

On the Approximation of ISP and User Utilities from Quality of Experience

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Abstract—While the network quality research has been oscillating between user- and technology-driven viewpoints, the evolution of a utility-centric perspective is still a good way off. Today, not only insufficient data exists on network quality market figures, but also on the user’s usage appreciation across service types and test ranges. Filling those research gaps, the present work presents a novel model, mainly constructed around existing empirical Quality of Experience (QoE) materials, which approximates both ISP and user utilities. A focus is set on the case of controlled quality and service degradations that intelligently adapt services upon resource shortages. In a case study, this model is applied to the case of Video on Demand services.

Keywords—Quality of Experience; Willingness-To-Pay; Market; Utility; Approximation

I. INTRODUCTION

In the last years, the quality understanding in the telecommunications industry has been oscillating between user-centric (early Quality of Service (QoS) and later Quality of Experience (QoE)) and technical considerations (QoS as viewed today; but also “objective” QoE). In this sphere, QoE, measured in Mean Opinion Scores (MOS) on ACR-5 (Absolute Category Rating) scale [1], provides a good basis for a Customer Satisfaction (CS) metric (in analogy to the definition in [2]), which gives indications on the user’s subjective service appreciation. Many works like [3] treat QoE as equivalent to utilities, in the sense of Von Neumann’s definition [4] (i.e., cardinal values, bound to rationality and linearity), whether to describe the user’s service valuation relative to alternatives (i.e., user utilities) or the ISP’s profits (i.e., ISP utilities). Despite the obvious relation between QoE and CS and the notable influence of QoE on the user utility, QoE and utility are disparate for a variety of reasons:

- 1) Contrary to monetary metrics, e.g., currencies like USD \$, QoE measured in MOS non-linearly relates to QoS input (cf. [5] or [6] relating to the Fechner scale [7]) and is non-trivially associated to monetary expenditures [8], i.e., Willingness-To-Pay (WTP).
- 2) While some users may appreciate high QoE (and indirectly QoS), they may have no intentions to purchase quality upgrades. Thus, monetary valuations, i.e., the classical utility, and QoE cannot be assumed to be generally identical.
- 3) Cognitive dissonance observations [9] induced by active quality purchase decisions support the disparity.
- 4) The comparison and linkage of solitary QoE ratings (s.t. test ranges, scenario, tariffs, service preferences,

usage intentions, etc.) is non-trivial. For example when users start a videoconference, the utility for audio calls will be lower despite contrary QoE ratings for the current QoS in laboratory trials.

- 5) Standardized QoE test methodologies, e.g., [10], recommend training sessions in which the test ranges are introduced to the users. In terms of utility assessments, this priming of users will bias the assessment.

The market for quality-differentiated network services has not taken on since its beginnings (see [11]), which may partially be explained by the absence of utility figures. Among others, modern network adaptation concepts like the controlled service degradation (cf. [12]), a process trying to for example maximize the social welfare through an intelligent and adaptive resource assignment, require utility information to optimally function. Especially client-side content adaptations—e.g., DASH [13] as used by services like Youtube¹ and Netflix²—have recently gained in importance.

Despite the desperate need for utility figures, the conversion of isolated QoE results to a utility-equivalent form has not yet been deciphered. QoE trials have not been designed to test the direct comparison of QoE results for different services or test ranges, and cross-service QoE models have centrally focused on QoS inputs only³. Only limited efforts have been dedicated to the mapping of QoE to monetary representations (see Sec. II). This transitively hampers the derivation of utility figures from QoE and in turn aggravates the practical deployment of human-centric communication services.

Accordingly, the main contributions of this paper are twofold: Firstly, a model approximating inter-service utilities mainly from the concatenation of QoE trials results and their relationship to WTP is proposed. Secondly, this model is tested in a case study on Video on Demand (VoD) services.

Thus, the current work aims at filling this gap for the first time by concatenating isolated QoE and comparable results in order to derive inter-service user and ISP utilities. This work specifically focuses on the realistic case of controlled service degradations (see Sec. III) where a user’s preferred service

¹<https://www.youtube.com/>, last accessed: April 17, 2015

²<http://www.netflix.com>, last accessed: April 17, 2015

³https://www.qu.tu-berlin.de/menue/forschung/laufende_projekte/cross-service_cross-user_quality_of_experience_cscu-qoe/, last accessed: April 17, 2015

type or quality cannot be provisioned due to capacity limitations, i.e., a resource scarcity scenario with clear customer preferences.

The remainder of this work is structured as follows: Upon related works in Sec. II and definitions in Sec. III we formulate a novel utility approximation model in Sec. IV. The resulting model will be instantiated in a case study in Sec. V. The present work closes with concluding remarks in Sec. VI.

II. WILLINGNESS-TO-PAY (WTP)

Among the handful WTP for QoS trials is a rather small experiment from the M3I project [14]. More recently two larger laboratory studies have been conducted on Standard Definition (SD) and High Definition (HD) VoD WTP and QoE in 2011 [9] and 2012 [8], [15] respectively. The latter experiment is hereinafter briefly revisited.

The 2012 laboratory study [8] has empirically tested the WTP for network video quality upgrades in an HD scenario. Test subjects have purchased improved bitrates with their *own money* solely based on price cognitions (price monitor) and quality perceptions (shown video). 17 quality classes Q_x ($x = 0, \dots, 16$) have been used with exponentially increasing bitrates from 128 kbit/s at $Q_{x=0}$ to 32768 kbit/s at $Q_{x=16}$. Three tariffs have been assessed in three test groups consisting of 43 subject in total. At $Q_{x=16}$ tariff A had a maximum price p_{max} of €2, tariff B of €3 and tariff C of €4 for 20 mins at Q_{16} (with linear pricing from $p = 0$ at Q_0). The following notable median WTP values (i.e., WTP for a representative user) have been retrieved: €0.95 (across all tariffs), €0.74 (tariff A), €0.95 (tariff B) and €1.26 (tariff C).

The demand d_{HD} (i.e., number of buyers) has been fitted per tested price-quality combination Q_x to the beta, as commonly used for third-degree price discrimination [16], and the normal distribution for comparison. The used beta regression B prediction functions (using a technique aggregating bins of three similar quality classes in order to reduce noise) for the Probability Density Functions (PDF) of the demand are (cf. Fig. 1)

$$B(x)_A := \frac{e^{-1.32512 - 0.03140 \cdot QC(x+1)}}{1 + e^{-1.32512 - 0.03140 \cdot (x+1)}}, \quad (1)$$

$$B(x)_B := \frac{e^{-1.10596 - 0.07594 \cdot QC(x+1)}}{1 + e^{-1.10596 - 0.07594 \cdot (x+1)}}, \quad (2)$$

$$B(x)_C := \frac{e^{-1.00800 - 0.08073 \cdot QC(x+1)}}{1 + e^{-1.00800 - 0.08073 \cdot (x+1)}}, \quad (3)$$

where QC maps the bitrate in Mbit/s to the quality classes x from [8], i.e., $QC \approx 2.88537 \cdot \log(7.8128 \cdot bw)$. For the normally distributed fitting, we obtain $N_A(\mu = 6.839; \sigma = 3.234; x)$, $N_B(5.824, 3.735; x)$ and $N_C(5.086, 3.524; x)$, where μ is the mean, σ the variance and $x = QC(bw)$. While the **WTP and demand levels** under a **single-choice** (e.g., *Do you accept quality A for price P?*) are well characterised by $B(x)_{\{A,B,C\}}$ (R^2 for the Cumulative Distribution Function (CDF) strictly above 0.95; the demand under a single choice), the **customer segments**, as relative assignment when buyers can choose the most attractive Q_x from **multiple offers**, is best approximated by $N_{\{A,B,C\}}$ (R^2 is

0.534, 0.779 and 0.848 for the PDF—cf. Fig. 1). In the single-choice case, price discrimination refers to separate testings.

III. ASSUMPTIONS & DEFINITIONS

In the following, we will provide a series of assumptions and definitions for the remainder of this work, which are specifically tailored to the controlled service degradation case:

- 1) For calculability reasons, the purchasing situation of each user is reduced to a **one-shot decision process** with constant location, time, budget, interests and WTP (absolute monetary expenditure) for services, and user context (lighting, noise, etc.), which is comparable to common empirical QoE laboratory test restrictions. Users have currently an intention to use a network-based service, e.g., video streaming or web surfing.
- 2) Users have a **strictly ordered preference**⁴ (i.e., the relative preference of one service over another one; also see [12]) for all considered services $s_{1\dots n} \in S : s_1 \succ s_2 \succ \dots s_{n-1} \succ s_n$ (where $s_1 \succ s_2$ represents a strict preference of s_1 over s_2 under the current conditions). For example, when users want to watch an episode of their favorite TV series at home at this moment (primary service), the utility for any different activity (e.g., watching a sportscast or listening to music) is lower.
- 3) Users are **willing to pay more for services they prefer** over any alternative (e.g., video stream over sportscast). In other words, when users are intending to watch a specific HD video stream, they have a lower consumption utility for any alternative. Whenever the QoS is acceptable, the following condition therefore holds:

$$WTP(s_k) > WTP(s_{k+1}) > WTP(s_{k+2}) \dots,$$

where $k = 1$ is the primary service choice and $k + 1$ is the next best alternative.

- 4) Specific attention will be paid to **controlled degradations** within (e.g., lowering bitrates or switching from HD to SD and between service types (e.g., from video to audio). The controlled degradation is triggered whenever the QoE is critical and non-optimal, e.g., switching from poor HD to acceptable SD streams. We will further assume users are willing to pay more for more challenging media-rich services (corresponding to their service preferences). Otherwise, a controlled degradation is futile, as lower bandwidth consuming services with higher user utility have dominantly higher ISP utility alike.

IV. APPROXIMATION MODEL

Due to the non-trivial relationship between WTP and QoE and the small number of WTP measurements, the approximation of utilities needs to be carefully designed around known empirical anchor points, i.e., WTP of other service types and

⁴This assumption represents a simplification of the reality for modelling purposes, which may not be generally applicable, esp. for less concrete usage scenarios.

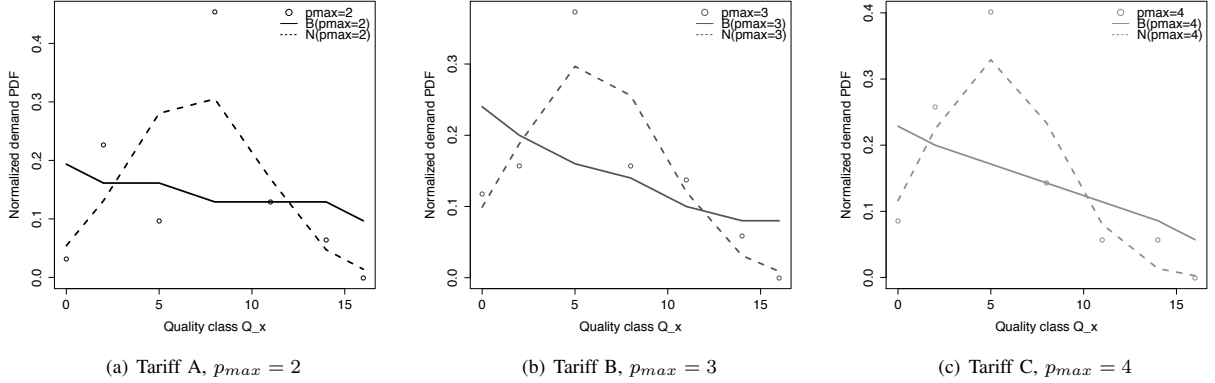


Fig. 1. Reconditioned demand PDF for quality classes Q_x from [8] (fitted to the beta B and normal N distributions).

a broad set of QoE ratings where esp. adaptive streaming scenarios may provide interesting starting points. As WTP or QoE trials considering price cognitions across services are rare, we originate our inter-service utility approximation from classical QoE data based on the assumptions given in Sec. III.

A. Stage 1 (SI): Subjective QoE data without price

The first stage targets the concatenation of individual QoE assessments for particular test ranges, service types or scenarios, e.g., SD and HD video streams (cf. Fig. 2). This process requires a recalibration of raw QoE data, which is reflected in the hereinafter presented Stage 1 process:

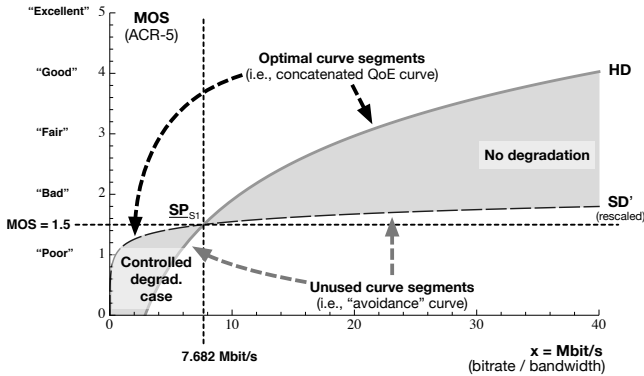


Fig. 2. QoE for controlled Video on Demand service degradations.

- 1) The isolated QoE curves for all considered services are transferred to a functional representation, e.g., via the commonly used logarithmic curve [17] fittings.
- 2) When taking the service preference into account, a switching MOS needs to be defined. Located at the switching MOS, users will be indifferent whether to retain service k or the next best alternative $k + 1$ under the current QoS conditions, i.e., k 's original and $k + 1$'s rescaled QoE curve intersect at this switching point SP_{S1} . This process stands in analogy to Gomez et al.'s [18] QoE- and QoS-aware network management where adaptations actions are triggered

whenever the QoE drops below a defined threshold. Depending on the extent of the service (type) degradation disutility we propose to use different switching MOS values. Whenever service k is distinctly preferred over $k + 1$ the $MOS_{SP_{S1}}$ is reasonably parametrized with 1.5, while 2.5 may be suitable for close calls. If the content type cannot be retained, the switching MOS may be affected more severely. For example from Full HD (1080p) to 720p video quality we suggest to set the switching MOS to 3 (on ACR scale) for service k , i.e., “fair” quality, while a drop to CIF is better reflected by a MOS of 1.5. If not even the content type can be retained, SP_{S1} may be affected more severely. With the existence of more comparable QoE data, a more fine-granular chain of service degradations can be constructed.

- 3) The MOS data of each service s_{k+1} (e.g., SD video) will be rescaled to peak at the switching MOS of the next best service (e.g., HD) in the preference of the user (s_k)—see (4). With this process, the QoE for service s_k will strictly be higher in an acceptable QoS range, while outside this range users may reconsider their preference. SP_{S1} in particular forms the new MOS maximum for service $k + 1$ relative to k instead of locally measured maximum MOS_{max} of for example 4.5. As the considered QoS range (minimum, maximum) will not be altered, the new QoE curve will be less QoS-sensitive.

For the rescaling we propose to use

$$MOS_{k+1}(QoS) := w(MOS_k(QoS)) \quad (4)$$

where

$$\begin{aligned} (w(MOS_{k+1}(QoS)) = MOS_{max}) &= \\ &= (MOS_k(QoS) = MOS_{SP_{S1}}), \\ (w(MOS_{k+1}(QoS)) = MOS_{min}) &= \\ &= (MOS_{k+1}(QoS) = MOS_{min}). \end{aligned}$$

$MOS_{k+1}(QoS)$ and $MOS_k(QoS)$ are the QoE functions for service k and $k+1$ s.t. the QoS, $MOS_{\{SP_{S1}, max, min\}}$ is the switching, maximum and minimum MOS resp., and w is a weighting function for intersecting the curves at SP_{S1} .

B. Stage 2 (S2): User Utility

In this phase, the attention shifts from classical QoE data to the analysis of QoE ratings under price cognitions p , i.e., QoE^p . Data without price cognitions (as result of classical QoE trials such as [19]) cannot directly be compared with QoE values involving purchasing decisions. Thus, due to alterations induced by price cognitions (expectations, justification of purchases, etc.), the QoS-to-QoE shapes cannot be retained from Stage 1, but need to be inferred from an empirically tested case (w.l.o.g. we will assume it to be service k). Thereafter, we can approximate $k+1$'s curve as follows:

- 1) We transfer the SP_{S1} at Stage 1 to a Stage 2 representation SP_{S2} : The MOS-level on k 's tested QoE curve with price cognitions is retrieved for the QoS demands at SP_{S1} , e.g., 7.682 Mbit/s in Fig. 2.
- 2) In order to form QoE_{k+1}^p we rescale the known QoE_k^p curve between the minimum ($QoE = 1.0$) and maximum point ($QoS(SP_{S2}), QoE(SP_{S2})$). The service-specific minimum point is inferred from $S1$ for $k+1$ and shifted minorly according to the relative movement of k 's minimum point from $S1$ to $S2$. The entire rescaling process is described by a weighting function $w()$.

In analogy to Stage 1, the curves can be concatenated and normalized in $[0, 1]$ to form $QoE_{k \cup k+1}^p$, i.e., the user utility aggregating price and quality considerations.

C. Stage 3 (S3): ISP Utility

Empirically tested WTP and demand (customer segments) curves for network quality—distinctly different to QoS-to-QoE relations—will characterize the ISP's utility curves. In order to match untested services, the tested WTP curves will be shifted by a factor derived from Stage 2, i.e., the **Average Service Preference Weighting** (ASPW) (the average degree of preferring the primary service k over a given alternative $k+1$). The ASPW is the fraction of point P_{min} 's euclidean distance \mathcal{E} to SP_{S2} and P_{max} , where point P_{max} is where $QoE_{k \cup k+1}^p = MOS_{max}$ and point P_{min} is where $QoE_{k \cup k+1}^p = MOS_{min}$. Thus when shifting the SP_{S2} to a point with higher bandwidth demands, the service k becomes more sensitive, which would increase the value of the service $k+1$. The MOS value at SP_{S2} reflects the satisfaction with the current pricing, i.e., the higher the value, the smaller the quality sensitivity of the demand.

The WTP as representative user revenue is characterized by demand and price curves. As the user is indifferent between the quality of services k and $k+1$ at SP_{S2} , we can infer that the WTP will be identical at this point. In addition, at the maximum of the considered bitrate range bw_{max} (e.g., where $QoE_{bw_{max}}^p = MOS_{max}$) the difference will be determined by the multiplier $ASPW$. Due to the non-trivial estimation of the demand curves for the $k+1$ service, we will adjust tariffs to match the known WTP points for service $k+1$.

When normalising the prospective user revenue in $[0, 1]$, the **ISP utility** results in a comparable form to the user utility.

D. Stage 4 (S4): Individualization (Optional)

Contrary to representative users, the ASPW parameter may not entirely characterize the preference of each specific user. One user may for example want "premium" video qualities and may have a low WTP for audio qualities. Such user-specific preference combinations may optionally be generated on the basis of customer segments distributions (see Sec. II), i.e., using distributions as customer segment probability for each service and user. The details of Stage 4 go beyond the scope of the present work.

V. CASE STUDY: VIDEO ON DEMAND

In this section, we will apply our approximation technique to a case study on VoD services. In particular, we will model the controlled degradation from HD (primary service k), backed by empirical QoE and WTP data, to SD video ($k+1$) streams.

A. Stage 1: Subjective QoE data without price

For SD video QoE we use the Video Quality Metric (VQM) [20] (an efficient QoE estimator [21]) with the Common Intermediate Format (CIF⁵) content given in [3]. Through a reverse engineering of the highly QoE-sensitive "soccer" data from [3] we have obtained the following logarithmic curve (coefficient of determination R^2 above 0.99⁶):

$$MOS_{SD}(bw) := 4.355147 + 0.6965466 \cdot \log(bw) \quad (5)$$

When transferring the empiric QoE data from [19] (challenging "CrowdRun" sequence, 1080p50) to an ACR-5 scale, we can create a logarithmic MOS fit for HD⁷ h264 videos with an R^2 of almost 0.99:

$$MOS_{HD}(bw) := -1.623658 + 1.532008 \cdot \log(bw) \quad (6)$$

where bw represents the bitrate in Mbit/s. While both Stage 1 and 2 data can be retrieved from [8], [15], we will rely on the more extensive results from [19] for the QoE-only case.

Due to the significant experience difference between HD and CIF content, we will construct an SP at $MOS = 1.5$ (between "bad" and "poor" experience). Applying the above introduced method, we can rescale MOS_{SD} as follows:

$$MOS_{SD}(bw)' := z \cdot (v + 4.355147 + w \cdot 0.6965466 \cdot \log(bw)) \quad (7)$$

where the parameters v (offset), w (steepness) and z (maximum rescaling) are instantiations of the $w()$ function for logarithmic curves. We obtain $v = -0.716$ and $w = 0.606$

⁵CIF resolution is only 352×288 pixels.

⁶Almost 99% of the variance is explained by the model.

⁷HD resolution is 1920×1080 pixels.

around the $SP(bw, MOS_{SD}, MOS_{HD}) = (7.68, 4.5, 1.5)$. The parameter $z = \frac{1.5}{4.5} = \frac{1}{3}$ where 4.5 is SD's original maximum and 1.5 is the new maximum⁸. The resulting concatenated QoE curve is depicted in Fig. 2 where at any available bandwidth the highest MOS is preferred by the user (whether it is SD or HD content).

B. Stage 2: User Utility

In this phase, we will use the QoE results from [8], [15] as fitted to a logarithmic shape from an aggregate p_{max} around €3 (due to sample size reasons):

$$MOS_{HD}^p(bw) := 3.0143 + 0.3163 \cdot \log(bw) \quad , \quad (8)$$

where bw is the video bitrate in Mbit/s and p the price cognitions. While the sketched shape will characterize both the HD and SD curves, the SD curve is rescaled to its minimum ($bw = 0.008 \text{ Mbit/s}$; $MOS = 1.0$), relative to HD's point, and maximum at the SP_{S2} (7.68 Mbit/s as in Stage 1; $MOS_{HD}^p(SP_{S2}) = 3.65927$). Thus, we obtain QoE curve under price cognitions in the form

$$MOS_{SD}^p(bw) := z \cdot (v + 3.0143 + w \cdot 0.3163 \cdot \log(bw)) \quad , \quad (9)$$

where $v = 0.999$, $w = 0.753$ and $z = 0.813$ (calculated as in Stage 1). When normalizing the concatenated curve $MOS_{SD \cup HD}^p(bw)$ (best MOS for each bandwidth setting) to $[0, 1]$ with the considered minimum 0 at $MOS^p = 1.0$ and the considered maximum 1 at $MOS^p = 4.5$, we obtain the per service **user utility** \mathcal{U}^u ,

$$\mathcal{U}_{SD \cup HD}^u(bw) := \frac{MOS_{SD \cup HD}^p(bw) - 1.5}{3.0} \quad . \quad (10)$$

C. Stage 3: ISP Utility

We derive the SD curve's analogue for HD streams by shifting the demand (d_{HD} , see $B(x)$) and customer segments curves (see $N(\mu, \sigma)$) using the multiplier ASPW. Based on the \mathcal{E} between SP_{S2} and $P_{max}(bw = 22.557 \text{ Mbit/s}, MOS = 4.5)$ resp., and $P_{min}(0.484 \text{ Mbit/s}, 1.0)$, we retrieve $ASPW = 0.345$. Satisfying the identical WTP condition for SD and HD services at SP_{S2} and the entire ASPW multiplier at P_{max} , we can derive the corresponding SD price p_{SD} around the given p_{HD} in order to keep $d_{SD} = d_{HD}$:

$$p_{SD}(bw) := 0.576541 + 0.0153333 \cdot bw \quad , \quad (11)$$

$$p_{HD}(bw) := 0.0919118 \cdot (-0.128 + bw) \quad . \quad (12)$$

Together with the demand figures from Sec. II we can estimate the **ISP revenue** \mathcal{U}_I both when users can choose from a single (Fig. 3(a)) or multiple offers (Fig. 3(b)), formed with price curve B (linear price increase s.t. the chosen quality). Controlled degradations always improve \mathcal{U}_I whenever the QoS is below the critical point SP_{S3} (mirroring SP_{S2} to

revenue/utility curves). Counterintuitively, high revenue levels are obtained for very low qualities. This results from the high demand for quality levels Q_x with $x < 10$ (cf. Fig. 1), which are shaped by the linearly increasing prices. This effect becomes even more apparent for the SD content, where users cannot profit from high quality classes and are hence not willing to purchase those for the given price.

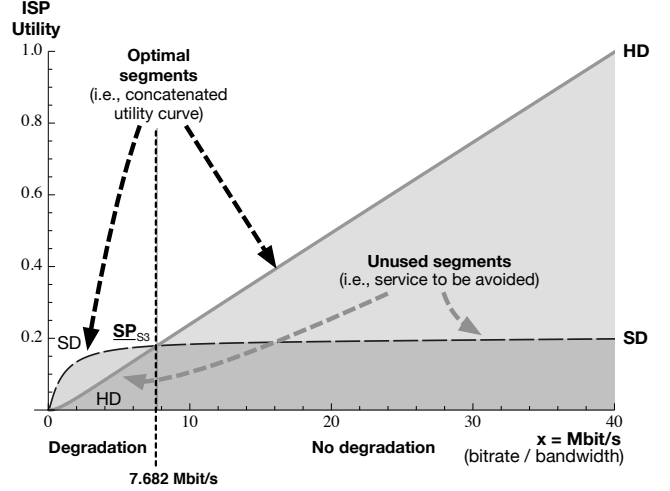


Fig. 4. ISP utilities \mathcal{U}_I (multi-choice) in $[0, 1]$ based on demand CDFs and new price curves.

The ISP utility can be formulated by normalizing the CDF of the demand times the $p_{SD/HD}(bw)$ curves in $[0, 1]$ (cf. Fig. 4). Any QoS decline will lower the ISP utility (cf. Fig. 4 based on multi-choice data). Below the inflection point SP_{S3} controlled degradation successfully improves the ISP utility.

In operations, the SP has to consider both the user \mathcal{U}^u (long term retention of customers) and the ISP utility \mathcal{U}^i (short term profits). Depending on the chosen objective, various flavours of social welfare optimizations may be applied:

$$c \cdot \mathcal{U}_{SD \cup HD}^u(bw) + d \cdot \mathcal{U}_{SD \cup HD}^i(bw) \quad (13)$$

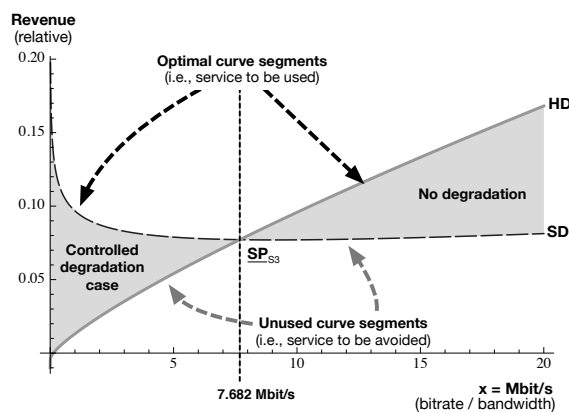
with $c + d = 1$ where the state $c = 1.0$ is user utility, $d = 1.0$ is profit, and $c = d = 0.5$ is classical social welfare optimization.

VI. CONCLUSIONS

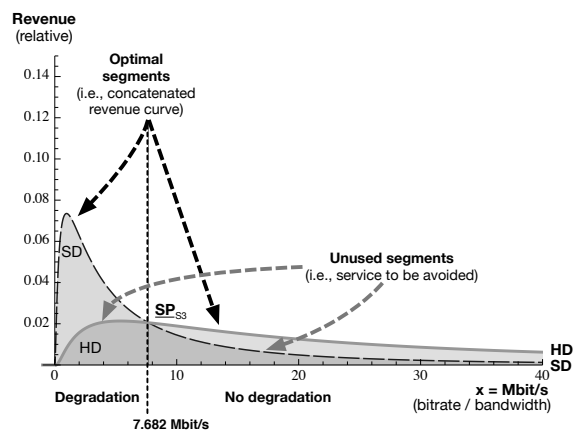
Today, insufficient data exists on the relative service valuation (utility) in the communication services domain, e.g., w.r.t. to comparing QoE figures across services or trials. Correspondingly, the derivation of user and ISP utilities around QoE figures has not yet emerged, but desperately required for efforts of creating and marketizing more user-oriented communication services.

On that account, we have presented a technique to approximate key QoE market figures, namely ISP and user utilities, as global inter-service valuation metrics. Outcomes can be used for controlled service degradations as experimentally illustrated in a case study considering HD and SD qualities for VoD services. The smart transfer to less demanding services has yielded promising ISP and user utility increase potentials.

⁸Practically irrelevant values above 1.5 due to functional input form.



(a) Single-choice (global)



(b) Multiple-choice (customer segments, local)

Fig. 3. ISP Revenue figures for tariff B.

Further empirical evidence is required for validating the model and its WTP input so as to avoid propagation errors. In addition, the parameterization of SPs (critical QoE points upon which actions are triggered) and the linkage to technology, e.g., to the access and resource assignment in [12] or flow path computation in [22], require attention in future work.

ACKNOWLEDGMENT

The research leading to these results has received funding from the FP7 PRECIOUS project. The authors would like to thank the members of the Dagstuhl seminar 15022 and the COST Qualinet project for supporting the scientific exchange among the authors.

REFERENCES

- [1] *Absolute Category Rating*, ITU-T P.800 (06/98), International Telecommunication Union (ITU), 1998.
- [2] C. Homburg, N. Koschate, and W. D. Hoyer, "Do satisfied customers really pay more? A study of the relationship between customer satisfaction and willingness to pay," *Journal of Marketing*, pp. 84–96, 2005.
- [3] B. Fu, D. Staehle, G. Kunzmann, E. Steinbach, and W. Kellerer, "QoE-aware Priority Marking and Traffic Management for H.264/SVC-based Mobile Video Delivery," in *8th ACM Workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks*. ACM, 2013, pp. 173–180.
- [4] J. Von Neumann and O. Morgenstern, *Theory of Games and Economic Behavior*. Princeton University Press, 1944.
- [5] M. Fiedler, T. Hossfeld, and P. Tran-Gia, "A generic quantitative relationship between quality of experience and quality of service," *IEEE Network*, vol. 24, no. 2, pp. 36–41, 2010.
- [6] P. Reichl, P. Maillé, P. Zwickl, and A. Sackl, "A Fixed-Point Model for QoE-based Charging," in *Proceedings of the ACM SIGCOMM Workshop on Future human-centric Multimedia Networking*. ACM Press, 2013, pp. 33–38.
- [7] M. Heidelberger, *Nature from within: Gustav Theodor Fechner and his psychophysical worldview*. University of Pittsburgh Press, 2004.
- [8] P. Zwickl, A. Sackl, and P. Reichl, "Market Entrance, User Interaction and Willingness-to-Pay: Exploring Fundamentals of QoE-based Charging for VoD Services," in *IEEE Globecom'13*, 2013.
- [9] A. Sackl, P. Zwickl, S. Egger, and P. Reichl, "The Role of Cognitive Dissonance for QoE Evaluation of Multimedia Services," in *Proceedings of the Globecom Workshops*. IEEE, 2012.
- [10] International Telecommunication Union (ITU), *ITU-T Rec. P9.10 Subjective video quality assessment methods for multimedia applications*.
- [11] L. Burgstahler, K. Dolzer, C. Hauser, J. Jähnert, S. Junghans, C. Macián, and W. Payer, "Beyond technology: The missing pieces for QoS success," in *Proceedings of the ACM SIGCOMM workshop on Revisiting IP QoS: What have we learned, why do we care?* ACM, 2003, pp. 121–130.
- [12] K. Ivešić, L. Skrin-Kapov, and M. Matijašević, "Cross-layer QoE-driven Admission Control and Resource Allocation for Adaptive Multimedia Services in LTE," *Journal of Network and Computer Applications*, 2014.
- [13] *ISO/IEC 23009-1:2012: Information Technology – Dynamic Adaptive Streaming over HTTP (DASH) – Part 1: Media Presentation Description and Segment Formats*, International Organization for Standardization (ISO), 2012.
- [14] FP5 Project M3I, IST-1999-11429, "Deliverable 15/2 – M3I user experiment results," 2002.
- [15] A. Sackl, P. Zwickl, and P. Reichl, "The Trouble with Choice: An Empirical Study to Investigate the Influence of Charging Strategies and Content Selection on QoE," in *Proceedings of the 8th International Workshop on Internet Charging and QoS Technologies (ICQT'13)*, 2013.
- [16] S. Cowan, "The Welfare Effects of Third-degree Price Discrimination with Non-linear Demand Functions," Oxford University – Department of Economics, Tech. Rep., 2007.
- [17] P. Reichl, S. Egger, R. Schatz, and A. D'Alconzo, "The Logarithmic Nature of QoE and the Role of the Weber-Fechner Law in QoE Assessment," in *Proceedings of the International Conference on Communications (ICC 2010)*. IEEE, 2010.
- [18] G. Gómez, J. Lorca, R. García, and Q. Pérez, "Towards a QoE-Driven Resource Control in LTE and LTE-A Networks," *Journal of Computer Networks and Communications*, vol. 2013, no. 2, pp. 1–15, 2013.
- [19] C. Keimel, A. Redl, and K. Diepold, "The TUM High Definition Video Datasets," in *Proceedings of the Fourth International Workshop on Quality of Multimedia Experience (QoMEX)*. IEEE, 2012, pp. 97–102.
- [20] M. Pinson and S. Wolf, "A new standardized method for objectively measuring video quality," *IEEE Transaction on Broadcasting*, vol. 50, no. 3, pp. 312–322, 2004.
- [21] Video Quality Experts Group, "Final report from the Video Quality Experts Group on the validation of objective models of video quality assessment, Phase II (FR_TV2)," 2003.
- [22] O. Dobrijevic, A. J. Kassler, L. Skrin-Kapov, and M. Matijasevic, "Q-POINT: QoE-Driven Path Optimization Model for Multimedia Services," in *Proceedings of the 12th International Conference on Wired & Wireless Internet Communications (WWIC'14)*, ser. LNCS. Springer, 2014.