to a non-differential equation between QoE and QoS. It can be concluded that difference is preferred to ratio when looking for a numerical relationship between QoE and QoS. This is why all differential-based relations (in the form of logarithmic and exponential function) fit more adequately in comparison with power function. All the proposed relations in [9-12] and [31], which are differential-based, also confirm our claim that differential relations can better serve in devising QoE-QoS numerical relations compared with ratio. This can be seen as a necessity which behoves us to seek for a new definition of QoE-QoS relationship based on a differential form rather than a ratio form. Another fact to be addressed is that neither stimulus-centric nor perception-centric relations are dominant in QoE assessment based on QoS parameters. In VoIP and video streaming services where an objective measurement was conducted, perception-centric relation can better explain the dependency of QoE and QoS, something which is also stated in [12, 13, 15]. On the other hand, stimulus-centric relations (especially in logarithmic function form) can better explain the correlation of QoE and QoS in services which quality disturbance is not recognized by the end user very fast. A good case in point is web browsing QoE as a function of available bandwidth. In this experiment, a subjective measurement was conducted, and the stimulus-centric relations (in both forms of function) could fit better than the perception-centric relation in the form of exponential function. The results presented in [10, 29] confirm this statement. In other words, results shows that non of the existing relations can be considered as a preeminent solution to explain the connection between QoE and QoS. Therefore, devising a new definition of QoE-QoS relationship which can work precisely under different circumstances seems necessary.

Despite all discussion up to now, the question still remains as to why the QoE-QoS relationship has dissimilar solutions at the same time. According to the obtained results, there is not a uniform quantitative relationship which can explain the dependency of QoE and QoS in different services and under different situations. Although all the stimulus-centric or perception-centric relations mentioned in this paper are not wrong, they consider QoE as a function of only stimulus or only perception factors at one time. In this way, they cannot present a holistic view toward QoE changes. In fact, the reason that a variety of quantitative relationships exists lies in the deficiency found in the definition of a QoE-QoS relationship. To put it simply, conducted experiments in section 4 revealed that a new definition of QoE-QoS relationship should include both stimulus and perception parameters. Stimulus-centric relations consider QoE as a function of just QoS parameter changes. Thus, they try to express the relationship between QoE and QoS with a partial differential equation in which all contributing factors of QoE are considered as some constants except QoS parameters (such as equation (3)). In contrast, perception-centric relation considered QoE as a function of the current QoE level only, meaning that all other contributing factors to QoE are considered as some constants except user perception, which changes. This leads to a partial differential equation (like equation (7)). For a more comprehensive view of the QoE-QoS solution, QoE must be considered as a function of both QoS changes and the current level of user perception simultaneously. Such a look toward QoE-QoS dependency can bring both stimulus and perception factors into account at the same time. This definition will lead to an equation with complete differential form (as opposed to partial differential equations in stimulus-centric and perception-centric relations). Because this complete differential form of function brings both QoS parameters and the current level of QoE into account simultaneously, it has a holistic and bi-directional look toward the QoE-QoS relationship (not a one-sided look toward the QoE-QoS relationship in stimulus and perception-centric relations). In fact, the QoE-QoS dependency is considered from both stimulus and perception perspectives at one time. Thus, it can be considered a potentially successful candidate when a robust and uniform solution is needed for the dependency of QoE and QoS. This way, we can avoid a variety of proposed functions which can potentially result in one problem having completely dissimilar solutions at the same time.

5. Proposed Quantitative Relationship between QoE and QoS

According to the discussion in Section 4.6, a potentially reliable relation that can explain the interdependency between QoE and QoS can be characterized as follows:

- It should be founded on a difference basis (rather than ratio basis).
- It should be expressed in a complete differential form of function in order to reflect the influence of both stimulus and perception contributing factors on QoE.
- It should consider QoE changes in two dimensions at the same time. It implies that QoE can change simultaneously as a function of the current level of user perception along with the possible fluctuations in QoS parameters.

With respect to the above-mentioned characteristics, it can be stated that:

$$QoE = f(stimulus, perception) = f(s, p) \tag{21}$$

Simultaneous changes in stimulus and perception will result in QoE variations. Therefore, a complete differential function form is required. The general form of the function is:

$$df(s,p) = \frac{\delta f(s,p)}{\delta s} ds + \frac{\delta f(s,p)}{\delta p} dp \qquad (22)$$

To illustrate how QoE changes in two different ways at the same time, and also why (22) is used to explain this phenomenon, the following example can be beneficial. Imagine a person starts moving from south to north. The weather temperature that he feels is a function of both time and location. When he begins his journey in the morning, the temperature is average. Come noon the temperature increases and towards night the temperature decreases. At the same time, location is also noteworthy. The more he moves towards north, the more the temperature decreases. Besides, the closer he goes south, the higher the temperature gets. In fact, temperature changes as a function of both location and time. This example shows how an entity can change as a function of more than one parameter concurrently. The QoE also functions in this manner, by fluctuating as a function of the current level of human perception along with variations in QoS parameters. For this reason a differential function form was introduced in (22). This equation implies that improving QoS parameters does not necessarily lead to a higher QoE level since QoE is not only influenced by QoS parameters. Moreover, the new relationship, as proposed in a complete differential form, indicates that when a user experiences a high level of QoE, even minute disturbance in the QoS parameters can be bothersome. In contrast, when QoE level is low and the user does not experience acceptable service quality, even significant fluctuations in the amount of QoS parameters may be disregarded by the user. This applies to what happens in the relationship between temperature and its two contributing factors. Temperature drops dramatically when a person approaches north at night, then falls even more as time or location changes. At noon, however, when temperature is elevated, prominent changes in time or location do not drastically disturb temperature.

In accordance to the investigation in previous sections, a logarithmic function can better reflect changes of QoE as a function of stimulus changes. Besides, an exponential function is reliable when it comes to QoE changes in relation to the user's perception level. To put it in formula terms, the following applies:

$$\frac{\delta f(s,p)}{\delta s} = k.\ln s + c_1 \qquad (23)$$

$$\frac{\delta f(s,p)}{\delta p} = \alpha.e^{-\beta.p} + c_2 \qquad (24)$$

If (22) is solved with respect to (23) and (24), the generic quantitative relationship between QoE and QoS can be defined as:

$$QoE = f(s,p) = ks.\ln s - (k - c_1)s - \frac{\alpha e^{-\beta.p}}{\beta \ln(\alpha e)} \qquad (25)$$

where s is stimulus, p is perception while c_1 and c_2 are two constants that appear once the differential form introduced in (22) has been solved. In addition, k, α and β are three non-negative constants defined in accord with the experimental environment. Against the functions listed in **Table 1**, Equation (25) can explain the QoE changes in two dimensions. **Fig. 11** illustrates how QoE alters in relation to stimulus and perception at the same time, demonstrating how QoE changes in a complete differential form. The shape in **Fig. 11** changes in two dimensions depending on how QoE can be affected by various service types. In services such as VoIP where QoE is sensitive to QoS disturbances, the stimulus factor has a great influence on the diagram's skewness toward QoE. In contrast, in services like web browsing in which human perception plays an important role regarding QoE level, the perception factor has considerable effect on the shape's skewness toward QoE. A comparison between the curves illustrated in **Fig. 3** with the ones presented in **Fig. 11(A-C)** demonstrates the manner in which Equation (25) can explain QoE changes in connection with both stimulus and perception factors. While in **Fig. 3** all three numerical relations in three forms of power, logarithmic and exponential functions explain QoE changes as a function of only one single factor, the curves in **Fig. 11** show how QoE can alter in two aspects simultaneously.

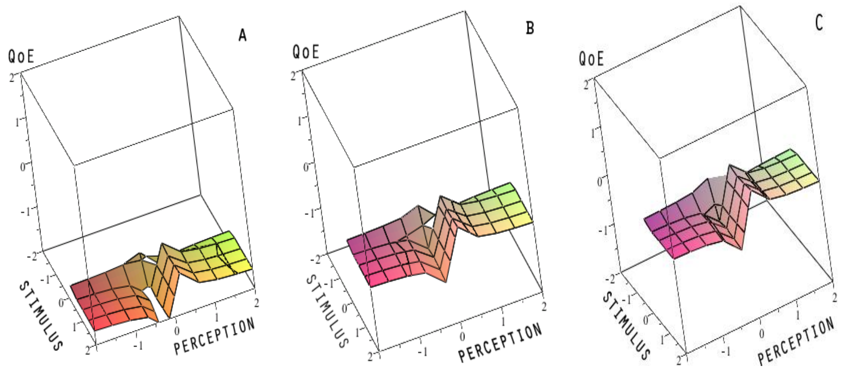

Fig. 11 QoE as a function of both stimulus and perception

Equation (25) has also been verified in the three scenarios of the test bed offered in Section 4, with the results provided in **Table 5**. The new relation, which brings both perception and stimulus factors into account, can obviously better explain the interdependency between QoE and QoS as opposed to the equations introduced in **Table 1**. In other words, greater amounts of r and R^2 indicate that the estimated relations in **Table 5** can better explain the interdependency of QoE and QoS than the relations elaborated in **Tables 2-4**.

Table 5. Estimated relations between QoE and QoS in complete differential form of function

Service Type	Estimated Relation (Regression Model)	Goodness of Fit Measures		
		r	R^2	MSE
Video Streaming	$-0.725s\ln(s)+0.323s+\dfrac{e^{-2.4p}}{2.4\ln(e)}$	0.997	0.994	0.008
VoIP	$1.205s\ln(s)-0.357s-\dfrac{1.015e^{-0.68p}}{0.68\ln(1.015e)}$	0.991	0.982	0.001
Web Browsing	$-0.542s\ln(s)+0.137s+\dfrac{0.844e^{1.492p}}{1.492\ln(0.844e)}$	0.995	0.990	0.003

6. Conclusions and Outlook

In this article, three different generic quantitative relationships between QoE and QoS were presented and evaluated. They are expressed in three different forms of function. According to how they define a general relationship between QoE and QoS, these relations are classified as perception-centric and stimulus-centric relations. The first group considers QoE as a function of QoS parameter changes, while the latter states that QoE changes in accordance to the current level of user perception. These two groups were compared and analyzed theoretically and practically. The results indicate that redefining the connection between QoE and QoS appears to be necessary. Both stimulus-centric and perception-centric methods regard the QoE-QoS relationship as one sided, meaning that user QoE is considered to be a function of only stimulus or present perception level. Even though these definitions are not incorrect, they do not indicate both aspects of QoE changes. Also, the QoE-QoS dependency is mutual, in that QoE changes according to the existing level of user perception as well as QoS parameter fluctuations at the same time. Thus, this paper introduced a new definition of QoE-QoS relationship which results in a complete differential form of function. This function can explain strongly how QoE changes in two different aspects at a same time.

Future work should address one important issue in particular. Obviously, based on the new QoE-QoS relationship definition a new quantitative form of the function is proposed, which takes into account both stimulus and perception factors. However, this relation works with single parameters of QoS and user perception at a time. It seems that finding relations which consider QoE as a function of more than one QoS and user perception parameters should be explored further. Multi-variant function results should do better at explaining real-life scenarios. In fact, we look for a quantitative relationship that can explain the QoE-QoS dependency related to more than one QoS parameter along with user perception changes in a form of complete differential function.

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