A Deterministic QoE Formalization of User Satisfaction Demands (DQX)

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***Abstract*—Measuring the impact of technical variables, such as latency, bandwidth, or resources priority-access, on Quality-of-Experience (QoE) of various services demands an extensive feedback from end-users, when those variables change. Estimating QoE in a given scenario becomes harder, when non-technical variables, such as price, need to be considered in addition to technical ones. In any case, detailed feedback that correlates all variables affecting QoE is needed by end-users for each service separately. In this work a deterministic mathematical model (DQX) encapsulating user demands, service characteristics, and variable specifications is proposed to formalize the QoE calculation, considering one or multiple and diverse variables. The output of QoE functions presented here can be normalized such that results will be compatible with the five-point scale Mean Opinion Score (MOS), proposed by the ITU-T.**

***Index Terms*—Quality-of-Experience (QoE), Mean Opinion Score (MOS), generic quantitative relationship, user perception mapping, measurable variables**

I. INTRODUCTION

Quality-of-Experience (QoE) is a user-centric concept reflecting the end-user satisfaction of a service while considering various technical variables, such as latency, bandwidth, or jitter, in Voice-over-IP (VoIP) services of the telecommunication field [10] or in video streaming of the entertainment field [4][18][27]. Furthermore, the QoE concept can also be used when considering pricing for IP-based services [12][21][22], since a price of a service affects the overall end-user experience. Thus, QoE can be affected by (a) diverse technical variables and (b) by economical/non-technical variables.

In Information Technology (IT) ecosystem such variables are usually defined in the Service Level Agreement (SLA) between the Service Provider (SP) and its customer. When one or more of these variables do not meet the agreed level, an SLA violation is occurred. However, an SLA violation does not mean that the end-user dissatisfaction cannot be avoided. There are certain actions that a SP can take, such as offering the service at a lower price or offering a service upgrade, such as a higher bandwidth for the same price, to maintain the QoE of an end-user at a certain level of satisfaction. To prevent a potential decrement of QoE in case of an SLA violation, it is important to know which variables and how exactly they affect the end-user's QoE. A proper adjustment of involved variable(s) on the QoE, might counterbalance the incident that caused the SLA violation in terms of the end-user satisfaction. However, such a process assumes a formal complete and generic overview of the QoE concept that is missing nowadays. The need to illustrate QoE contributed to the creation of standards, such as the Mean Opinion Score (MOS) [13][14][15]. The MOS reflects the end-user satisfaction at a numerical scale where the higher the score is the higher the end-user's satisfaction is and vice versa. However, since the MOS defines a subjective value, a complete and formal calculation of the MOS while considering all variables that might affect the QoE is the missing piece toward the precise user satisfaction demands estimation.

This work formalizes QoE in a Deterministic mathematical model (DQX) which considers the agreed values of a set of variables described in the SLA and the measured values of those variables when/while a service is provided. Such measurable information that defines the Quality-of-Service (QoS) is used to calculate a MOS-normalized value that represents the end-user's QoE. Thus, the definition of an SLA violation in this work is the situation where there is no possible adjustment for any variable(s) which can result into an agreed upon MOS score between the end-user and the SP. QoE calculation equations in this work here can be used to export MOS results once the set of the QoE model parameters and variables is defined. Key QoE parameters are: (1) the minimum and maximum values of a variable (*e.g.*, price, bandwidth, or latency) affecting QoE; (2) the expected, or agreed in the SLA values of each variable; (3) the importance and the influence factor of each variable for each service; and (4) the desired codomain of the QoE functions. In this work the scenario of an Internet Service Provider (ISP) is selected to present how the parameters of the QoE model should be selected.

Comparing cloud services, such as performance cloud servers, load balancers, and file servers offered by different Cloud Providers (CPs) is not trivial. Large cloud providers, such as Rackspace [20], GoGrid [7], and Amazon Elastic Compute Cloud (EC2) [2], offer comparable services with slightly different characteristics concerning Central Processing Unit (CPU), Random Access Memory (RAM), available bandwidth, Operating System (OS), and charging schemes. There is not always an exact mapping of services across those CPs. Thus, it is hard for the end-user to decide which is the right product and CP to choose, when considering main characteristics and constraints of a service. A mathematical model that can generate a score for each product and CP, receiving as an input minimal service demands and end-user priorities concerning each variable, will be a powerful tool when CP's products comparison is requested. DQX is shown to be suitable for CPs service's-value indexing.

The remainder of this paper is structured as follows. Related work is discussed in Section II, followed in Section III by the QoE formalization model. Major details concerning the MOS calculation of one variable are presented in Subsection III-A and the influence factor selection mechanism is formalized in Subsection III-B. The QoE model is extended with more than one variable affecting the QoE (cf. Subsection III-C) to encapsulate all variables. The Telecommunications Standardization Sector of the International Telecommunications Union (ITU-T) MOS-compliant equations are illustrated in Subsection III-D. Subsection III-E presents a basic example, where parameters of DQX are selected for a home users broadband access scenario of an ISP in Switzerland. Finally, Section IV summarizes the paper, draws conclusions, and presents future work. Key mathematical proofs are added in the Appendix.

II. RELATED WORK

QoE is a subjective concept. However, when end-users are asked to rate the performance of a service in a given scenario there is a certain alignment on results. Thus, the quality of a conversation of a VoIP call that was performed with a specific codec is mapped to a specific MOS [8]. Furthermore, while comparing similar services with different variables, such as conversations on a VoIP network with different codecs, the MOS can be used as a comparison metric. Thus, a deterministic MOS calculation, addressing services affected by diverse variables, can be used for service-comparison purposes.

When a comparison between diverse but similar products, such as products offered by CPs, is needed the only constant parameter is the end-user's preference and services' constraints and demands. Thus, considering the latest to calculate the expected QoE before concluding the selection of a specific product is essential.

A. Interdependency of the QoE and QoS Hypothesis

Interdependency of the QoE and QoS Hypothesis (IQX) assumes an exponential relationship between QoE and Quality-of-Service (QoS) [5][9]. $QoE = \Phi(I_1, I_2, \ldots, I_n)$ in [9] is a function of n influence factors I_j, $1 \leq j \leq n$ (the equivalent term for influence factor is variable in DQX, since the term influence factor used for different purposes). To motivate the fundamental relationship between QoE and an impairment factor (decreasing variable in DQX) corresponding to QoS, the packet loss probability p_{loss} is examined in the VoIP scenario. Similar to [23] $QoE = \alpha \cdot e^{-\beta \cdot p_{loss}} + \gamma$ assumed to be an exponential function. Thus, fitting the curve of MOS measurements concerning the iLBC voice codec ($400 bits$ each $30 ms$) at [9] provided the numerical values for the parameters $\alpha = 3.0819$, $\beta = 4.6446$, and $\gamma = 1.07$ (cf. Figure 4 at [9]).

In DQX the concept of IQX is extended to more than one variable that can also affect QoE not only negatively but positively as well. Furthermore, the mathematical model that is proposed, provides more flexibility in respect to the influence that a variable, *e.g.*, p_{loss}, might have in different services *e.g.*, different VoIP codecs, or for different users, *e.g.*, business, and home users. The later is achieved by introducing influence factors for each variable affecting the overall QoE. The influence factor is a power operator that applies on variables and shows how fast QoE will be affected at a given fluctuation of each variable. Additionally, the concept of the Expected Variable Value (eV^2) for each variable is introduced here. The role of the eV^2 is fundamental in the selection and calculation of α, β, and γ that result from the curve fitting in IQX. Finally, IQX is extended in DQX by introducing the concept of the Expected MOS (eMOS), which is a value that is less than the maximum possible MOS. The latest facilitates the assumption that a certain level of QoE can be maintained even if one variable, *e.g.*, p_loss, changes.

B. Generic Exponential QoE Models

In [5] and [6] a generic QoE exponential model is proposed for the transition from the QoS to the QoE domain $QoE = \alpha \cdot e^{-\beta \cdot QoS} + \gamma$. However, such a model is inflexible in the sense that the parameters α, β, and γ can be extracted through experimental sessions. End-users are asked to provide their satisfaction level concerning a service, when one important variable affecting their QoE is changing. Such a process is time consuming and demands a large and diverse sample of end-users to export reliable conclusions. DQX defines parameters such α, β, and γ through service-specific QoS values through a deterministic mathematical model.

C. Background

There are various scenarios where DQX will be a powerful instrument. Comparing similar services with diverse QoS parameters is one possible use case where DQX provides valuable input, especially when a price consideration is essential.

1) Auction-based Charging User-centric System: The Auction-based Charging User-centric System (AbaCUS) [1] is an approach that enables the competition in the mobile termination-service market [16] through an auction. In countries where the Calling Party Pays (CPP) principle is applied, the person that is dialing (caller) the phone number of a mobile user (callee) has to pay the termination rate that the Mobile Network Operator (MNO) of the callee demands from the MNO of the caller to deliver the call. AbaCUS proposes a Global System for Mobile Communications (GSM) overlay, where the caller can select another MNO operating in the area of the callee to deliver the call. Recently it has been proven that an automatic and on-demand MNO selection is technically possible as well as energy and time efficient [24]. The next step is to define how the proper MNO should be selected. AbaCUS describes at [26] an auction mechanism where the caller will select across a set of variables concerning the network access

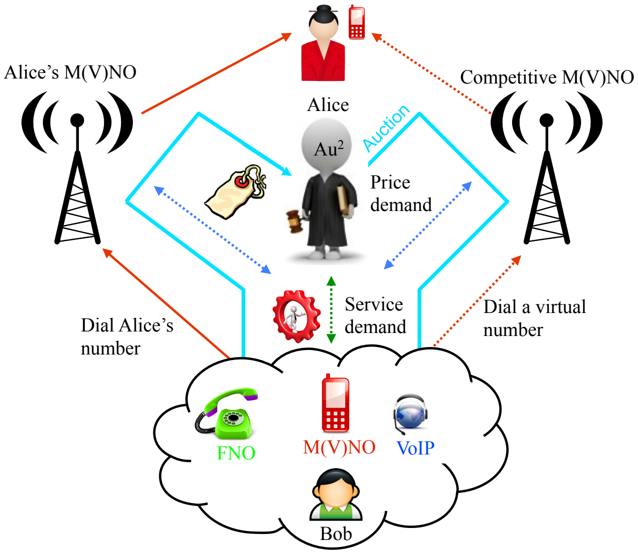

Figure 1. The AbaCUS Ecosystem [26]

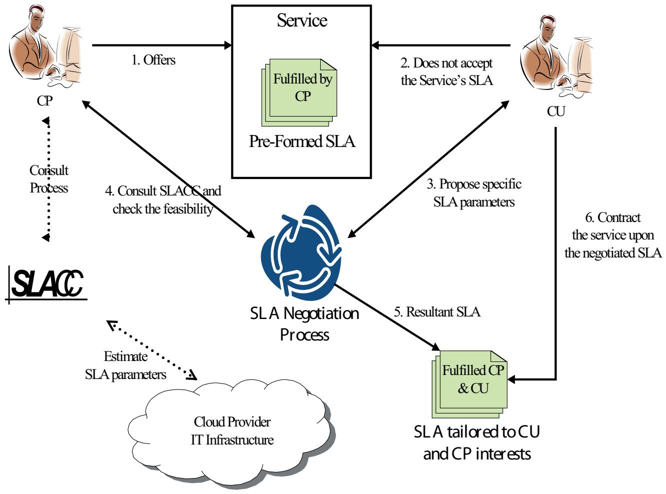

Figure 2. SLACC Solution Overview [17]

priority, the sound quality and the price of the service. Figure 1 presents the AbaCUS ecosystem where the caller defines his preference selecting among a predefined set of variables (priority/sound quality and price). MNOs bid on the same set of variables and the MNO that will offer the best price for the priority/sound quality pair is selected to terminate the call. However, such an approach is not flexible enough, because all MNOs should agree, or forced by the regulator, on offering the same priority/sound-quality service plans and need to have the same pricing schemes so a comparison between the different MNO's bids is possible. Using DQX will enable comparing diverse services without identical variables. According to the end-user preferences the MOS for each MNO can be calculated and used as a bidding metric in the AbaCUS auction mechanism.

2) *Investigations of an SLA Support System for Cloud Computing:* The SLA Support System for Cloud Computing (SLACC) [17] assumes the existence of an SLA negotiation process (cf. Figure 2). CPs offer various pre-formed SLAs to end-users. However, end-users might have demands concerning the price and technical parameters, which are not satisfied by any predefined SLA. Thus, during the SLA negotiation process the end-user could advertise service demands. The CP could consider end-user's preferences input and try to maximize the estimated QoE while minimizing the SLA violation probability. Before the CP could make an SLA offer to the end-user, SLACC, which is a decision support system for CPs, would examine if such an SLA can be fulfilled. Thus, a mathematical model like the one presented in this work here could be used for the estimated QoE maximization process.

III. QOE FORMALIZATION IN DQX

A precise QoE formalization demands a mathematical model that is able to consider multiple and diverse variables, such as priority, price, and bandwidth that can affect the end-user QoE positively or negatively on a given situation. Furthermore, each variable might affect QoE in a different way in each scenario. Additionally, QoE is strongly depended on the end-user since each person might have different demands and priorities concerning the same services. The high-level formalization of the QoE is illustrated below.

$$QoE := f(user,\ service,\ variables) \tag{1}$$

When QoE formalization is needed QoE should be treated as a bounded concept since a user cannot be infinitely satisfied or dissatisfied. *E.g.*, doubling the price of a service that is not affordable, will not satisfy less the end-user since the service was already not accessible due to high cost. Additionally, doubling the bandwidth of an average broadband plan without increasing the price, will not affect QoE proportionally, since services such as browsing, video streaming, or VoIP, perform equally well without such a bandwidth increment. Thus, it is assumed that there is a minimum μ and a maximum M QoE that can be represented, without any loss of generality, by the positive parameters, $\mu, M \in (0, \infty)$. Since $\mu < M$, let h be a positive parameter that represents the size of the QoE interval scale (cf. Equation 2).

$$h = M - \mu > 0 \tag{2}$$

Figure 3 illustrates QoE of the end-user for two different variables. The Y-axis shows the MOS of a variable in the interval h and the X-axis the normalized value x of each variable. The value e_0 on the Y-axis is the MOS that corresponds to the expected, agreed, or defined in the SLA value x_0 of each variable. Thus, let e_0 be the Expected MOS (eMOS) and x_0 the Expected Variable Value (eV^2). On one hand, the e_i curve reflects the MOS of a variable, such as bandwidth. Such variables while increasing to a maximum value x_{max}, imply an asymptotical QoE increment to the maximum MOS value M. Those variables in this work are termed Increasing Variables (IVs). Furthermore, when the value of an IV is minimum x_{min}, the MOS value is also

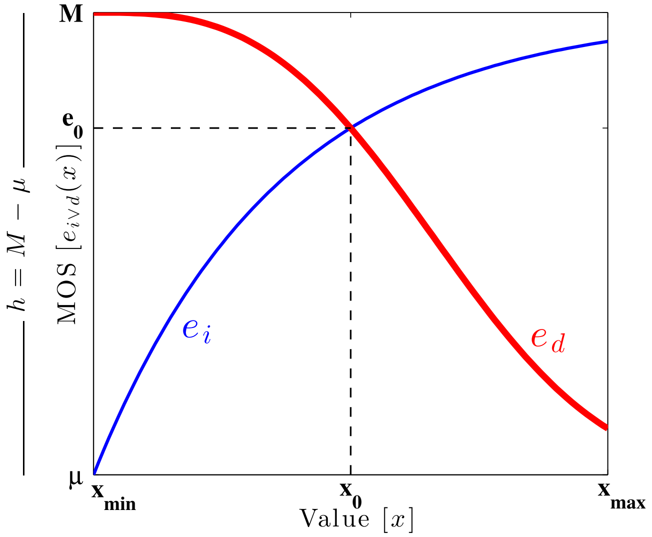

Figure 3. MOS Evolution for IVs (e_i) and DVs (e_d)

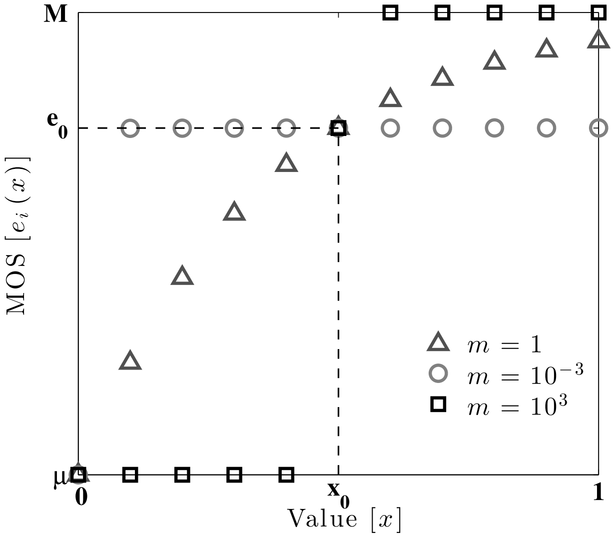

Figure 4. Plot for Different m Values of Equation 6

minimum (μ). On the other hand, the e_d curve reflects the MOS of a variable, such as the price of a service. Such variables, contrary to IVs, while increasing to a maximum value x_{max}, imply an asymptotical QoE decrement to the minimum MOS μ. Those variables are termed Decreasing Variables (DVs). Last but not least, when the value of a DV is x_{min} the MOS is M. *E.g.*, when a service is provided without charging the QoE is maximum.

The IV or DV characterization of a variable describes the nature of the argument $variables$ in Equation 1. The x_{min} and x_{max} values are related to the argument $service$ in the same equation. *E.g.*, the maximum throughput attainable is governed by the mobile link technology. The average sector throughput in Long Term Evolution (LTE) multiple-input and multiple-output (MIMO) 4x4 with 20 MHz bandwidth, the most deployed form of LTE, provides a maximum of 12.7 $Mbps$ uplink and 50.1 $Mbps$ downlink throughput [19].

Finally, x_0 ($x_{min} < x_0 < x_{max}$), is a value concerning a variable that affects QoE, and reflects the effect of the argument $service$ in the high-level QoE Equation 1. The value x_0 of a variable might not necessarily be related to the technology. *E.g.*, Hulu, a website and over-the-top (OTT) subscription service offering ad-supported on-demand video-streaming, recommends a downstream throughput of at least 1.5 $Mbps$ for smooth playback experience of Standard Definition (SD) 480p videos [11].

A. Specific QoE Functions

Without any loss of generality unity-based normalization of IVs values x is assumed (cf. Equation 3), to enable plotting the MOS of multiple valuables in one graph.

$$x := \frac{x - x_{min}}{x_{max} - x_{min}} \;\forall\, x \in \mathbb{R} \tag{3}$$

1) IVs QoE Function: The function $[0,1] \overset{e_i}{\to} [\mu, M]$, $m \in [0, \infty)$ (cf. Equation 4) is used to calculate QoE of an IV, such as bandwidth. The exponential function e_i that is illustrated in Figure 4 behaves like a step function for large values of m and like a constant function for small ones. Furthermore, for $m \in [1,3]$ e_i changes in a smooth way. The influence factor of a parameter m denotes the end-user's tolerance in fluctuations of variable's value x. Services that demand not less than a specific amount of bandwidth will see a high influence factor, while if the bandwidth does not affect QoE a lot, the influence factor will be low.

$$e_i(x) := h \cdot \left(1 - e^{-\lambda \cdot x^m}\right) + \mu \tag{4}$$

The eV^2 x_0 ($0 < x_0 < 1$) results in an eMOS e_0, where $\mu < e_0 < M$. Thus, given this assumption the parameter λ is presented in Equation 5. The formal proof of this equation can be found on the appendix.

$$e_i(x_0) := e_0 \overset{(4)}{\Longleftrightarrow} \lambda = x_0^{-m} \ln\left(\frac{h}{h - e_0 + \mu}\right) \tag{5}$$

Replacing λ above in Equation 4 results Equation 6, which is the QoE function that is used for MOS calculations of an IV (cf. Figure 4).

$$(4,5) \Rightarrow e_i(x) = h \cdot \left(1 - e^{-\left(\frac{x}{x_0}\right)^m \cdot \ln\left(\frac{h}{h - e_0 + \mu}\right)}\right) + \mu \tag{6}$$

2) DVs QoE Function: The function $[0,1] \overset{e_d}{\to} [\mu, M]$, $m \in [0, \infty)$ (cf. Equation 7) is used to calculate QoE of a DV (*e.g.*, price). The exponential function e_d is illustrated in Figure 5. Similarly with e_i values x are unity-based normalized to enable multiple variables plotting in one graph. Furthermore, e_j behaves also like a step function for large values of the influence factor m and like a constant function for small ones.

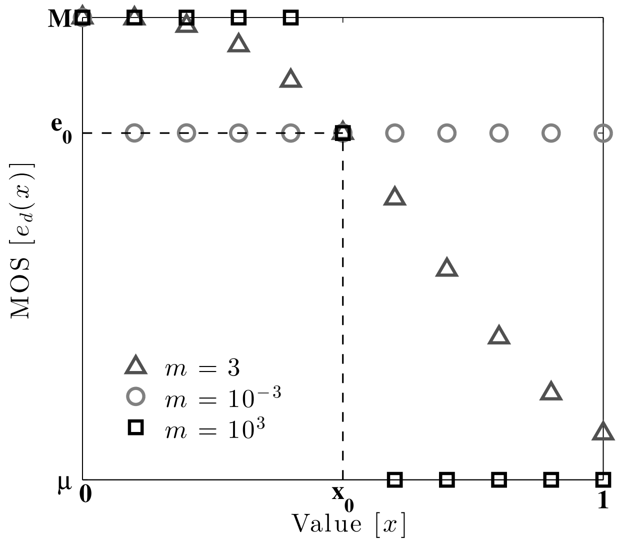

Figure 5. Plot for Different m Values of Equation 9

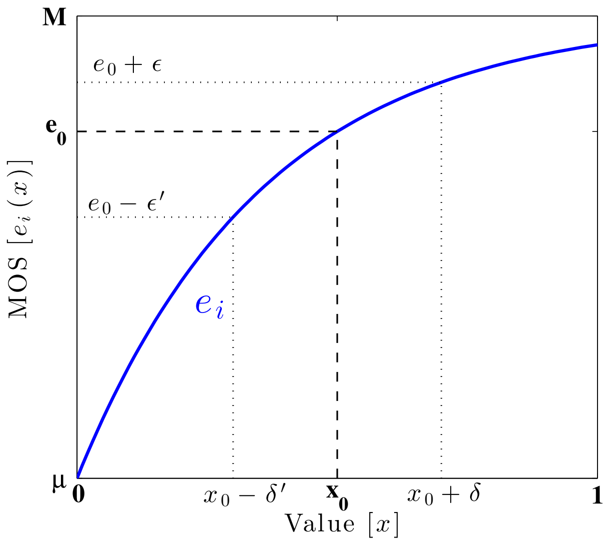

Figure 6. MOS Change for IVs

Finally, for $m \in [1, 3]$ e_d also changes in a smooth way.

$$e_d(x) := h \cdot e^{-\lambda \cdot x^m} + \mu \tag{7}$$

In the DV case the eV^2 x_0 $(0 < x_0 < 1)$ results an eMOS e_0 $(\mu < e_0 < M)$. Thus, λ is presented in Equation 8, with the formal proof be in the appendix.

$$e_d(x_0) := e_0 \overset{(7)}{\iff} \lambda = x_0^{-m} \ln\left(\frac{h}{e_0 - \mu}\right) \tag{8}$$

Replacinf λ above in Equation 7 results Equation 9, which is the QoE function that is used for MOS calculations of a DV (cf. Figure 5).

$$(7, 8) \Rightarrow e_d(x) = h \cdot e^{-\left(\frac{x}{x_0}\right)^m \cdot \ln\left(\frac{h}{e_0 - \mu}\right)} + \mu \tag{9}$$

B. Influence Factors Calculation

Selecting non-constant values of influence factors m represents the flexibility of diverse end-user's preferences on different scenarios. *E.g.*, increasing the price $\alpha > 0$ of a product to $\alpha = \alpha + \xi$ for $\xi > 0$ can effect differently end-user's QoE than decreasing the price of the same product to $\alpha = \alpha - \xi$. Thus, Equation 10 shows that the influence factor m can be a function of the value x.

$$m := f(x) = \begin{cases} m^- > 0 & \text{for } x < x_0 \\ 0 & \text{for } x = x_0 \\ m^+ > 0 & \text{for } x > x_0 \end{cases} \tag{10}$$

1) IVs Influence Factors Calculation: Equation 11 calculates m^+ if $x = x_0 + \delta \leq 1$ for $\delta > 0$ for when the MOS of an IV is calculated (IVs case). Figure 6 shows that $e(x) = e_0 + \epsilon < M$ for $\epsilon > 0$. Thus, the appropriate influence factor can be selected, if the impact of a specific value change on QoE is known. *E.g*, the quality of a video streaming session will drop from High Definition (HD) to Standard Definition (SD) if the bandwidth will drop from from $3Mbps$ to $1.5Mbps$ [11]. QoE decrement will follow accordingly.

$$e_i(x_0 + \delta) = e_0 + \epsilon \overset{(2,4,5,10)}{\iff}$$

$$\vdots \quad \text{(formally proven in the Appendix)}$$

$$\Leftrightarrow m^+ = \log_{\left(\frac{x_0+\delta}{x_0}\right)}\left[\log_{\left(\frac{M-e_0}{h}\right)}\left(\frac{M - e_0 - \epsilon}{h}\right)\right] \tag{11}$$

The base and the argument of each logarithm in Equation 11 is positive and different than 1, because (a) $0 < \frac{x_0+\delta}{x_0} < 1$, (b) $0 < \frac{M-e_0}{h} < 1$, and (c) $0 < \frac{M-e_0-\epsilon}{h} < 1$. Thus, Equation 11 after changing the logarithm to the natural logarithm is rewritten below (any logarithm with a positive base different than 1 can be selected for the logarithm base change). A careful selection of logarithms' base can simplify calculations *e.g.*, $log_\alpha \alpha = 1$ where $0 < \alpha = {}^{M-\epsilon_0}/_{h} \neq 1$.

$$(11) \Rightarrow m^+ = \frac{\ln\left(\frac{\ln\frac{M-e_0-\epsilon}{h}}{\ln\frac{M-e_0}{h}}\right)}{\ln\frac{x_0+\delta}{x_0}} \tag{12}$$

Similarly to the previous case, when $x = x_0 - \delta' \geq 0$ for $\delta' > 0$ and $e_0 - \epsilon' \geq \mu$ for $\epsilon' > 0$ (cf. Figure 6), m^- is seen in Equation 13 below.

$$e_i(x_0 - \delta') = e_0 - \epsilon' \overset{\cdots}{\iff} m^- = \frac{\ln\left(\frac{\ln\frac{M-e_0+\epsilon'}{h}}{\ln\frac{M-e_0}{h}}\right)}{\ln\frac{x_0-\delta'}{x_0}} \tag{13}$$

2) DVs Influence Factors Calculation: Symmetrical steps as in the IVs case are taken when considering DVs (cf. Figure 7). Furthermore, symmetrical assumptions are done concerning δ, δ', $x_0 + \delta$, $x_0 - \delta'$ and ϵ, ϵ', $e_0 + \epsilon$, $e_0 - \epsilon'$, so that the flexibility on logarithms' base selection applies also in the

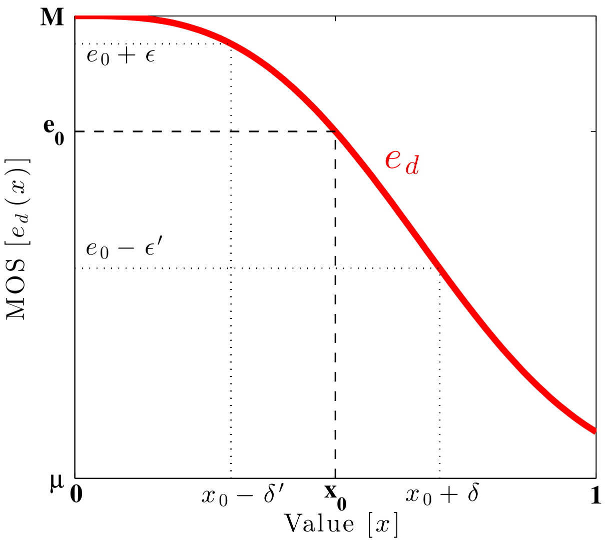

Figure 7. MOS Change for DVs

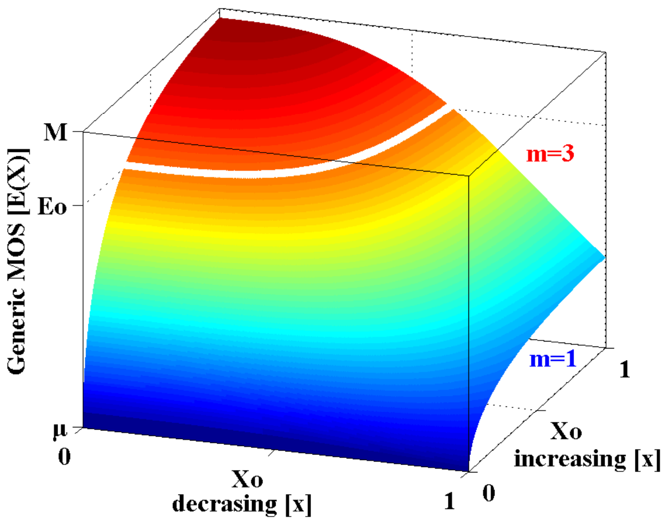

Figure 8. Generic MOS Evolution for Equally Participating IV ($m = 1$) and DV ($m = 3$)

DVs case. Therefore Equation 14, Equation 15, and Equation 16 are obtained.

For $x = x_0 + \delta \leq 1$, where $\delta > 0$ and $e_0 - \epsilon' > \mu$, where $\epsilon' > 0$ (cf. Figure 7), m^+ is calculated in Equation 14 below.

$$e_d\left(x_0 + \delta\right) = e_0 - \epsilon' \qquad \overset{(7,8,10)}{\Longleftrightarrow}$$

$$\vdots \quad \text{(formally proven in the Appendix)}$$

$$\Leftrightarrow m^+ = \log_{\left(\frac{x_0+\delta}{x_0}\right)}\left[\log_{\left(\frac{e_0-\mu}{h}\right)}\left(\frac{e_0 - \mu - \epsilon'}{h}\right)\right] \tag{14}$$

Changing all the logarithms in Equation 14 to the natural logarithms is allowed since all the bases and arguments are positive and not equal to 1. Thus, m^+ is seen in Equation 15. Similar to the IVs case any logarithm with a positive base different than 1 can be selected for the logarithm base change.

$$(14) \Rightarrow m^+ = \frac{\ln\left(\frac{\ln\frac{e_0-\mu-\epsilon'}{h}}{\ln\frac{e_0-\mu}{h}}\right)}{\ln\frac{x_0+\delta}{x_0}} \tag{15}$$

For $x = x_0 - \delta' \geq 0$ where $\delta' > 0$ and $e_0 + \epsilon \leq M$ for $\epsilon > 0$ (cf. Figure 7), m^- is seen in Equation 16 below.

$$e_d\left(x_0 - \delta'\right) = e_0 + \epsilon \overset{\cdots}{\Longleftrightarrow} m^- = \frac{\ln\left(\frac{\ln\frac{e_0-\mu+\epsilon}{h}}{\ln\frac{e_0-\mu}{h}}\right)}{\ln\frac{x_0-\delta'}{x_0}} \tag{16}$$

C. Generic QoE Functions

Each service's unique characteristics, define a unique affect of QoE when some variable(s) are changing. Thus, combining a set $X = \{x_1, \ldots, x_k, \ldots, x_N\}$ of $N \in \mathbb{N}^+$ diverse variables values x_k, to calculate a generic MOS, demands weights w_k for each variable, since their importance might be different for different services. Equation 17 defines the generic MOS function $E\left(X\right)$. Weights $w_k \in \mathbb{R}^+$ reflect the contribution of all variables. As a starting point the selection of $w_k = 1$ is made, since all variables consider to equally contribute in QoE. However, w_k is an additional degree of freedom that considers the diverse importance of each variable. Thus, w_k is used to calibrate DQX. For this purpose input from end-users can be used to extract those values of w_k that reflect better QoE as reported from end-users.

Figure 8 illustrates the generic MOS function $E(X)$ of a hypothetical service where one IV and one DV with an influence factor $m = 1$ and $m = 3$ respectively, affect the QoE. In this example the contribution weight of both parameters is selected to be 50% to show what is the QoE effect of an equal percent fluctuation of each parameter. The white area on the graph marks all the possible pairs of both variables values that results an eMOS $E = E_0$.

$$E\left(X\right) \coloneqq \mu + h \cdot \prod_{k=1}^{N}\left[\frac{e_{(i \vee d)}\left(x_k\right) - \mu}{h}\right]^{w_k} \tag{17}$$

The generic MOS in Equation 17 is chosen to be a weighted product of all variable-specific MOS' instead of a weighted summary. The reason for that is to ensure that if one variable's MOS is very low, and cannot be compensated by an improvement of other variables, the generic MOS will reflect it. In case of a weighted summary of each variable's MOS the generic MOS under specific circumstances can still be equal to the eMOS E_0 even if the MOS of a specific variable is the minimum one μ. Assume the following scenario where a MNO is offering a flat rate mobile data plan, and two variables (bandwidth (IV) and price (DV)) affecting equally the QoE of end-users. This is a realistic scenario since an end-user when selection such a service across different MNOs with similar network coverage, the standard case for urban areas, can compare only those two variables. Due to technical problems the MNO is unable to provide the service; considering only

Table I
THE MOS SCHEME RECOMMENDED BY THE ITU-T [14]

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

the bandwidth the MOS is minimum (μ) since there is no data connectivity. The MNO decides not to charge customers for the service during the non-functional period; considering only the price the MOS is maximum (M) since there is no cost for the service. If the generic MOS would be an equal weighted summary of the respective MOS', then $E = {}^{M}\!/_{2} + {}^{\mu}\!/_{2}$. For $M = 5$, $\mu = 1$, and $E_0 = 3$ the generic MOS would be $E = 3 = E_0$. However, the overall end-users' QoE despite the fact no payment is needed should be lower then the eMOS because no service is provided. Thus, the low credibility of the MNO should also be reflected in the generic MOS. Equation 17 states the necessity of an acceptable level for each variable affecting QoE. Thus, in the scenario mentioned above the generic MOS using Equation 17 would be $E = 1$, which means that there is no price that a MNO can offer to maintain end-users' QoE concerning the mobile data service if the service is not available. The latest result illustrates that the availability of a service, which in this scenario is encapsulated in the bandwidth variable, is an important parameter. Thus, the end-users' dissatisfaction and the MNO's credibility decrement is reflected by the generic MOS for the service unavailability scenario described above.

D. ITU-T MOS-Compilant QoE Functions

The ITU-T has defined in recommendations P.800 [14], P.800.1 [13], and P.805 [15] a five-point scale that represents QoE of end-users. The ITU-T MOS scale is summarized in Table I. In DQX model, the eMOS e_0 when the value of a variable x is equal to the eV^2 x_0 selected to be equal with the ITU-T numerical representation of "Good" QoE. Thus, Equation (18) illustrates the ITU-T MOS-compilant maximum M, expected e_0, and minimum μ MOS values.

$$\left.\begin{aligned} M &:= 5 \\ \mu &:= 1 \end{aligned}\right\} \xRightarrow{(2)} h = 4 \text{ and } e_0 := 4 \tag{18}$$

Given this input, the ITU-T MOS-compilant equation for IVs and the influence factor m equations, as presented in subsection III-A and subsection III-B respectively, can be seen in Equation 19. Similarly for DVs, the same results are formalized in Equation 20. Those equations can be used to express the QoE in the ITU-T standardize five point scale *e.g.* when considering telephony services.

Table II
BROADBAND PLANS FOR HOME-USERS OF A SWISS ISP [3]

Uplink bandwidth [Mbit/s]	**Downlink bandwidth [Mbit/s]**	**Price per month [CHF]**
15	250	89
10	125	69
5	50	59
2	20	45
0.2	2	0

$$\begin{gathered} (6, 12, 13, 18) \Rightarrow e_i\left(x\right) = 4 \cdot \left(1 - e^{-\left(\frac{x}{x_0}\right)^m \cdot \ln 4}\right) + 1 \\ m^- = \frac{\ln\left(\frac{\ln \frac{1+\epsilon}{4}}{-\ln 4}\right)}{\ln \frac{x_0-\delta}{x_0}} \quad m^+ = \frac{\ln\left(\frac{\ln \frac{1-\epsilon}{4}}{-\ln 4}\right)}{\ln \frac{x_0+\delta}{x_0}} \end{gathered} \tag{19}$$

$$\begin{gathered} (9, 15, 16, 18) \Rightarrow e_d\left(x\right) = 4 \cdot e^{-\left(\frac{x}{x_0}\right)^m \cdot \ln {}^{4}\!/_{3}} + 1 \\ m^- = \frac{\ln\left(\frac{\ln \frac{3+\epsilon}{4}}{\ln {}^{3}\!/_{4}}\right)}{\ln \frac{x_0-\delta}{x_0}} \quad m^+ = \frac{\ln\left(\frac{\ln \frac{3-\epsilon}{4}}{\ln {}^{3}\!/_{4}}\right)}{\ln \frac{x_0+\delta}{x_0}} \end{gathered} \tag{20}$$

Finally, Equation 21 generates the generic ITU-T MOS-compilant MOS $E(X)$ considering a set X of IVs' and DVs' values. Such an method is used at [25] to calculate the MOS of various services on mobile networks such as VoIP, video streaming, browsing, and random flow data streaming.

$$(17, 18) \Rightarrow E\left(X\right) = 1 + 4 \cdot \prod_{k=1}^{N} \left[\frac{e_{(i \vee d)}\left(x_k\right) - 1}{4}\right]^{w_k} \tag{21}$$

E. DQX Parameters Selection Example

Table II summarizes broadband plans that are offered by an ISP in Switzerland [3]. In this scenario there are three variables that affect QoE. Those variables are: (1) uplink bandwidth $u \in [0.2, 15]$, (2) downlink bandwidth $d \in [2, 250]$, and (3) price $p \in [0, 89]$ of broadband plans. Thus the set of variables affecting QoE is $X = \{u, d, p\}$. On one hand, both u and d follow the rule "the more you have the better it is". On the other hand, p is better if it is low. So, u and d are considered to be IVs and Equation 19 will be used for MOS calculations concerning those variables. Price p is considered to be DV and Equation 20 should be used to calculate the price-related MOS.

To export the eV^2 for each variable assume a customer that selected the plan offering 5 $Mbit/s$ uplink and 50 $Mbit/s$ uplink, for 59 CHF per month. Thus from Equation 3 derives $u_0 = \frac{5-0.2}{15-0.2} = 0.324$, $d_0 = \frac{50-2}{250-2} = 0.194$, and $p_0 = \frac{59-0}{89-0} = 0.663$. To calculate influence factors m assume that 50% lower than u_0 and d_0 values would drop the MOS concerning u and d from 4 (Good) to 2 (Poor). Such information can be extracted in this case by observing when end-users report to their ISP that their broadband connection is underperforming, thus they get dissatisfied because of it. Thus, Equation 22 is used to calculate m^- in this example. Following a similar way of thinking m^+ factor can be calculated using the respective Equation. Concerning p, the influence factors m^- and m^+ can be calculated while considering the percent discount and increment of the price that would satisfy and dissatisfy respectively an end-user. Finally, weight parameters $w_u = w_d = w_p = 1$ are assumed to be equal to reflect equal importance of all QoE-related variables for end-users. However, weight parameters can be adjusted to calibrate DQX, when end-users QoE feedback, in scenarios where more than one variables change simultaneously, is available.

$$(19) \Rightarrow m^- = \frac{\ln\left(\frac{\ln\frac{1+2}{4}}{-\ln 4}\right)}{\ln\frac{50}{100}} = 2.27 \tag{22}$$

IV. DISCUSSION, CONCLUSIONS, AND FUTURE WORK

DQX contrary to a generic exponential QoE model (cf. Table III) proposes a deterministic mathematical model that can be used to generate a MOS illustrating end-user QoE, considering one or multiple and diverse variables, such as bandwidth, network access priority, or price. The model requires a minimum and maximum satisfaction score in the positive numbers space and a value between those numbers to represents the end-user's satisfaction, when each variable has the desired/expected value, such as the minimum required bandwidth needed to achieve HD video streaming quality. Furthermore, for each variable a positive number is needed showing the effect of the parameter's fluctuation in QoE. This influence factor can be calculated from those equations that are provided here. In case of more than one participating variable in the MOS calculation the weight of each variable needs to be specified.

Concluding, such a model presented here is very well suited (a) to calculate the MOS provided the value of measurable variables and (b) to estimate which actions are needed in case of a change, of one or more variable(s') value(s), to maintain the same end-user's satisfaction level if possible. Having such a method in place can save the time needed to perform a survey to observe end-user behavior. Also, the MOS generation mathematical model presented here, can be used to generate a comparison index on similar services for the end-user, across different service providers, such as CPs, with different variables and values.

DQX is beneficial for end-uses when comparing different services across multiple SPs. SPs can also estimate the end-user's QoE with such a mathematical model while considering (a) their available resources, (b) demands of the end-user, and (c) minimum service requirements. Furthermore, since this model can consider variables such as the price of a service, SPs can maximize their revenues, while maintaining their customer's QoE at a certain level. Thus, it is essential for SPs to create end-user and service profiles by calculating all parameters of this model. Such a calculation can be initiated through end-user's demands (*e.g.*, maximum price for a service), and/or service's characteristics (*e.g.*, maximum latency allowed on a VoIP session).

Table III
COMPARISON OF DQX WITH IQX

Model	**Deterministic**	**Multiple Parameters Support**
DQX	Yes	Yes
IQX	No	No

In future work all necessary input parameters, such as influence factors, minimum, maximum, and expected variable's values, as well as variable's weights, will be defined for each variable of the AbaCUS scenario (network access priority, voice quality, and price) so that an auction based on a single metric will be enabled. Such a feature bypasses the necessity of the assumption that all MNOs offer precisely the same QoS/price plans. Finally, the QoE model presented in this work here will be used to evaluate data measurements on a mobile environment and generate a MNOs QoE map for services, such as, browsing, video streaming, and VoIP.

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APPENDIX

λ calculation proof of IVs (Equation 5).

$$
\begin{aligned}
& e_i\left(x_0\right) = e_0 && \overset{(4)}{\Longleftrightarrow} \\
\Leftrightarrow\ & e_0 = h \cdot \left(1 - e^{-\lambda \cdot x_0^m}\right) + \mu && \Longleftrightarrow \\
\Leftrightarrow\ & \frac{e_0 - \mu}{h} = 1 - e^{-\lambda \cdot x_0^m} && \Longleftrightarrow \\
\Leftrightarrow\ & \frac{h - e_0 + \mu}{h} = e^{-\lambda \cdot x_0^m} && \Longleftrightarrow \\
\Leftrightarrow\ & \ln\left(\frac{h - e_0 + \mu}{h}\right) = -\lambda \cdot x_0^m && \Longleftrightarrow \\
\Leftrightarrow\ & \lambda = x_0^{-m} \ln\left(\frac{h}{h - e_0 + \mu}\right)
\end{aligned}
$$

λ calculation proof of DVs (Equation 8).

$$
\begin{aligned}
& e_d\left(x_0\right) = e_0 && \overset{(7)}{\Longleftrightarrow} \\
\Leftrightarrow\ & e_0 = h \cdot e^{-\lambda \cdot x_0^m} + \mu && \Longleftrightarrow \\
\Leftrightarrow\ & \frac{e_0 - \mu}{h} = e^{-\lambda \cdot x_0^m} && \Longleftrightarrow \\
\Leftrightarrow\ & \ln\left(\frac{e_0 - \mu}{h}\right) = -\lambda \cdot x_0^m && \Longleftrightarrow \\
\Leftrightarrow\ & \lambda = x_0^{-m} \ln\left(\frac{h}{e_0 - \mu}\right)
\end{aligned}
$$

Influence factor calculation (m^+) proof of IVs (Equation 11).

$$
\begin{aligned}
& e_i\left(x_0 + \delta\right) = e_0 + \epsilon && \overset{(4,10)}{\Longleftrightarrow} \\
\Leftrightarrow\ & h \cdot \left(1 - e^{-\lambda \cdot (x_0+\delta)^{m^+}}\right) + \mu = e_0 + \epsilon && \Longleftrightarrow \\
\Leftrightarrow\ & 1 - e^{-\lambda \cdot (x_0+\delta)^{m^+}} = \frac{e_0 - \mu + \epsilon}{h} && \Longleftrightarrow \\
\Leftrightarrow\ & e^{-\lambda \cdot (x_0+\delta)^{m^+}} = \frac{h - e_0 + \mu - \epsilon}{h} && \overset{(5)}{\Longleftrightarrow} \\
\Leftrightarrow\ & e^{-\left(\frac{x_0+\delta}{x_0}\right)^{m^+} \cdot \ln\left(\frac{h}{h - e_0 + \mu}\right)} = \frac{h - e_0 + \mu - \epsilon}{h} && \overset{(2)}{\Longleftrightarrow} \\
\Leftrightarrow\ & e^{\ln\left(\frac{h - e_0 + \mu}{h}\right)\left(\frac{x_0+\delta}{x_0}\right)^{m^+}} = \frac{M - e_0 - \epsilon}{h} && \Longleftrightarrow \\
\Leftrightarrow\ & \frac{h - e_0 + \mu}{h}^{\left(\frac{x_0+\delta}{x_0}\right)^{m^+}} = \frac{M - e_0 - \epsilon}{h} && \overset{(2)}{\Longleftrightarrow} \\
\Leftrightarrow\ & \frac{M - e_0}{h}^{\left(\frac{x_0+\delta}{x_0}\right)^{m^+}} = \frac{M - e_0 - \epsilon}{h} && \Longleftrightarrow \\
\Leftrightarrow\ & \left(\frac{x_0 + \delta}{x_0}\right)^{m^+} = \log_{\left(\frac{M - e_0}{h}\right)}\left(\frac{M - e_0 - \epsilon}{h}\right) && \Longleftrightarrow \\
\Leftrightarrow\ & m^+ = \log_{\left(\frac{x_0+\delta}{x_0}\right)}\left[\log_{\left(\frac{M - e_0}{h}\right)}\left(\frac{M - e_0 - \epsilon}{h}\right)\right]
\end{aligned}
$$

Influence factor calculation (m^+) proof of DVs (Equation 14).

$$
\begin{aligned}
& e_d\left(x_0 + \delta\right) = e_0 - \epsilon' && \overset{(7,10)}{\Longleftrightarrow} \\
\Leftrightarrow\ & h \cdot e^{-\lambda \cdot (x_0+\delta)^{m^+}} + \mu = e_0 - \epsilon' && \Longleftrightarrow \\
\Leftrightarrow\ & e^{-\lambda \cdot (x_0+\delta)^{m^+}} = \frac{e_0 - \mu - \epsilon'}{h} && \overset{(8)}{\Longleftrightarrow} \\
\Leftrightarrow\ & e^{-\left(\frac{x_0+\delta}{x_0}\right)^{m^+} \cdot ln\left(\frac{h}{e_0 - \mu}\right)} = \frac{e_0 - \mu - \epsilon'}{h} && \Longleftrightarrow \\
\Leftrightarrow\ & e^{\ln\left(\frac{e_0 - \mu}{h}\right)\left(\frac{x_0+\delta}{x_0}\right)^{m^+}} = \frac{e_0 - \mu - \epsilon'}{h} && \Longleftrightarrow \\
\Leftrightarrow\ & \left(\frac{e_0 - \mu}{h}\right)^{\left(\frac{x_0+\delta}{x_0}\right)^{m^+}} = \frac{e_0 - \mu - \epsilon'}{h} && \Longleftrightarrow \\
\Leftrightarrow\ & \left(\frac{x_0 + \delta}{x_0}\right)^{m^+} = log_{\left(\frac{e_0 - \mu}{h}\right)}\left(\frac{e_0 - \mu - \epsilon'}{h}\right) && \Longleftrightarrow \\
\Leftrightarrow\ & m^+ = \log_{\left(\frac{x_0+\delta}{x_0}\right)}\left[\log_{\left(\frac{e_0 - \mu}{h}\right)}\left(\frac{e_0 - \mu - \epsilon'}{h}\right)\right]
\end{aligned}
$$