

# 10 Years of Internet-QoE Measurements

## Video, Cloud, Conferencing, Web, and Apps

### What do we Need from the Network Side?

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**Abstract**—Quality of Experience (QoE) has become one of the guiding paradigms to enable a more user-centric understanding of the quality of data communication networks and services. In this extended abstract, I present an overview on the different work we have been conducting over the past decade on measuring (from the network perspective) and better understanding (from the user perspective) the QoE of the most relevant end-user services served through the Internet. Our work combines the multiple perspectives we believe are critical to tackle the problem of conceiving, dimensioning, and operating services and communication networks to offer the desired user experience for a plethora of services with very different performance requirements, covering general categories such as video streaming, remote cloud services, multimedia conferencing, web browsing, and mobile apps in general. In particular, our work has been focused on both subjective testing with real end-users, and (large-scale) network (and application) measurements.

The main question we have tried to answer is simple yet challenging: what do we need in terms of performance from the underlying network to offer a certain level of end user experience for a particular service? Do we need fast connections, low-latency access networks, responsive communication protocols, time-stable performance? The quick answer is that we need a bit of all of these properties for an end-to-end connection to realize seamless user experience. Naturally, the specific requirements depend on the type of service being offered – bandwidth-intensive applications such as YouTube require high speed connections, whereas interactive applications such as remote cloud office are additionally sensitive to network latency – but a more holistic, *network-session user experience* perspective requires nowadays to take all of them into account. Of particular interest is our study on the impact of network performance *fluctuations* on user experience – besides bandwidth and latency, stability turns out to be a highly relevant property of a network connection when it comes to QoE.

#### I. USER EXPERIENCE DIMENSIONS

Quality of Experience (QoE) represents the overall quality or performance of a provided service as perceived by the end-users; as such, it is a very appealing alternative to evaluate the quality of a provided service. Like Quality of Service (QoS), QoE may be incorporated in network mechanisms and specifically in network decision processes. “QoE-driven” or “QoE-aware” algorithms can help the network function in a more efficient and effective way. For example, QoE has been identified as a potential key driver in currently “softwarized” networks’ architecture, coupling the real-time monitoring of QoE for popular networking services and applications with the real-time, dynamic (re)-configuration of network resources. QoE-awareness may also drive a more

resource-efficient network operation, avoiding the traditional over-provisioning of network resources for those cases where additional QoS improvements would not be perceived by the end-user.

QoE awareness may be exploited in many other ways, for example, for anomaly detection and root cause analysis purposes, identifying network problems by insufficient QoE levels, leading to QoE-improvement actions. However, without the existence of proper QoE estimation and monitoring approaches, such QoE-based solutions are unfeasible, driving stakeholders to still rely on traditional QoS metrics.

QoE estimation and QoE monitoring require to properly understand which Key Quality Indicators (KQIs) are relevant from the end-user perspective, i.e., identify which perceivable performance parameters of the specific service or application influence the user experience, as well as modeling how these impact the QoE. For example, QoE in HTTP adaptive video streaming services - e.g., YouTube, is basically captured by initial playback times, re-buffering events, and video resolution.

QoE modeling is a complex and time-consuming task. In general terms, the experience of a user with any application is conditioned by multiple features, including dimensions such as technical characteristics of the application, user personality and expectations, user demographics, device usability, and usage context among others. Particularly when evaluating networking-based applications, the influence of the network itself as well as its interplay with the particular application have to be linked to the user’s experience, additionally identifying the corresponding KQIs. This mapping is realized by analyzing and correlating the three layers depicted in Figure 1: the network layer accounts for the influence of the network QoS parameters (e.g., network bandwidth, round-trip time, packet loss, etc.); the application layer considers both the technical characteristics (e.g., screen compression rate, screen resolution, color depth, video bit-rate) and the perceivable performance parameters or KQIs of the application (e.g., page-load times, response time, re-buffering events, etc.); finally, the user layer spans the user subjective opinions on the evaluated application (e.g., MOS values, acceptability, satisfaction, etc.), as well as his particular interactions with it (e.g., engagement, churn, conversion, etc.). Proper and comprehensive QoE modeling for networking-based applications requires measurement at all the three aforementioned layers.

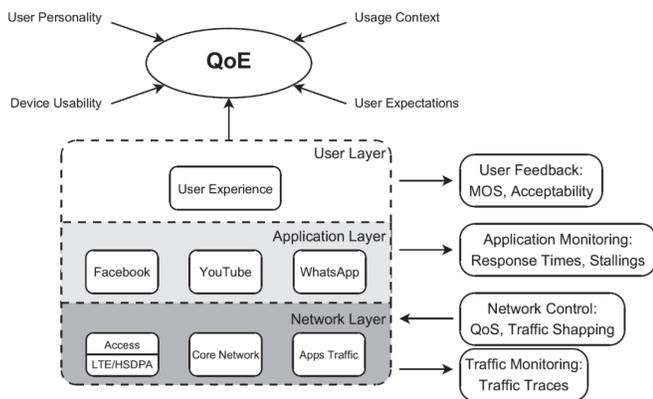


Fig. 1: Layered QoE evaluation methodology for networking services and applications.

In the next sections, I list the **most relevant papers where our work on Internet-QoE has been reported**. During the presentation at the *Measuring Network Quality for End-Users Workshop*, I would **elaborate on the main findings and lessons learned from these studies**. All our **Internet-QoE studies consider some variation of the layered QoE assessment methodology depicted in Figure 1**. Some of our studies are purely based on subjective lab testing, others rely on crowdsourcing QoE measurements and field trials, others rely on large-scale ISP measurements, and in all of them, measurement instrumentation (e.g., at the end devices) plays a central role, specially when considering challenging monitoring issues such as the wide adoption of end-to-end encryption, or measurement of general apps in mobile devices.

**Following the Internet-QoE research line listed below, I organized the Internet-QoE Workshop between 2016 and 2019, both at SIGCOMM and at MOBICOM.** The Workshop on QoE-based Analysis and Management of Data Communication Networks was born as a means to cover a growing need in the conception and applicability of user-centric, QoE-based solutions to the large scale analysis and management of modern operational networks. Internet-QoE served its main goal of bringing together researchers and practitioners from the Internet measurements and analysis domain and the QoE modeling and assessment domain, as well as industry players willing to integrate QoE aspects into their daily business, with direct applications in network dimensioning, monitoring, management, and troubleshooting among others.

## II. VIDEO STREAMING QOE

*ViCrypt to the Rescue: Real-time, Machine Learning-driven Video QoE Monitoring for Encrypted Streaming Traffic*, S. Wassermann, M. Seufert, P. Casas, G. Li, L. Kuang; IEEE Transactions on Network and Service Management, vol. 17, no. 4, pp. 2007-2023, 2020.

*Scoring High: Analysis and Prediction of Viewer Behavior and Engagement in the Context of 2018 FIFA WC Live Streaming*, N. Wehner, M. Seufert, S. Egger-Lampl, B. Gardlo, P. Casas, R.

Schatz; in 28th ACM International Conference on Multimedia (MM), Seattle, USA, 2020.

*Stream-based Machine Learning for Real-time QoE Analysis of Encrypted Video Streaming Traffic*, M. Seufert, P. Casas, N. Wehner, G. Li, L. Kuang; in 3rd International Workshop on Quality of Experience Management, Paris, France, 2019.

*Decrypting QoE in an Encrypted Internet – AI to the Rescue*, S. Wassermann, M. Seufert, P. Casas; in RIPE Academic Cooperation Initiative (RACI), RIPE 79, Rotterdam, Netherlands, 2019.

*I See What you See: Real Time Prediction of Video Quality from Encrypted Streaming Traffic*, S. Wassermann, M. Seufert, P. Casas, G. Li, L. Kuang; in 4th ACM MOBICOM Workshop on QoE-based Analysis and Management of Data Communication Networks (Internet-QoE), Los Cabos, Mexico, 2019.

*Studying the Impact of HAS QoE Factors on the Standardized QoE Model P.1203*, M. Seufert, N. Wehner, P. Casas; in 3rd Workshop on QoE-based Analysis and Management of Data Communication Networks (Internet QoE), Vienna, Austria, 2018.

*Modeling the YouTube Stack: from Packets to Quality of Experience*, F. Wamser, P. Casas, M. Seufert, C. Moldovan, P. Tran-Gia, T. Hossfeld; Computer Networks, ELSEVIER, vol. 109, part 2, pp. 211-224, 2016.

*YOUQMON: A System for On-line Monitoring of YouTube QoE in Operational 3G Networks*, P. Casas, M. Seufert, R. Schatz; ACM SIGMETRICS Performance Evaluation Review, vol. 41, no. 2, pp. 44-46, 2013.

## III. CLOUD QOE

*Quality of Experience in Cloud Services: Survey and Measurements*, P. Casas, R. Schatz; Computer Networks, ELSEVIER, vol. 68, pp. 149-165, 2014.

*A First Look at Quality of Experience in Personal Cloud Storage Services*, P. Casas, H. R. Fischer, S. Suetter, R. Schatz; in Proceedings of the IEEE ICC Workshop on Mobile Cloud Networking and Services, Budapest, Hungary, 2013.

*Quality of Experience in Remote Virtual Desktop Services*, P. Casas, M. Seufert, S. Egger, R. Schatz; in Proceedings of the IFIP/IEEE Workshop on QoE-Centric Management (QCMAN), Ghent, Belgium, 2013.

*Need for Speed? On QoE for File Storage Services*, P. Amrehn, K. Vandenbroucke, T. Hofeld, K. De Moor, M. Hirth, R. Schatz, P. Casas; in Proceedings of the 4th International Workshop on Perceptual Quality of Systems (PQS), Vienna, Austria, 2013.

## IV. MULTIMEDIA CONFERENCING QOE

*Characterizing Microsoft Lync Online in Mobile Networks: a Quality of Experience Perspective*, P. Casas, A. Sackl, S. Egger, R. Schatz; in Proceedings of the 3rd IEEE International Conference on Cloud Networking (CloudNet), Luxembourg, Luxembourg, 2014.

*Quality of Experience in Telepresence and Remote Collaboration Cloud Services*, P. Casas, D. Paraskevopoulou, G. Settanni, S. Suetter, P. Zwickl, R. Schatz; in Proceedings of the 4th International Workshop on Perceptual Quality of Systems (PQS), Vienna, Austria, 2013.

## V. WEB QOE

*Are you on Mobile or Desktop? On the Impact of End-User Device on Web QoE Inference from Encrypted Traffic*, S. Wassermann, P. Casas, Z. Ben Houidi, A. Huet, M. Seufert, N. Wehner, J. Schuler, S. Cai, H. Shi, J. Xu, T. Hofeld, D. Rossi; in 16th IEEE International Conference on Network and Service Management (CNSM), Izmir, Turkey, 2020.

*Mind the (QoE) Gap: On the Incompatibility of Web and Video QoE Models in the Wild*, M. Seufert, N. Wehner, V. Wieser, P. Casas, G. Capdehourat; in 16th IEEE International Conference on Network and Service Management (CNSM), Izmir, Turkey, 2020.

*Improving Web QoE Monitoring for Encrypted Network Traffic through Time Series Modeling*, N. Wehner, M. Seufert, J. Schler, S. Wassermann, P. Casas, T. Hofeld; in IFIP Performance 2020 Workshops, Workshop on AI in Networks (WAIN), Milano, Italy, 2020.

## VI. APPS QOE

*How are your Apps Doing? QoE Inference and Analysis in Mobile Devices*, N. Wehner, M. Seufert, J. Schler, P. Casas, T. Hofeld; in 17th IEEE International Conference on Network and Service Management (CNSM), Izmir, Turkey, 2021.

*Next to You: Monitoring Quality of Experience in Cellular Networks from the End-devices*, P. Casas, M. Seufert, F. Wamser, B. Gardlo, A. Sackl, R. Schatz; IEEE Transactions on Network and Service Management, vol. 13, no. 2, pp. 181-196, 2016.

*On the Analysis of YouTube QoE in Cellular Networks through in-Smartphone Measurements*, S. Wassermann, P. Casas, M. Seufert, F. Wamser; in 12th IFIP Wireless and Mobile Networking Conference (WMNC), Paris, France, 2019.

*Machine Learning Models for YouTube QoE and User Engagement Prediction in Smartphones*, S. Wassermann, N. Wehner, P. Casas; ACM SIGMETRICS Performance Evaluation Review, vol. 46, no. 3, pp. 155-158, 2018.

*YouTube QoE Monitoring with YoMoApp: A Web-based Data Interface for Researchers*, F. Wamser, N. Wehner, M. Seufert, P. Casas, P. Tran-Gia; in 2nd Network Traffic Measurement and Analysis Conference (TMA Conference), Vienna, Austria, 2018

*Exploring QoE in Cellular Networks: How Much Bandwidth do you Need for Popular Smartphone Apps?*, P. Casas, R. Schatz, F. Wamser, M. Seufert, R. Irmer; in Proceedings of the 5th ACM SIGCOMM Workshop on All Things Cellular: Operations, Applications and Challenges (ATC), London, UK, 2015.

*QoMOSN On the Analysis of Traffic and Quality of Experience in Mobile Online Social Networks*, P. Casas, P. Fiadino, M. Schiavone; in Proceedings of the European Conference on Networks and Communications (EuCNC), Paris, France, 2015.

## VII. SEAMLESS QOE AND STABLE NETWORK CONNECTIONS

*On the Quest for New KPIs in Mobile Networks: The Impact of Throughput Fluctuations on QoE*, P. Casas, A. Sackl, R. Schatz, L. Janowski, J. Turk, R. Irmer; in Proceedings of the IEEE ICC Workshop on Quality of Experience-based Management for Future Internet Applications and Services, London, UK, 2015.

*Quantifying the Impact of Network Bandwidth Fluctuations and Outages on Web QoE*, A. Sackl, P. Casas, R. Schatz, L. Janowski, R. Irmer; in Proceedings of the 7th International Workshop on Quality of Multimedia Experience (QoMEX), Messinia, Greece, 2015.

## VIII. CROWDSOURCED QOE MEASUREMENTS

*White Paper on Crowdsourced Network and QoE Measurements Definitions, Use Cases and Challenges*, A. Beyer, A. Hall, A. Schwind, C. Gassner, F. Guillemin, F. Wamser, K. Wascinski, M. Hirth, M. Seufert, P. Casas, P. Tran-Gia, S. Wunderer, T. Hofeld, W. Robitza, W. Wascinski, Z. Ben Houidi; Tobias Hofeld and Stefan Wunderer, eds., Wrzburg, Germany, 2020.

*Quality that Matters: QoE Monitoring in Education Service Provider (ESP) Networks*, N. Wehner, M. Seufert, V. Wieser, P. Casas, G. Capdehourat; in IFIP/IEEE International Symposium on Integrated Network Management (IM), Bordeaux, France, 2021.

## IX. QOE-DRIVEN NETWORK MANAGEMENT

*A Fair Share for All: TCP-inspired Adaptation Logic for QoE Fairness among Heterogeneous HTTP Adaptive Video Streaming Clients*, N. Wehner, M. Seufert, P. Casas; IEEE Transactions on Network and Service Management, vol. 16, no. 2, pp. 475-488, 2019.

*Considering User Behavior in the Quality of Experience Cycle: Towards Proactive QoE-Aware Traffic Management*, M. Seufert, S. Wassermann, P. Casas; IEEE Communications Letters, vol. 23, no. 7, pp. 1145-1148, 2019.

*Is QUIC becoming the New TCP? On the Potential Impact of a New Protocol on Networked Multimedia QoE*, M. Seufert, R. Schatz, N. Wehner, B. Gardlo, P. Casas; in 11th International Conference on Quality of Multimedia Experience, Berlin, Germany, 2019.

*QUICKer or not? an Empirical Analysis of QUIC vs TCP for Video Streaming QoE Provisioning*, M. Seufert, R. Schatz, N. Wehner, P. Casas; in 3rd International Workshop on Quality of Experience Management, Paris, France, 2019.

*An Educated Guess on QoE in Operational Networks through Large-Scale Measurements*, P. Casas, B. Gardlo, R. Schatz, M. Mellia; in Proceedings of the ACM SIGCOMM Workshop on QoE-based Analysis and Management of Data Communication Networks (Internet-QoE), Florianopolis, Brazil, 2016.

*Taming QoE in Cellular Networks: from Subjective Lab Studies to Measurements in the Field*, P. Casas, B. Gardlo, M. Seufert, F. Wamser, R. Schatz; in Proceedings of the 11th International Conference on Network and Service Management (CNSM), Barcelona, Spain, 2015.

*On the Analysis of QoE in Cellular Networks: from Subjective Tests to Large-scale Traffic Measurements*, P. Casas, M. Varela, P. Fiadino, M. Schiavone, H. Rivas, R. Schatz; in Proceedings of the 6th International Workshop on Traffic Analysis and Characterization (TRAC), Dubrovnik, Croatia, 2015.

*Passive YouTube QoE Monitoring for ISPs*, R. Schatz, T. Hofeld, P. Casas; in Proceedings of the 2nd International Workshop on Future Internet and Next Generation Networks, Palermo, Italy, 2012.