# Quality of Experience in Telecommunications: theory, fundamentals, application guidelines

Tutorial at EUCNC'25 & 6G Summit, 3 June 2025
by Pablo Perez and Tobias Hoßfeld

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EUCNC | 6G Summit
Poznan, Poland ▪ 3-6 June 2025

# Structure of the Tutorial

## Part 1: QoE Fundamentals

- QoE in 5G and 6G networks: landscape and challenges, 6G use cases
- What is QoE. Definitions and factors
- From QoS to QoE. Parametric and bitstream-based QoE models

## Part 2: QoE in Systems

- Concept: QoE in systems
- QoE metrics and their relation to MOS
- Fundamental relations and mathematical models
- QoE Fairness: Notion and definition

## Break: 15-30min

## Part 3: QoE in Practice: From Research to Operation

- Towards QoE management for CAPs and CSPs
- Guidelines to handle QoE in telecommunication networks: from research to operation

## Part 4: Current Activities and Efforts

- Joint Efforts: VQEG 5G-KPI Whitepaper
- Open Discussions

# Presenters

## Pablo Perez

- Lead Scientist at eXtended Reality Lab, Nokia, Madrid Spain
- Nokia delegate at ITU-T SG12 (QoS, QoE and Performance), chair of VQEG 5GKPI working group
- General chair QoMEX 2025
- 20+ year experience in video communications: from product R&D of IPTV/streaming solutions to research on XR technology and systems
- Nokia inventor award (2019), Bell Labs DMTS (2022), Ericsson PhD award (2014)
- Further information https://www.linkedin.com/in/pablop/

## Tobias Hoßfeld

- Professor at the Chair of Communication Networks, University of Würzburg, Germany
- Editorial board member: IEEE Communications Surveys & Tutorials, ACM SIGMM Records (QoE Columns), Springer Quality and User Experience
- TPC Co-Chair: IEEE ICC GreenNet workshop series, QoMEX 2019, QoMex 2024
- Fred W. Ellersick Prize 2013 (IEEE Comm. Soc.) for QoS-QoE model (IQX), VDE ITG 2024 Award for scalability metric & framework
- Further information https://comnets.org/hossfeld

# Supporting Projects

- Advanced 5G Open Platform for Large Scale Trials and Pilots across Europe (IMAGINE-B5G), Horizon Europe (GA 101096452).
  - https://imagineb5g.eu/

- Sustainable Technologies for Advanced Resilient and Energy-Efficient Networks (SUSTAINET), CELTIC-NEXT Next project.
  - https://www.celticnext.eu/project-sustainet/

# Abstract

*On the road to 6G, there is an opportunity to evolve existing 5G QoS model and make the network able to manage the users Quality of Experience (QoE). This tutorial consists of three parts. First, this tutorial will present the core concepts and principles required to implement QoE management in communication networks, from fundamentals to the state-of-the-art research and recent standardization initiatives on the topic. In particular, we will address the current landscape but also open challenges regarding QoE in 5G and 6G. The QoE influence factors are discussed, with a focus on 6G use cases like immersive media (6-DOF streaming, point clouds, etc.). The fundamentals of QoE include a proper definition of (a variety of) QoE metrics like MOS or Poor-or-Worse ratios, as well as their relationships. Some concrete QoE models are discussed to illustrate how to get from QoS to QoE.*

*The second part discusses then QoE in a 6G environment. We will introduce the concept of "system QoE", as a means to evaluate the QoE across a set of users in a system. To this end, the fundamental relationships and mathematical models for system QoE are presented. This also includes the concept of QoE fairness and appropriate models. Thus, the first two parts will cover in-depth the theoretical knowledge required to successfully manage QoE in a telecommunication framework: an actionable definition of QoE, statistical models of subjective ratings and their relations and principles of QoE management.*

*Finally, the third part will present the state of the art of QoE management approaches, providing practical solutions for most relevant use cases. To this end, this tutorial will leverage the current joint effort being done by the Video Quality Experts Group to write a white paper on QoE management for future communication networks. Open discussions on those topics and getting involved in the VQEG 5G-KPI Whitepaper will conclude the tutorial.*

# Upon attending this tutorial, you will learn about

- Quality of Experience (QoE) Fundamentals: QoE influence factors, QoE metrics, mathematical models for QoE across users, QoE fairness, benchmarking of systems
- State-of-the-art QoE management approaches, control loops between stakeholders (CSPs, CAPs, users), insights from VQEG 5G-KPI, current standards, industry efforts
- QoE for interactive immersive media, end-to-end QoE management in future 6G, advanced QoE related 6G use cases

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Use proper citation when using content from this tutorial
(Thanks to Christian Timmerer, Marta Orduna, Kamil Koniuch, Francois Blouin, Lea Skorin-Kapov, Martin Varela, Poul Heegaard, VQEG 5G-KPI group.... and many others for helping with the material)

# Open Issues and Research Questions

*We provide pointers and hints …*

- Unresolved Challenges in QoE & 6G
  - Identification of key gaps in current research,
  - including QoE modeling, system QoE, and real-world deployment hurdles
- Future Research Directions & Open Questions
  - Exploration of emerging topics
  - Interactions and control loops
  - next-generation interactive immersive media experiences

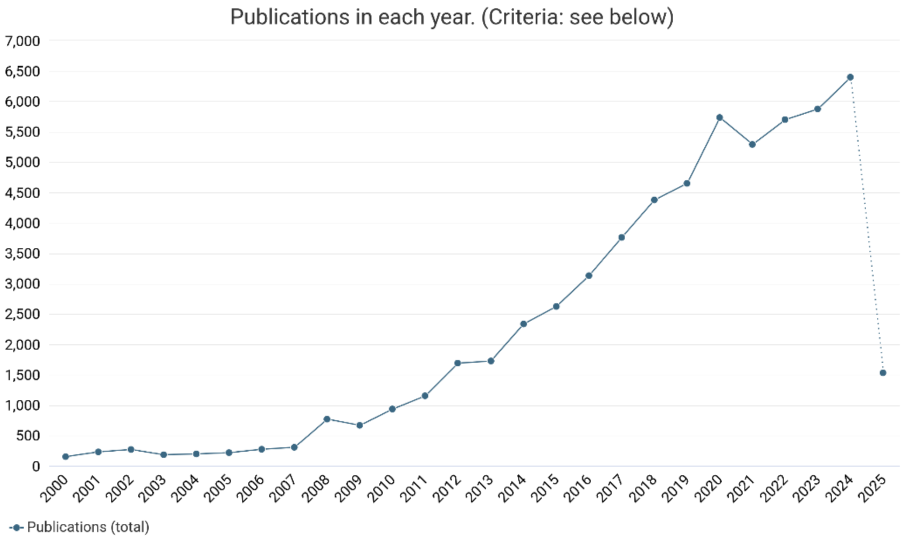
*… pointers are highlighted using this icon* 

# Part 1: QoE Fundamentals

QoE in 5G and 6G networks: landscape and challenges, use cases.
QoE definition, influence factors, metrics. Parametric and bitstream-based QoE models.

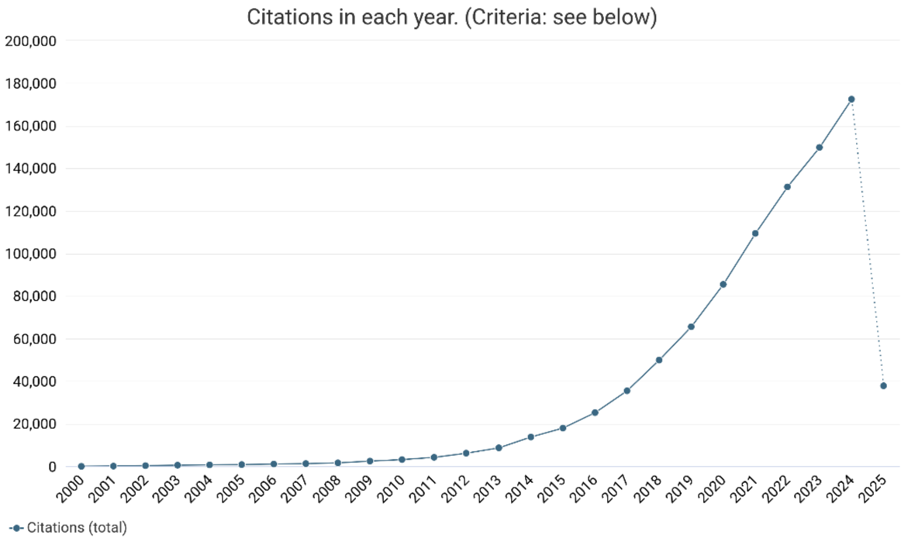
# Interest in QoE over the Last 25 Years

- Number of publications per year when searching for „QoE“ (using app.dimensions.ai)




Source: https://app.dimensions.ai
Exported: April 22, 2025
Criteria: 'QoE' in full data; Publication Year is 2000 or 2001 or 2002 or 2003 or 2004 or 2005 or 2006 or 2007 or 2008 or 2009 or 2010 or 2011 or 2012 or 2013 or 2014 or 2015 or 2016 or 2017 or 2018 or 2019 or 2020 or 2021 or 2022 or 2023 or 2024 or 2025.



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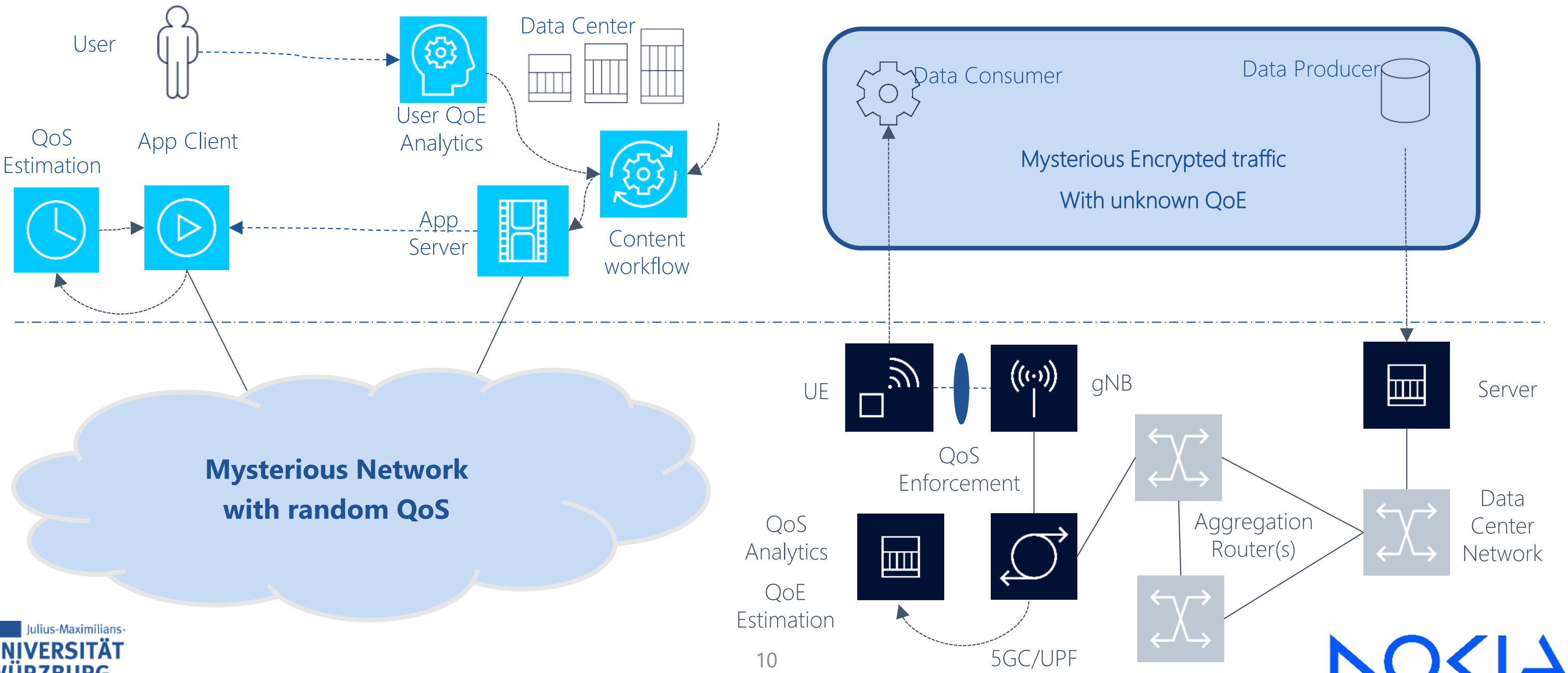
# User Experience vs. Network Quality

- Content & Application Providers (CAP) vs. Communication Service Providers (CSP)

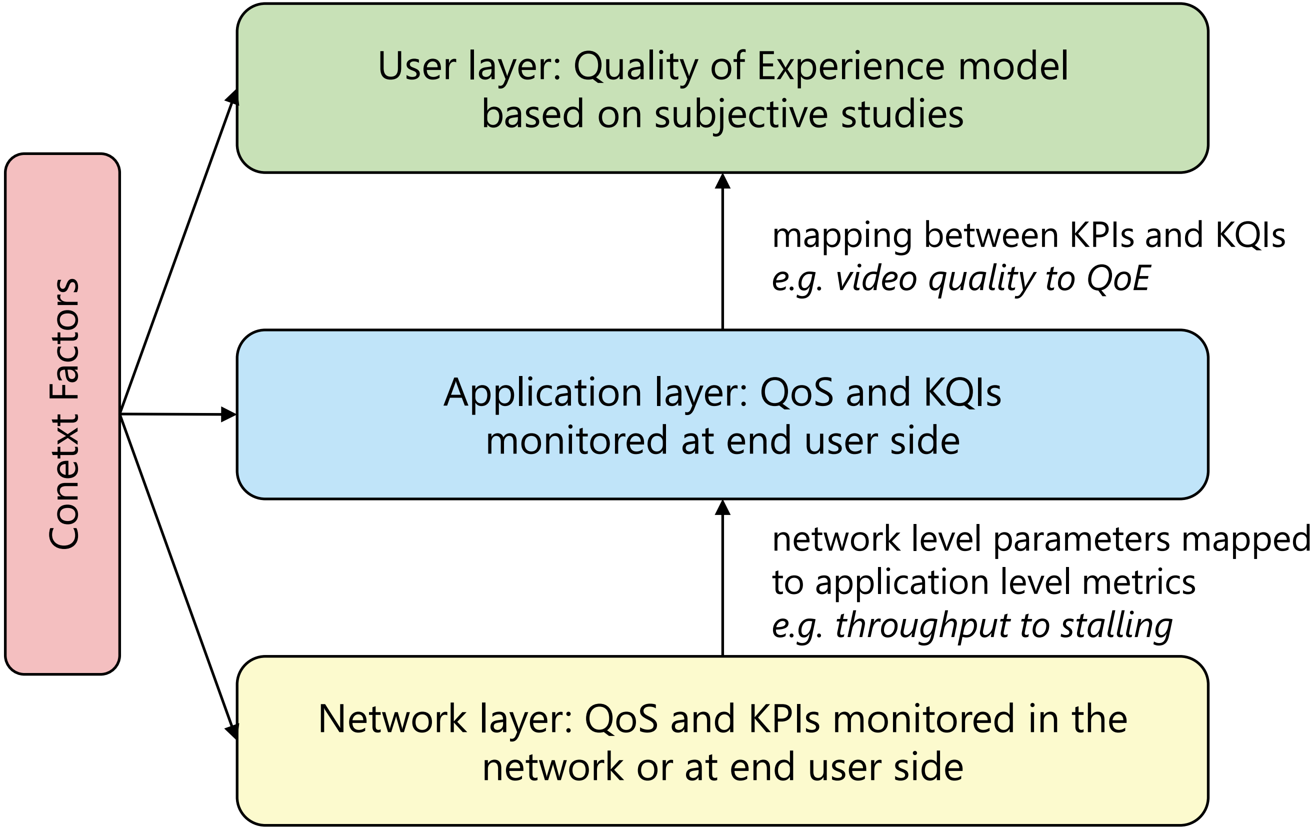


# Performance Measures

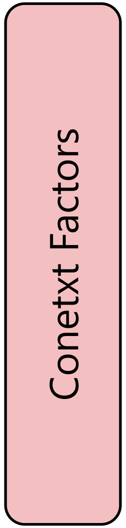
Is 5% packet loss okay?

- Network level: **Key Performance Indicators (KPIs)**
  - Measuring Quality of Service (QoS) parameters on network level
  - E.g. bandwidth, throughput, delays, delay variation (jitter), packet reordering, packet loss
- Application level: **Key Quality Indicators (KQIs)**
  - Measuring QoS parameters on application level (application-level QoS)
  - **Application specific**: e.g. for video streaming: stalling duration, lost video frames, initial delays, quality switches
  - Generic parameters: service availability, reliability, usability
  - Combination of network-level and application-level QoS into KQI
- **Quality of Experience (QoE)**
  - User perceived quality when using a service
  - QoE model aims to quantify "degree of delight or annoyance of the user of an application or service"

# From QoS to QoE



# Context Factors




# KQI Example: Consistent Quality

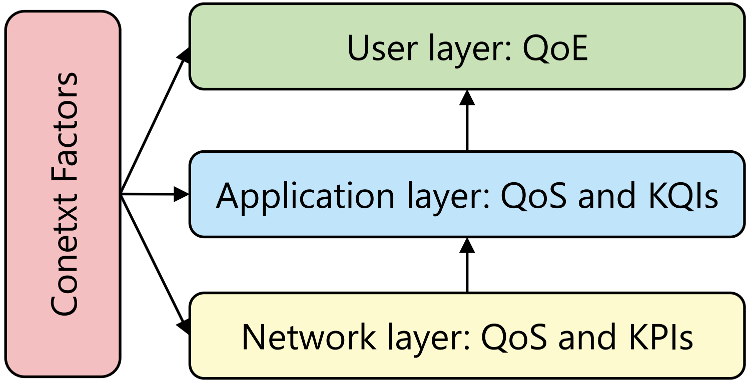
- KPIs have different meaning and thresholds for acceptable quality
  - depends on the concrete application
  - several KPIs may be considered
- **Key quality indicator (KQI)**
  - application-layer QoS parameters relevant for user, e.g. stalling, time-to-first-byte
  - KQI model based on KPIs

- Example: consistent quality by industrial stakeholders, e.g. OpenSignal (Tutela)
  - ratio of connections where thresholds for all QoS parameters are met

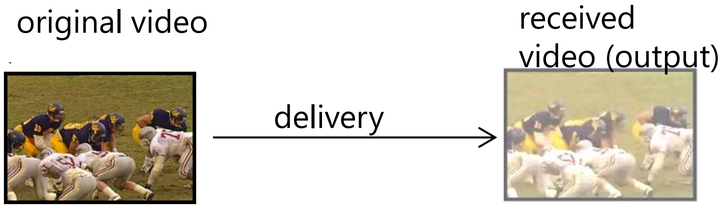
| **QoS** | Average download speed | Average upload speed | Latency | Jitter | Packet loss | Time to first byte |
|---|---|---|---|---|---|---|
| **Minimum acceptable value** | 5 Mbps | 1.5 Mbps | 50 ms | 30 ms | 1% | 3.2 s |

# From QoS to QoE

- Example: video user
  - interested in video quality, smooth playout (KQI)
  - influenced by QoS: packet loss, delay, jitter, …
  - QoE: degree of delight of users of a service




- Measurement of QoE
  - subjective test: ask user and let them evaluate output (= delivered content)
  - derive a model
    - compare input and output (full reference)
    - use output and some additional information (reduced reference)
    - use output only (no reference)



# QoE Definition

**Quality of Experience (QoE) is the degree of delight or annoyance of the user of an application or service.**

- It results from the fulfillment of expectations with respect to
  - the utility and / or
  - enjoyment of the application or service
  - in the light of the user's personality and current state.
- QoE focuses on the entire service experience
- Holistic concept, with its roots in telecommunication

P. Le Callet, S. Möller, A. Perkis, et al. QUALINET White Paper on Definitions of Quality of Experience. European Network on Quality of Experience in Multimedia Systems and Services (COST Action IC 1003). 2012, http://www.qualinet.eu/

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# QoE Features and Influence Factors

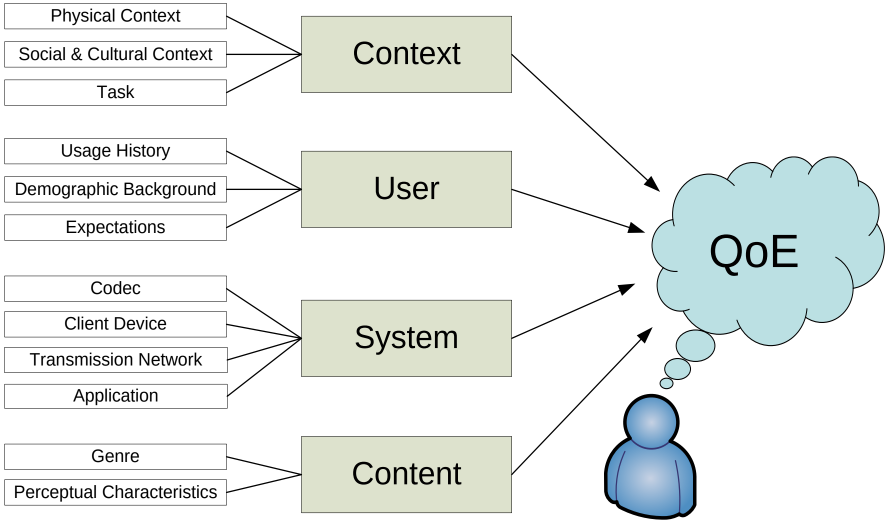
- **Experience:** An experience is an individual's stream of perception and interpretation of one or multiple events.
- **QoE feature:** A perceivable, recognized and namable characteristic of the individual's experience of a service which contributes to its quality.
- **Influence Factor:** Any characteristic of a user, system, service, application, or context whose actual state or setting may have influence on the Quality of Experience for the user.

*In the context of communication services, QoE can be influenced by factors such as service, content, network, device, application, and context of use.*

- QoE Definition is part of ITU recommendation.

# Quality of Experience (QoE) … Influence Factors

**"Degree of delight or annoyance of the user of an application or service as**
**perceived subjectively …**
**… includes the complete end-to-end system effects …**
**… may be influenced by user state, content and context."**

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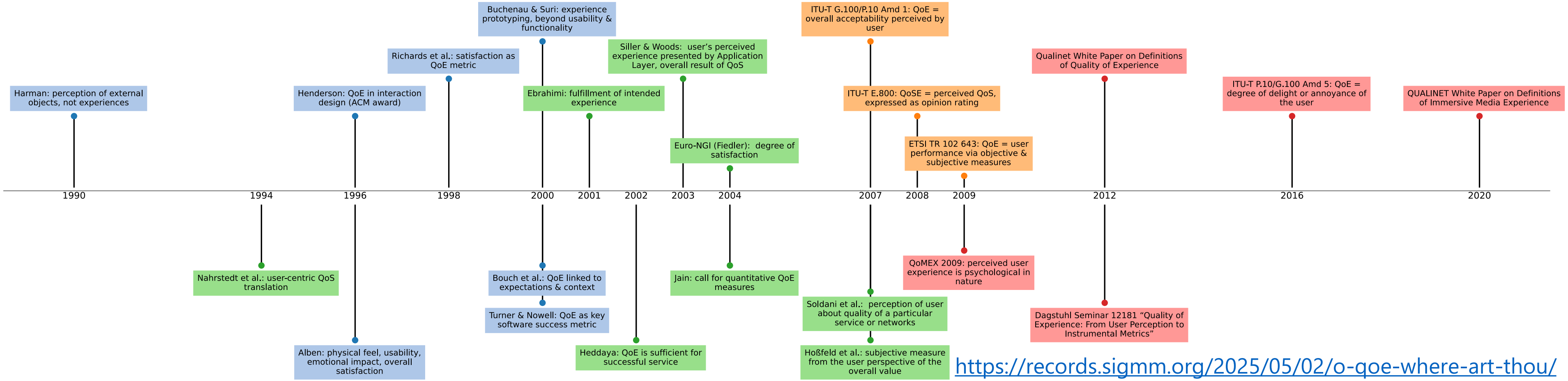
# Evolution of Notion of QoE

- 1990s: Early focus on perception and interaction design.
- Early 2000s: Growing focus on subjectivity, expectation, emotion, context.
- Mid-2000s: Need for metrics and quantification: QoE = f(QoS)
- Late 2000s–2010s: QoE defined around subjective perception and system-wide impact
- 2010s: Unified, multidisciplinary understanding, initiatives like QUALINET or QoMEX



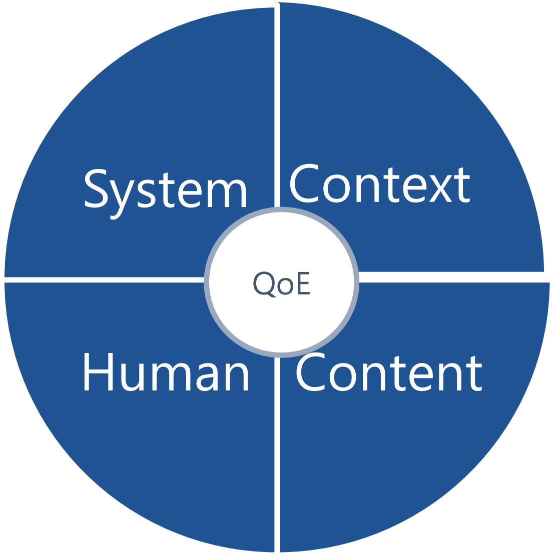

https://records.sigmm.org/2025/05/02/o-qoe-where-art-thou/

# Definition of QoE: Accepted and Standardized

**Quality of Experience (QoE):** the degree of delight or annoyance of the user with an application or service - Qualinet whitepaper, adopted by ITU-T P.10/G.100

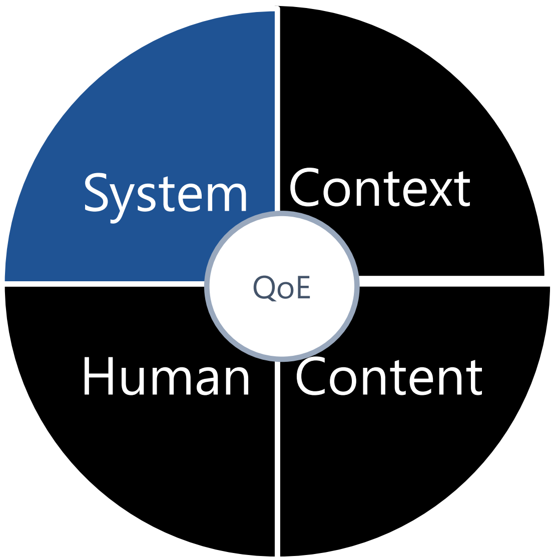
The **Influencing Factors** (IFs) of QoE can be divided into three categories:

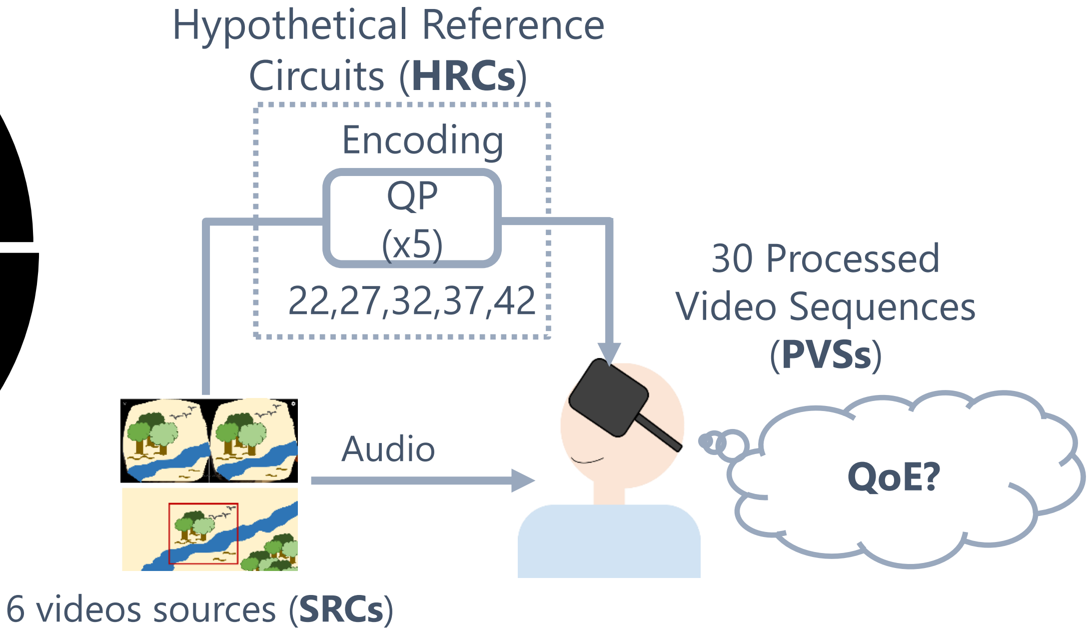
- **System** (media capture, coding, transmission, storage, rendering, and reproduction/display…)
- **Context** (user's environment in terms of physical, temporal, social, economic…)
- **Human** (user/human role in terms of experience, expectations, gender, age…)



# Practical Example

- Encoding (QP)
- Device (HMD)



# User-reported QoE

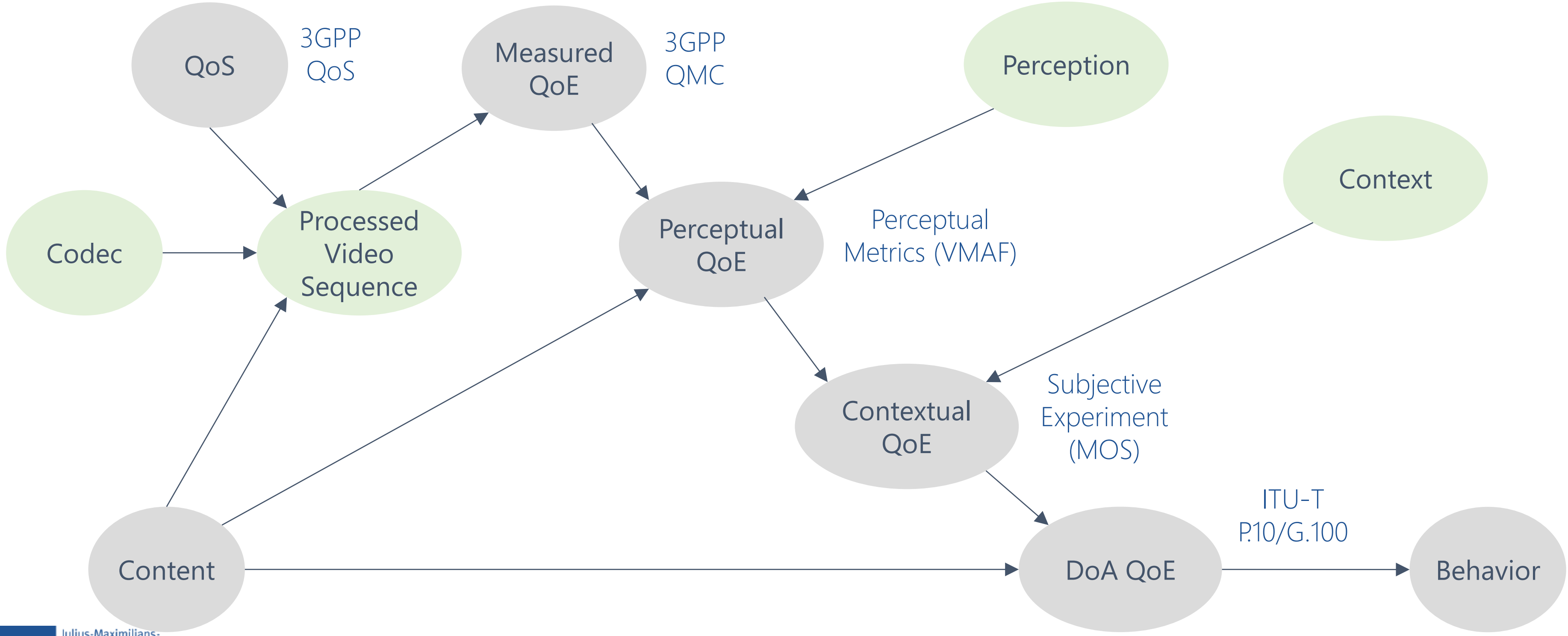
We define **user-reported QoE** as the quantification of the impact of a system on user delight or annoyance, through self-report, behavioral, or psychophysiological studies.

This impact can be caused by the application, network, or hardware and is moderated by the usage context.

*VQEG White Paper on QoE Management in Communication Networks (in progress – see later in the tutorial)*

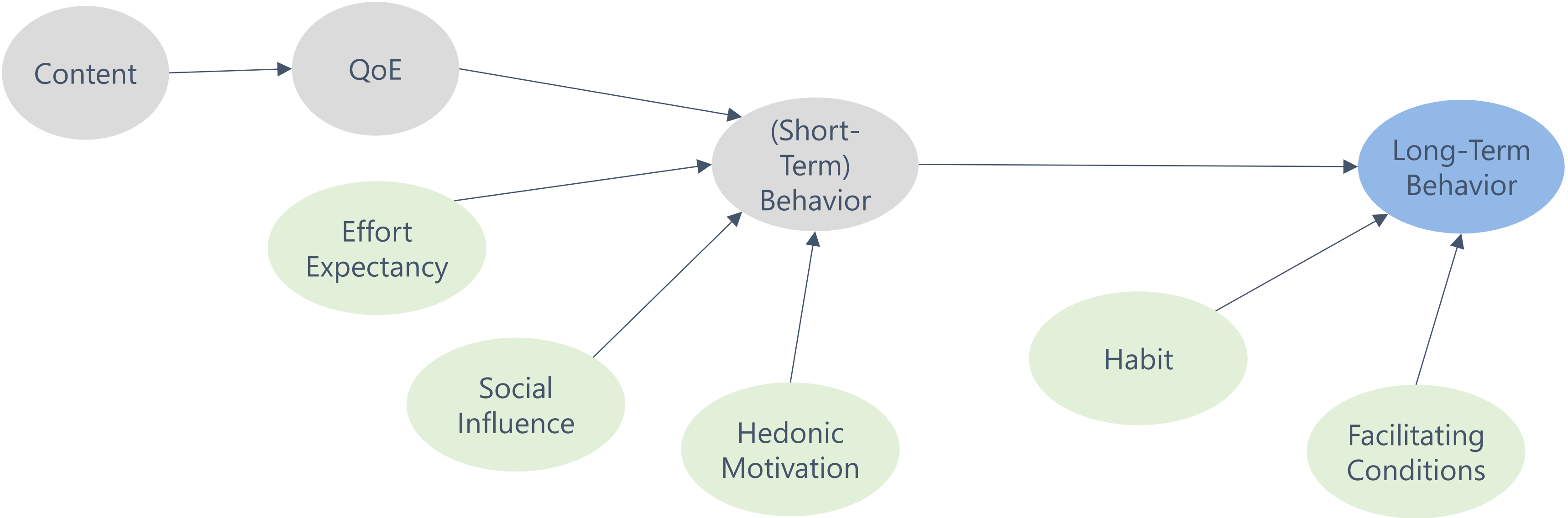
# Different QoE Definitions

- QoE at different abstraction levels: main influencing factors



# ...and this is only a (small) part of the story

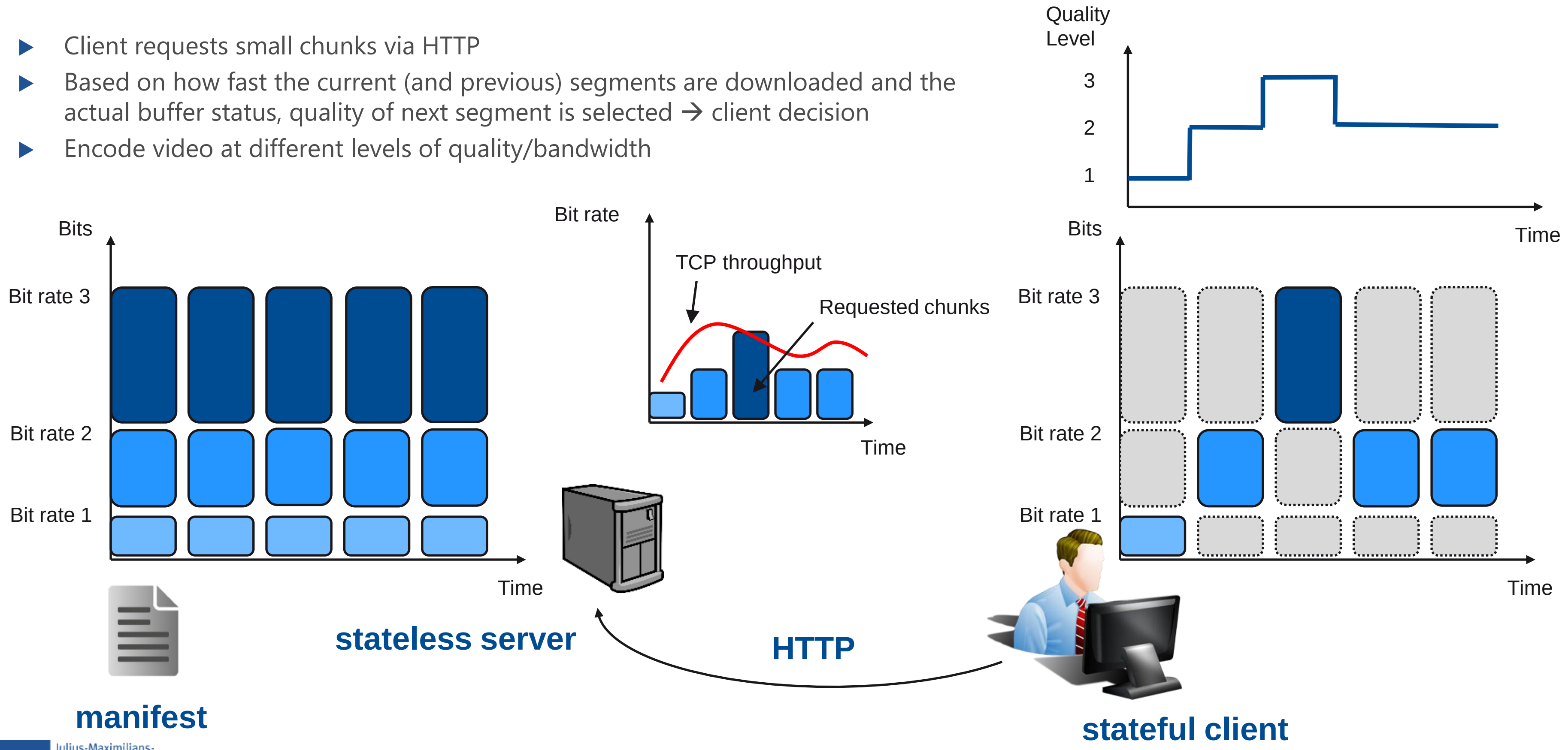
- QoE only covers a fraction of the factors influencing technology acceptance




Adapted from Marikyan, D. & Papagiannidis, S. , “Unified Theory of Acceptance and Use of Technology: A review”, http://open.ncl.ac.uk / ISBN: 9781739604400

# Dynamic Adaptive Streaming over HTTP: DASH

- Client requests small chunks via HTTP
- Based on how fast the current (and previous) segments are downloaded and the actual buffer status, quality of next segment is selected → client decision
- Encode video at different levels of quality/bandwidth



# Quality of Experience for DASH

## Objective

Initial or startup delay (low)

Buffer underrun / stalls (zero)

Quality switches (low)

Media throughput (high)

[Other media-related configuration: encoding, representations, segment length, …]

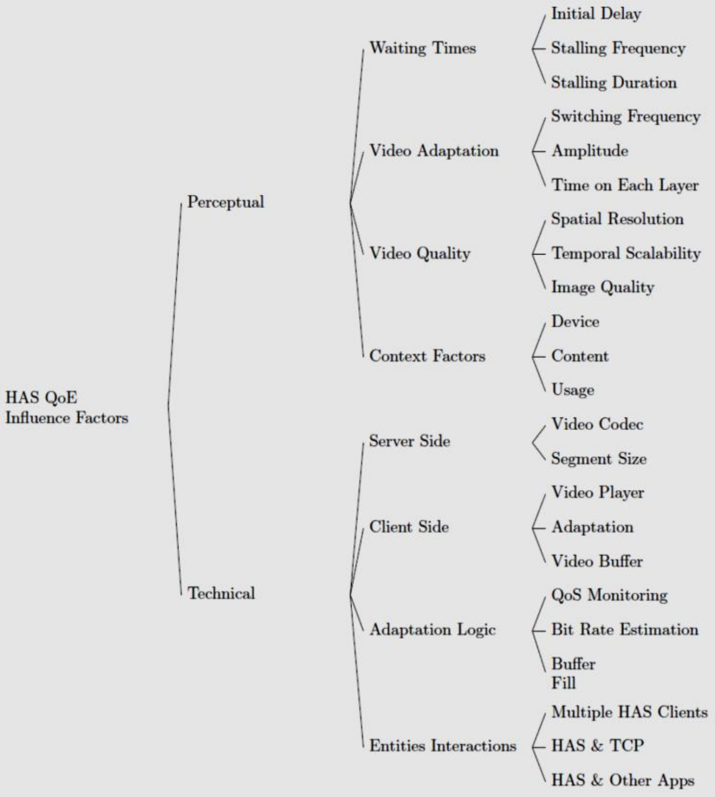
## Subjective

Mean Opinion Score (MOS) – various scales

Various methodologies (e.g., DSCQS, DSIS, ACR, PC, …)

*And more QoE metrics beyond MOS (see next part)*

# … and more QoE Influence Factors




QoE studies with controlled perceptual impairments

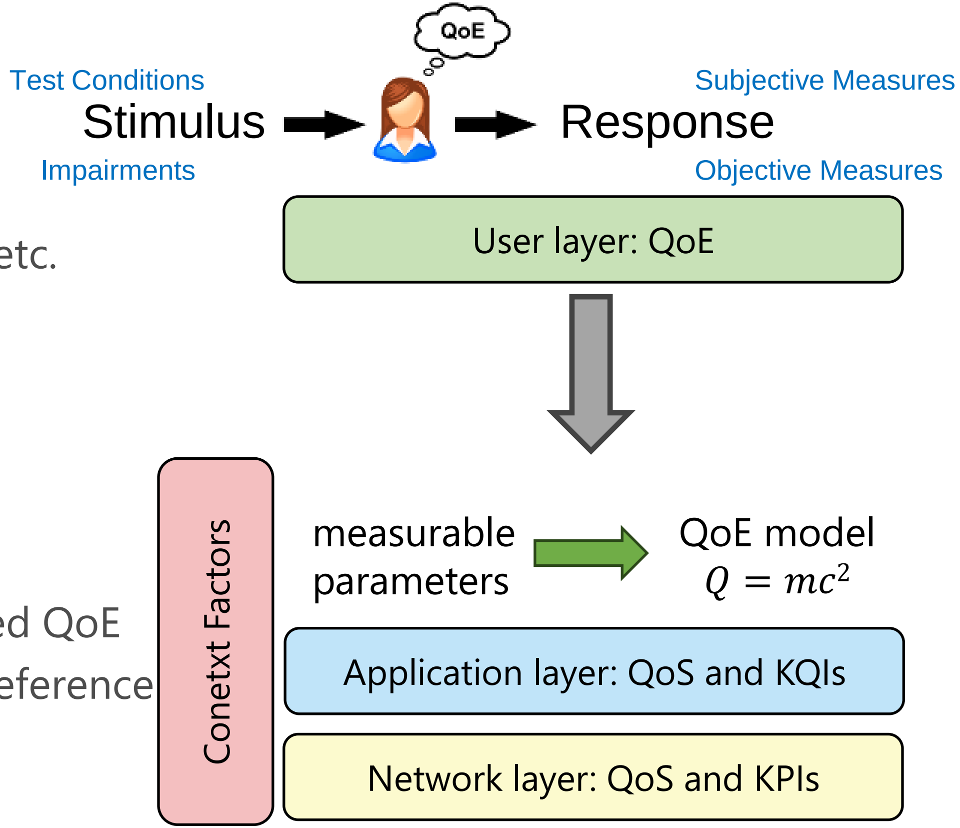
Objective measurement studies

M. Seufert, et al., "A Survey on Quality of Experience of HTTP Adaptive Streaming,". IEEE Communications Surveys & Tutorials, vol. 2014 (2014). https://doi.org/10.1109/COMST.2014.2360940

# How to Measure QoE?

- Subjective QoE Assessment
  - based on end-user involvement
  - typically: user opinion, ratings
  - but also: task performance, behavior, etc.

- „Objective“ QoE Prediction
  - based on analytical/statistical models
  - translate input parameters to estimated QoE
  - full reference, reduced reference, no reference



# Objective Video Quality Metric and Beyond

- Simple metrics, not close to human visual quality and QoE
- Many extensions: objective video quality metrics reflecting the user perception

- Some examples
  - PSNR: Peak signal-to-noise-ratio
  - SSIM: Structural Similarity Index
  - VMAF: Video Multi-method Assessment Fusion
  - VIF: Visual Information Fidelity
  - OPVQ: The Open Perceptual Video Quality metric
  - …

Often MOS as groundtruth

# Video Quality Assessment (VQA)

- Significant research efforts
- Ongoing research on perception-based VQA models

Often MOS as groundtruth



**Table 5** Overview of NR VQA models

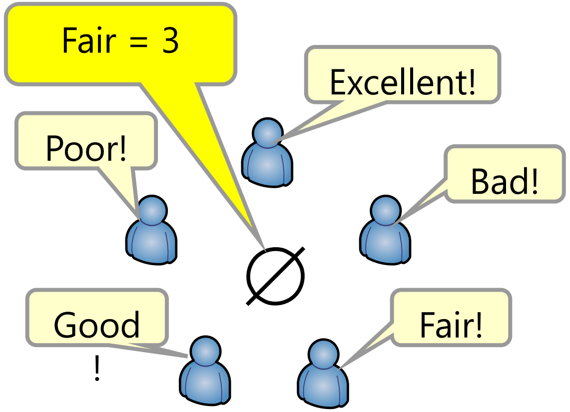
| Type | Algorithm | Methodology | Extracted quality features | Quality fusion |
|---|---|---|---|---|
| | Wang et al. [111] | Hand-crafted feature | Structure similarity, motion vector | Weighted sum |
| | NIQE [169] | Hand-crafted feature | Natural image statistics | Weighted sum |
| | IL-NIQE [170] | Hand-crafted feature | Natural image statistics | Weighted sum |
| | V-CORNIA [171] | Hand-crafted feature | CORNIA, temporal pooling | Weighted sum |
| | VIIDEO [172] | Hand-crafted feature | Natural video statistics, inter sub-band statistics | Weighted sum |
| | STEM [173] | Hand-crafted feature | NIQE, bandpass filter | Weighted sum |
| | VIQE [174] | Hand-crafted feature | NIQE, SLEEQ, E-SLEEQ, temporal straightening model | Weighted sum |
| | Video BLIINDS [175] | Hand-crafted feature | Spatial-temporal natural video statistics (NVS), motion vector | SVR |
| | TLVQM [176] | Hand-crafted feature | 45 low complexity & 30 high complexity features | SVR |
| | VIDEVAL [177] | Hand-crafted feature | BRISQUE, GM-LOG, HIGRADE-GRAD, FRIQUEE, TLVQM | SVR |
| | Chip-QA [178] | Hand-crafted feature | space-time chip, luma, color, gradient | SVR |
| | VSFA [179] | Pre-trained DNN model | ResNet-50 | GRU |
| | MDVSFA [180] | Pre-trained DNN model | ResNet-50 | GRU |
| | Tang et al. [181] | Pre-trained DNN model | VGG-16 | MLP, temporal memory-based pooling |
| | RIRNet [182] | Pre-trained DNN model | ResNet-50 with SPP | GRU |
| | Chen et al. [183] | Pre-trained DNN model | VGG-16 with attention module | GRU |
| | You [184] | Pre-trained DNN model | ResNet-50 with FPN and attention module | Transformer encoder |
| | You and Lin [185] | Pre-trained DNN model | ResNet-50 with FPN | Transformer encoder |
| | Wu et al. [186] | Pre-trained DNN model | Swin-T | STDE, TCT |
| | STDAM [187] | Pre-trained DNN model | ResNet-18 with graph convolution module and attention module | Bi-directional LSTM |
| NR | PatchVQ [40] | Pre-trained DNN model | PaQ-2-PiQ, 3D ResNet-18 | InceptionTime |
| | Ying et al. [188] | Pre-trained DNN model | MobileNetV3, 3D ResNet-18, MobileNetV1 | GRU-FCN |
| | Li et al. [189, 190] | Pre-trained DNN model | UNIQUE, SlowFast | GRU |
| | Liu et al. [191] | Pre-trained DNN model | KonCept512, SlowFast | Progressively Residual Aggregation |
| | UVQ [43] | Pre-trained DNN model | EfficientNet-B0, D3D | MLP |
| | UVQ-lite [192] | Pre-trained DNN model | MobileNet, MoViNet | MLP |
| | Telili et al. [193] | Pre-trained DNN model | ResNet-50 | Bi-LSTM |
| | Lu et al. [194] | Pre-trained DNN model | ResNet-50 | GRU |
| | MD-VQA [45] | Pre-trained DNN model | EfficientNetV2, ResNet3D-18, blur, noise, block effect, exposure, colorfulness | MLP |
| | Zhu et al. [195] | Pre-trained DNN model | ResNeXt-101 | Transformer encoder |
| | Zhang et al. [196] | Pre-trained DNN model | ConvNeXt, SAMNet, SlowFast | GRU |
| | Chen et al. [197] | Pre-trained DNN model | ResNet-50, C3D, RIRNet, PVQ, LSCT-PHIQNet | MLP |
| | Kwong et al. [198] | Pre-trained DNN model | Multi-channel CNN | GRU |
| | Wu et al. [199, 200] | Pre-trained DNN model | NIQE, TPQI, CLIP | Weighted sum |
| | Wu et al. [199] | Pre-trained DNN model | FAST-VQA, CLIP-visual, CLIP | MLP, cosine similarity |
| | Liu et al. [201] | Pre-trained DNN model | EfficientNet-b7, ir-CSN-152, CLIP, Swin-B, TimeSformer, Video Swin-B, SlowFast | MLP |
| | Liu et al. [202] | End-to-end training | 3D-CNN | MLP |
| | You and Korhonen [203] | End-to-end training | 3D-CNN | LSTM |
| | Yi et al. [204] | End-to-end training | VGG-16 with non-local module | MLP |
| | Wen and Wang [205] | End-to-end training | ResNet-18 | MLP |
| | SimpleVQA [206] | End-to-end training | ResNet-50 | MLP |
| | Minimalistic VQA [207] | End-to-end training | ResNet-50 or Swin-B | MLP |
| | StarVQA [208] | End-to-end training | Transformer | MLP |
| | Lin et al. [209] | End-to-end training | HED, I3D | Transformer encoder, MLP |
| | Shen et al. [210] | End-to-end training | 2D-CNN, 3D-CNN | MLP |
| | Xian et al. [211] | End-to-end training | DeblurGAN-v2, 3D-CNN | MLP |
| | Guan et al. [212] | End-to-end training | ResNet-50 | ConvLSTM, MLP |
| | Lu et al. [213] | End-to-end training | ResNet-18 | MLP |
| | FAST-VQA [214] | End-to-end training | Video Swin-T | MLP |
| | DOVER [215] | End-to-end training | Video Swin-T, ConvNeXt-T | MLP |
| | Kou et al. [216] | End-to-end training | Swin-T, 3D ResNet, blur encoder | MLP |
| | Yuan et al. [217] | End-to-end training | Visual quality transformer | MLP |
| | Ke et al. [218] | End-to-end training | Spatial and temporal Transformer encoder | MLP |
| | Liu et al. [219, 220] | Self-supervised learning | R(2+1)D | MLP |
| | Chen et al. [221] | Self-supervised learning | C3D | MLP |
| | Chen et al. [222] | Self-supervised learning | VSFA or RIRNet | GRU, MLP |
| | Madhusudana et al. [223] | Self-supervised learning | ResNet-50 | GRU, regularized linear regressor |
| | Mitra and Soundararajan [224] | Self-supervised learning | ResNet-50 | Weighted sum |
| | Jiang et al. [225] | Self-supervised learning | 2D-CNN, 3D-CNN | Transformer encoder, MLP |

Min, X., Duan, H., Sun, W., Zhu, Y., & Zhai, G. (2024). Perceptual video quality assessment: A survey. Science China Information Sciences, 67(11): https://doi.org/10.1007/s11432-024-4133-3

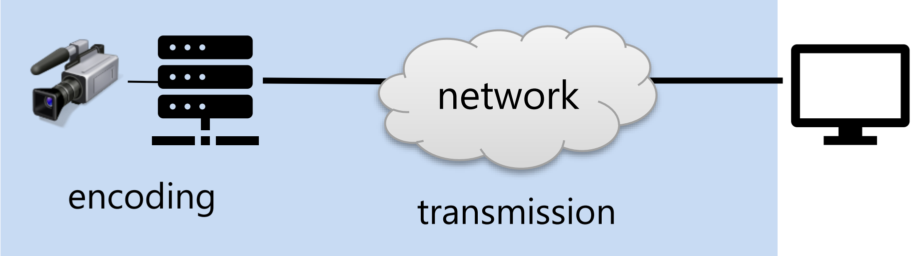
# QoE Metric: Mean Opinion Score (MOS)

- Numerical indication of perceived quality of received media after compression and/or transmission

| MOS | Quality | Impairment |
|---|---|---|
| 5 | Excellent | Imperceptible |
| 4 | Good | Perceptible |
| 3 | Fair | Slightly annoying |
| 2 | Poor | Annoying |
| 1 | Bad | Very annoying |




subjective study
- in the lab
- crowdsourcing




can be simulated

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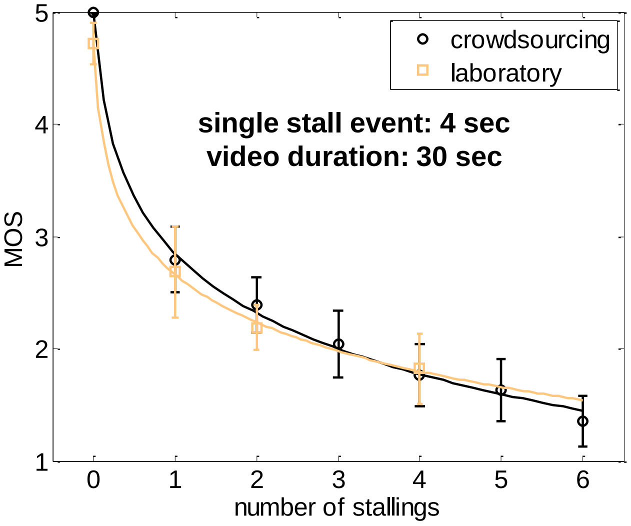
# Crowdsourcing vs. Lab Studies

- One study in a test lab
- Same study with crowdsourcing platform
- What are the differences between both studies?




**2,035 User from more than 60 countries evaluated 8.163 videos. Costs < €200,-**

**➔ User diversity**

**➔ Realistic test environment**

**➔ Statistically significant results**

**➔ Low costs, fast results**

Hoßfeld, Tobias, et al. "Best practices for QoE crowdtesting: QoE assessment with crowdsourcing." IEEE transactions on multimedia 16.2 (2013). https://doi.org/10.1109/TMM.2013.2291663

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# Examples: 6G Use Cases

- A diversity of use cases.
- Each one has its own QoE parametrization – but the network cannot distinguish!

**TODAY**

Streaming

Video Call

Online Gaming

**TOMORROW**

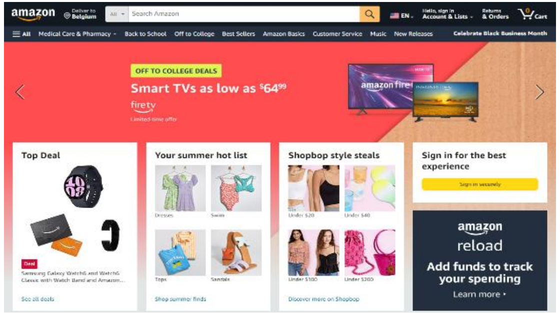
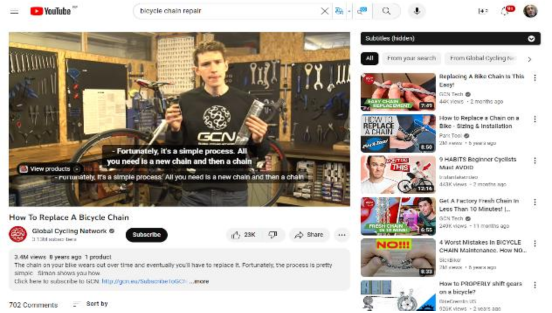
XR TeleMeeting

Remote Driving

First-Responder Support

# Quality of Experience for Established Services

- Mainly a question of throughput delivery

| Web (and smartphone apps) | Video-on-demand | Multi-user gaming |
| --- | --- | --- |
|  |  |  |
| Web page loading time < 3 sec | Fast start-up (~sec) , no buffering | Low ping time for user interactivity |





Content optimization + content delivery networks (CDN) + best effort broadband

Regional cloud + broadband

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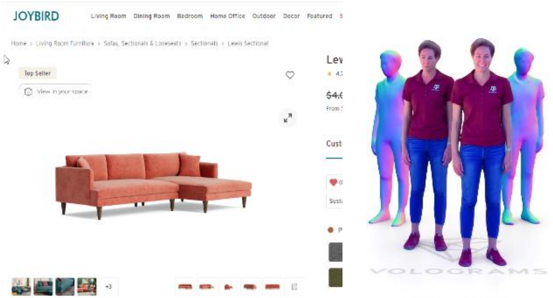
# QoE for Emerging Services (Spatial Computing and AI)

- Combination of advanced networking and heavy compute

## 3D web objects and volumetric video



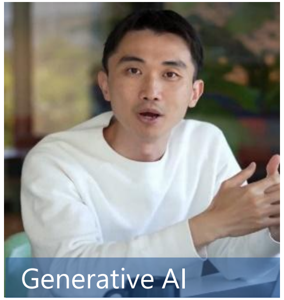

- Fast delivery (<3 sec) of 3D models
- Volumetric video on demand

~ established web and video, at higher bandwidths

## Cloud gaming and pixel streaming


- Sustained high-bandwidth low-latency video stream = novel traffic type
- High cloud compute load

## AI Web





- Bi-directional traffic (voice, photo/video upload…) ~ conferencing traffic ?
- High cloud compute load

Need to address networking and compute together for QoE ?

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# Discussion: Which (New) QoE Influence Factors for 6G Use Cases?

**+ network performance**
**+ network reliability**

- Cloud gaming
  - reaction time, frame rate stability
- AI-driven web
  - AI response time, load time, AI response accuracy
  - Context retention, session continuity, privacy perception
- XR Telemeeting (AR/VR-based Remote Collaboration)
  - motion-to-photon latency, interaction latency, motion sickness
  - rendering quality, 3D spatial audio synchronization (spatial movements)
  - immersion score: How "real" the meeting feels
- Remote driving
  - real-time control stability, control responsiveness: steering, braking, acceleration
  - HD perception quality, live feeds with minimal compression artifacts
- First-Responder Support
  - AI analytics response
  - data prioritization: Life-saving info (like gas leak detection)
  - situation Awareness Score: "How well could operators understand the scene?"

# Discussion: How to Measure QoE for Immersive Media and 6G?

- Application areas
  - gaming
  - omni-directional audio & video
  - AR/VR/MR communication
  - Immersive theaters
  - …

- Methodology
  - Active tests: experiment with user interactions
    - Uncontrolled, but realistic environment
    - Leads to „noise“ and increased variances
  - Passive tests: e.g. watching a video
    - Controlled environment, but missing interactions
    - Higher discriminative power and less „noise“
  - Lab studies vs. crowdsourcing studies

# From QoS to QoE. Parametric & bitstream-based QoE models

# From QoS to QoE. Parametric & bitstream-based QoE models

- Model complex relationship between system factors (QoS) and perceived quality (QoE)
- First models: speech (analogue telephony), from 1970s
- Two options
  - Based on QoS statistics for network planning (opinion models)
  - Based on QoS measures for network monitoring (bitstream or hybrid models)

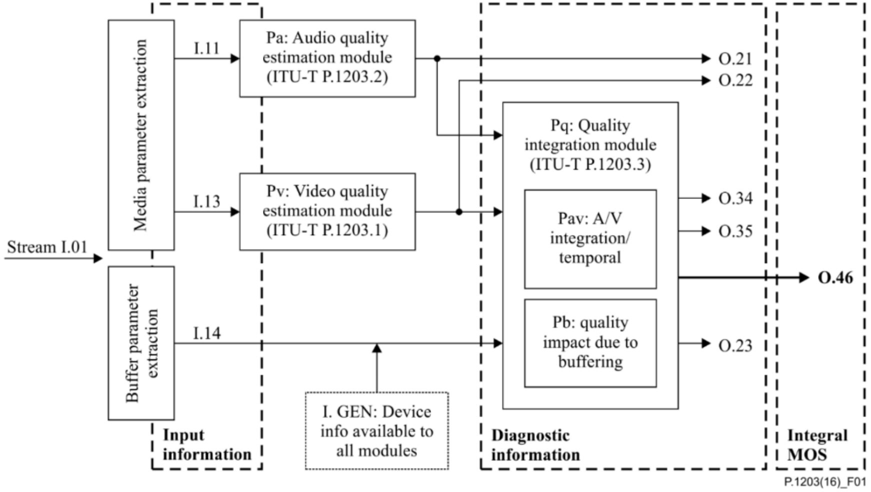



**Figure 1 – Building blocks of the ITU-T P.1203 model**

# IQX Relationship between QoE and QoS

- IQX: Interdependency of QoE and QoS hypothesis
- QoE is a function of $n$ influence factors (impairments)

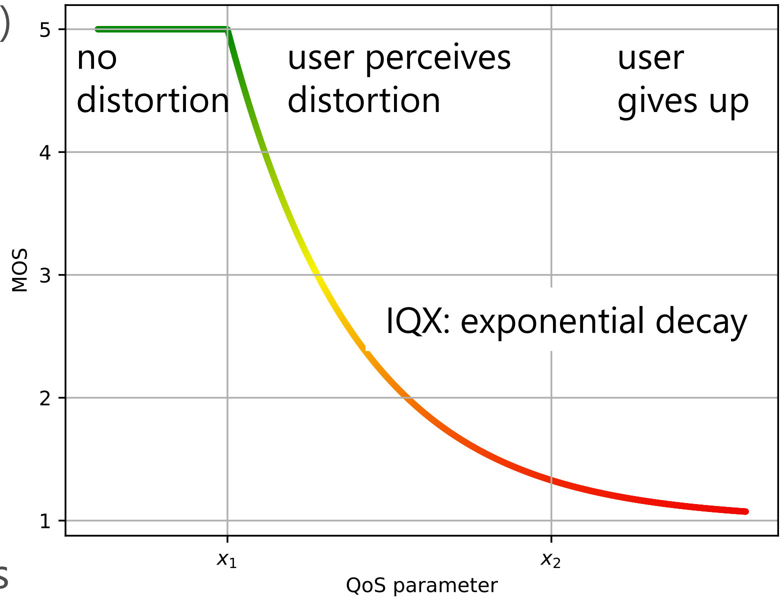
$$QoE = \Phi(I_1, I_2, \dots, I_n)$$

- Subjective sensitivity of QoE
  - higher for high QoE
  - lower for low QoE

$$\frac{\partial QoE}{\partial x} = -\tilde{\beta}(QoE - \gamma)$$

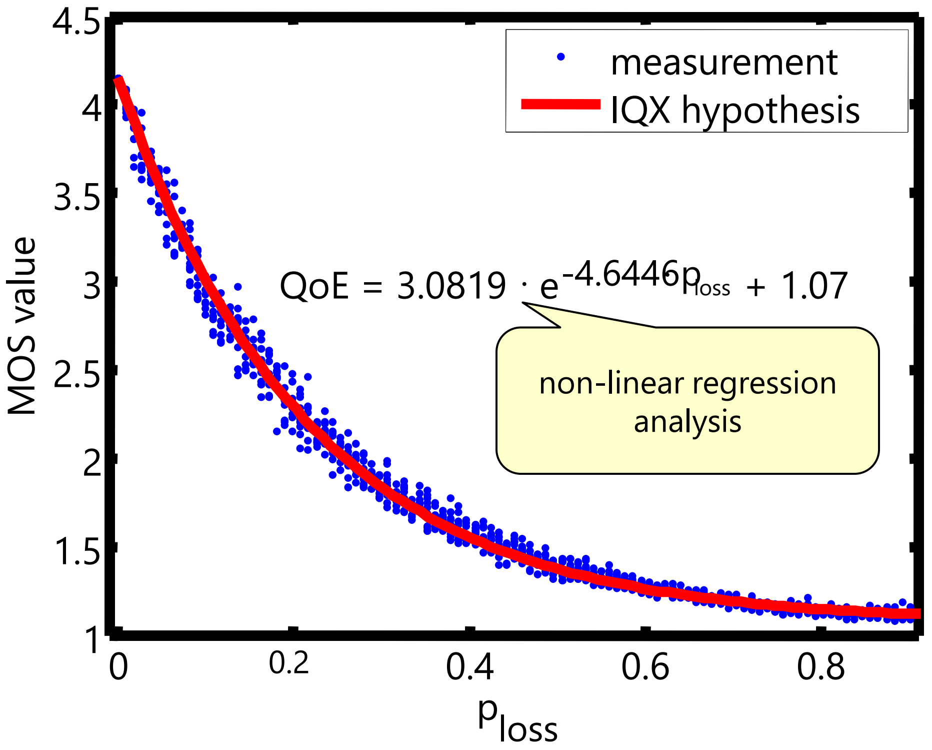
- Derivation of exponential solution for IQX hypothesis

$$QoE = \alpha e^{-\beta \cdot x} + \gamma$$




Fiedler, M., Hossfeld, T., & Tran-Gia, P. (2010). A generic quantitative relationship between quality of experience and quality of service. Ieee Network, 24(2), 36-41. https://doi.org/10.1109/MNET.2010.5430142

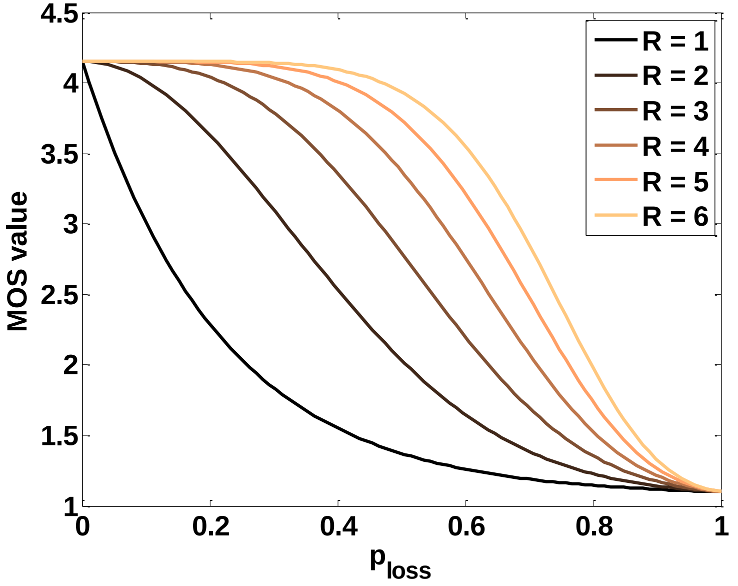
# Example: VoIP




loss as perceived
on application layer
by the users
*(see next slide)*

# Replication: Impact on Packet Loss

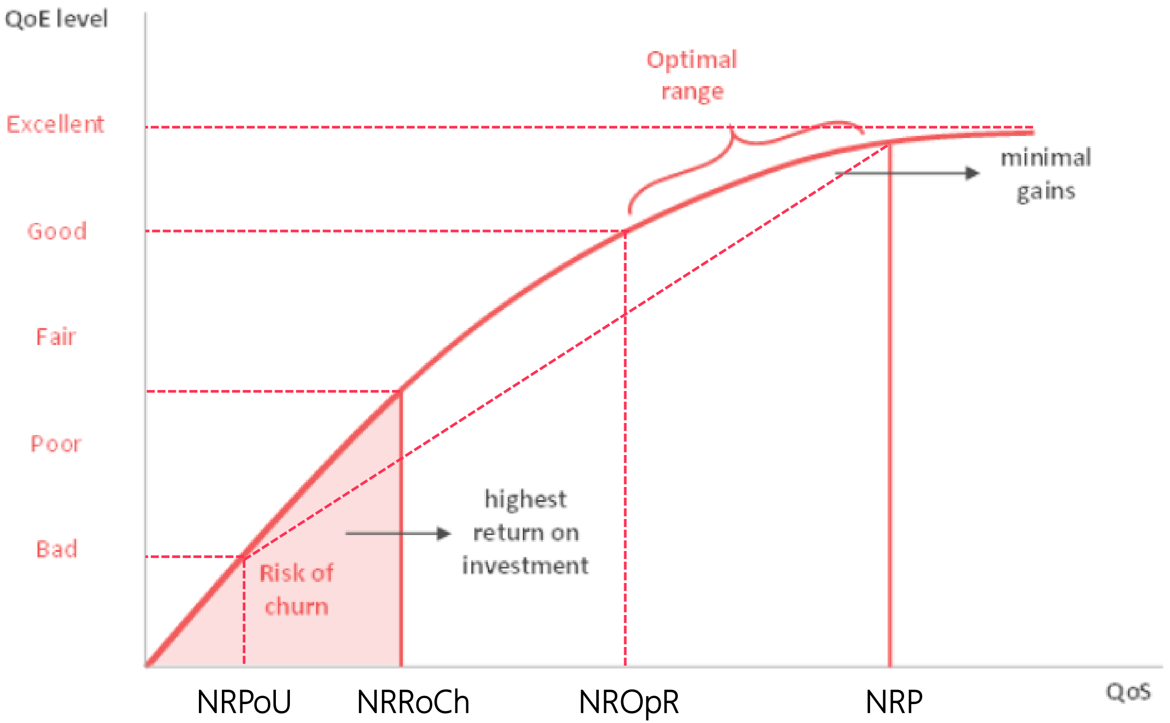
- Replication: datagram is sent in R consecutive packets
- Effective voice packet loss probability $p_{voice}$
  for a given packet loss probability $p_{loss}$ leads to $p_{voice} = p_{loss}^R$




Hoßfeld, T., Tran-Gia, P., & Fiedler, M.. Quantification of quality of experience for edge-based applications. ITC 2007. https://doi.org/10.1007/978-3-540-72990-7_34

# QoS vs. QoE: Understanding the Relation

- How network performance impacts QoE levels




- **NRP**
  Network Requirement for Perfection
- **NRRoCh**
  Network Requirement Risk of Churn
- **NROpR**
  Network Requirement Optimal Range
- **NRPoU**
  Network Requirement Point of Unusableness

# ITU-T QoE Recommendations

A sample of relevant ITU-T Recommendations (see ITU-T G.1011 for details)

<table>
<tr><th>Service</th><th>General</th><th>Subjective</th><th>Objective (pixel)[1]</th><th>Objective (bitstream)[2]</th><th>Opinion Model[3]</th></tr>
<tr><td>VoIP</td><td></td><td>P.800, P.1301</td><td>P.862 / P.863</td><td>P.561 / P.562</td><td>G.107</td></tr>
<tr><td>Video-phone</td><td></td><td>P.920</td><td></td><td></td><td>G.1070</td></tr>
<tr><td>(IP)TV</td><td>G.1080</td><td rowspan="2">P.910<br>P.913</td><td rowspan="2">J.144<br>J.247<br>J.343</td><td>P.1201</td><td>G.1071</td></tr>
<tr><td>Adaptive Streaming</td><td>-</td><td>P.1203<br>P.1204</td><td>-</td></tr>
<tr><td>VR</td><td>G.1035</td><td>P.919</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Gaming</td><td>G.1032</td><td>P.809</td><td>-</td><td>-</td><td>G.1072</td></tr>
</table>

Application: [1]codec evaluation, [2]service monitoring, [3]network planning.

# Anatomy of a Parametric Model: ITU-T P.1203

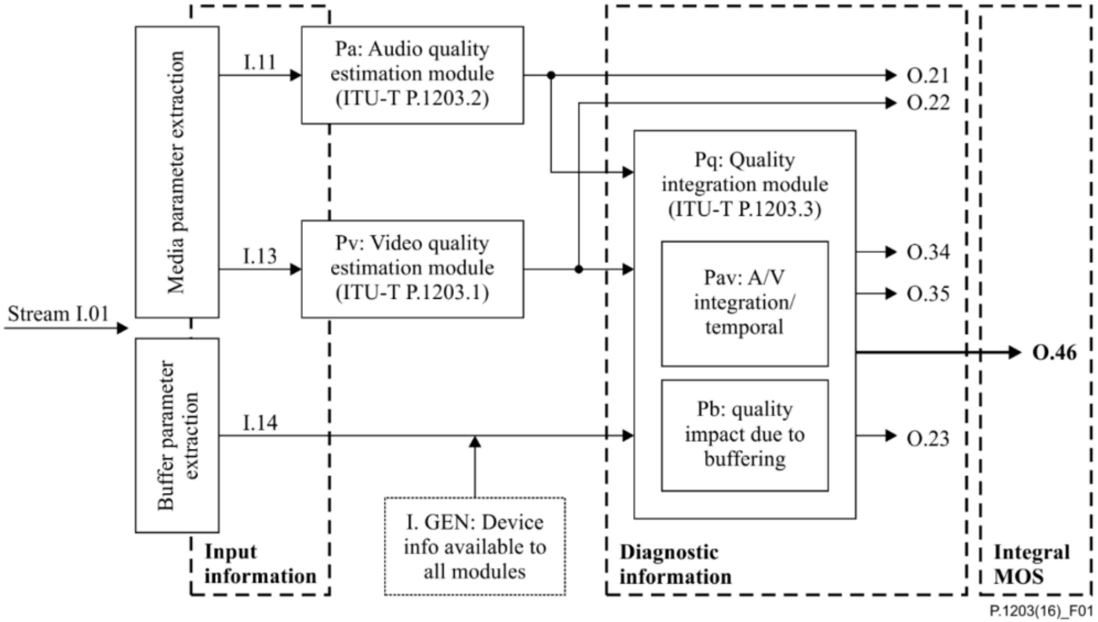



**Figure 1 – Building blocks of the ITU-T P.1203 model**

- Parametric model for adaptive streaming
- Instant quality
  - Video (O.21)
  - Audio (O.22)
  - A/V integration (O.34)
- Long-term effects
  - Long-term A/V (O.35)
  - Stalling (O.23)
- Integral MOS (O.46)

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# ITU-T P.1203 – Some Details

- Instant quality
  - A/V integration (O.34) =f [Video (O.21), Audio (O.22)]

$$\boldsymbol{O.34(t) = max(min(av_1 + av_2 \times O.21(t) + av_3 \times O.22(t) + av_4 \times O.21(t) \times O.22(t), 5), 1),}$$

- Long-term effects
  - Long-term A/V (O.35)
  - Stalling (O.23)

$$O.35 = O.35_{baseline} - negBias - oscComp - adaptComp, \quad \text{(Eq. 8-2)}$$

$$O.35_{baseline} = \frac{\sum_t w_1(t) \cdot w_2(t) \cdot O.34[t]}{\sum_t w_1(t) \cdot w_2(t)}, \quad \text{(Eq. 8-3)}$$

$$w_1(t) = t_1 + t_2 \cdot e^{t/(T/t_3)}, \quad \text{(Eq. 8-4)}$$

$$w_2(t) = t_4 - t_5 \cdot O.34[t], \quad \text{(Eq. 8-5)}$$

$$negBias = \text{see clause 8.1.2.1} \quad \text{(Eq. 8-6)}$$

$$oscComp = \begin{cases} 0, & oscTest\ is\ false \\ min\left(qDiff \cdot e^{min(c1 \cdot qDirChangesTot + c2, 1.5)}\right), & oscTest\ is\ true \end{cases} \quad \text{(Eq. 8-7)}$$

$$oscTest = \left(\frac{qDirChangesTot}{dur} < 0.25\right)\ AND\ (qDirChangesLongest < 30) \quad \text{(Eq. 8-8)}$$

$$adaptComp = \begin{cases} 0, & adaptTest\ is\ false \\ min(c3 \cdot vidQualSpread \cdot vidQualChangeRate + c4), & adaptTest\ is\ true \end{cases}. \quad \text{(Eq. 8-9)}$$

$$adaptTest = \left(\frac{qDirChangesTot}{dur} < 0.25\right) \quad \text{(Eq. 8-10)}$$

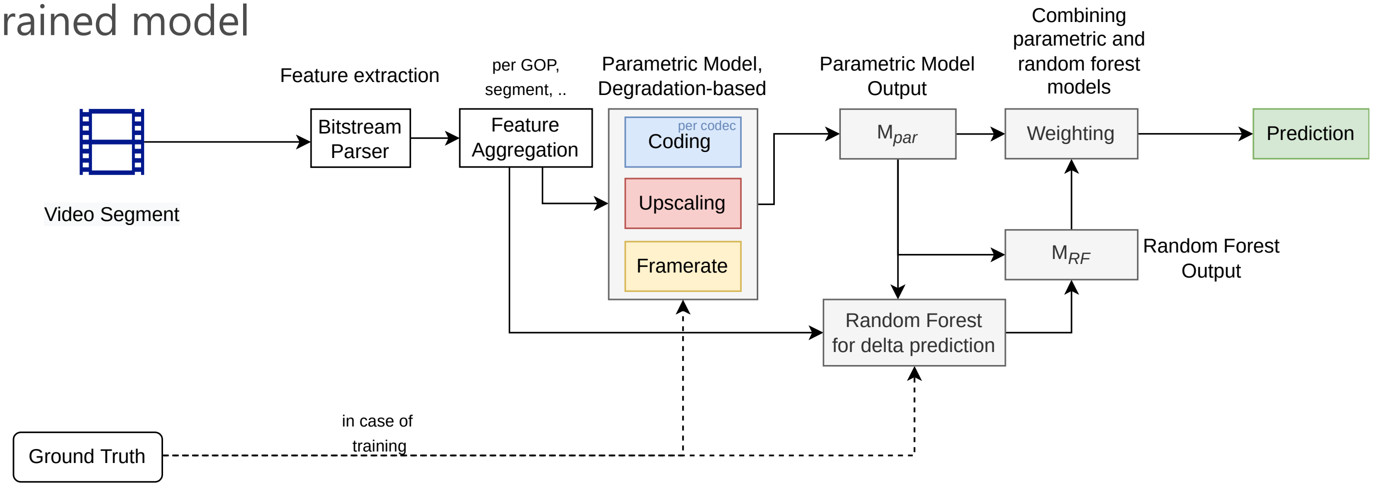
$$qDiff = max(0.1 + \log_{10}(vidQualSpread + 0.01)) \quad \text{(Eq. 8-11)}$$

- Integral MOS (O.46)

# ITU-T P.1204.3

- Bistream-only model for adaptive streaming: **video quality only**

- Combination of
  - Parametric model
  - Trained model




Rao, R. R. R., Göring, S., List, P., Robitza, W., Feiten, B., Wüstenhagen, U., & Raake, A. (2020, May). Bitstream-based model standard for 4K/UHD: ITU-T P. 1204.3–Model details, evaluation, analysis and open source implementation. In 2020 Twelfth International Conference on Quality of Multimedia Experience (QoMEX) (pp. 1-6). IEEE..

# ITU-T P.1204.3 Parametric Part

$$M_{\boldsymbol{q}} = q_{\mathbf{1}} + q_{\mathbf{2}} \exp(q_{\mathbf{3}} * \boldsymbol{quant} + q_{\mathbf{4}})$$

$q_i$ parameters depend on codec type

MOS->R

$$D_{\boldsymbol{u}} = x \log\left(y \frac{\boldsymbol{display\_res}}{\boldsymbol{coding\_res}}\right)$$

$$D_{\boldsymbol{t}} = z \log\left(k \frac{\boldsymbol{coding\_fr}}{60}\right)$$

$$R = R_{\boldsymbol{q}} - D_{\boldsymbol{u}} - D_{\boldsymbol{t}}$$

R –> MOS

R is "transmission rating" scale

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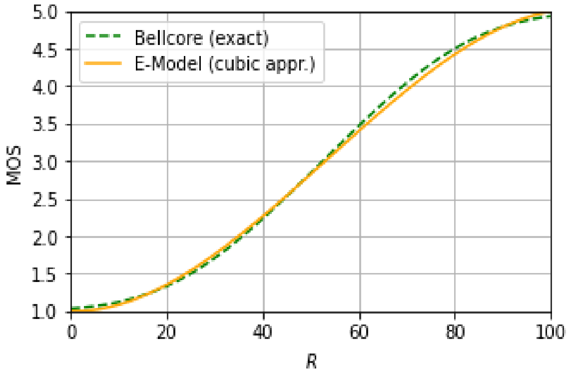
# Transmission Rating Scale is Linear to μ Scale

- R scale provides a cubic mapping to MOS

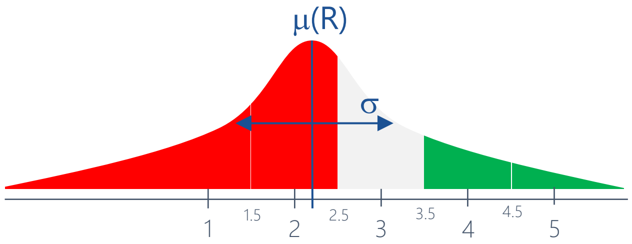
$$MOS = 1 + 0.04R + R(R-60)(100-R) * 7 * 10^{-6}$$




- Which is equivalent to a linear mapping to μ

$$\mu(R) = \frac{R}{15} - 0.5;\ \sigma = \frac{16}{15}$$

- This allows direct estimation of GoB (green) / PoW (red)




- However, mapping was derived for speech!
  - New coefficients should be computed for video
  - (This is not part of P.1204.3)




- Pérez, P. (2023, June). The Transmission Rating Scale and its Relation to Subjective Scores. In 2023 15th International Conference on Quality of Multimedia Experience (QoMEX) (pp. 31-36). IEEE.

# ITU-T P.1204.3 – Trained (random forest)

$$target\_residual = MOS - M_{parametric}$$

$$M_{random\_forest} = M_{parametric} + predicted\_residual$$

$$Prediction = w \cdot M_{parametric} + (1-w) \cdot M_{random\_forest}$$

| **Aggregated Feature** | **Type** |
|---|---|
| Framerate | float |
| Resolution $(width \cdot height)$ of the distorted video | int |
| Codec (H.264, H.264_10bit, H.265, H.265_10bit, VP9) | boolean |
| $M_{parametric}$ | float |
| Mean bitrate per segments | float |
| Maximum frame size | int |
| Kurtosis of the non-I frame sizes | float |
| Standard deviation of frame size of non-I frame in bits | float |
| Quant | float |
| IQR of the average QP of non-I frames | float |
| IQR of the minimum QP per frame | float |
| Kurtosis of the average QP of non-I frames | float |
| Mean of the average QP of non-I frames | float |
| Standard deviation of maximum QP of non-I frames | float |
| Kurtosis of the average motion per frame over all frames in a segment | float |
| Minimum standard deviation of motion in the x-direction (horizontal motion) per frame | float |

# ITU-T P.1204.3 Results

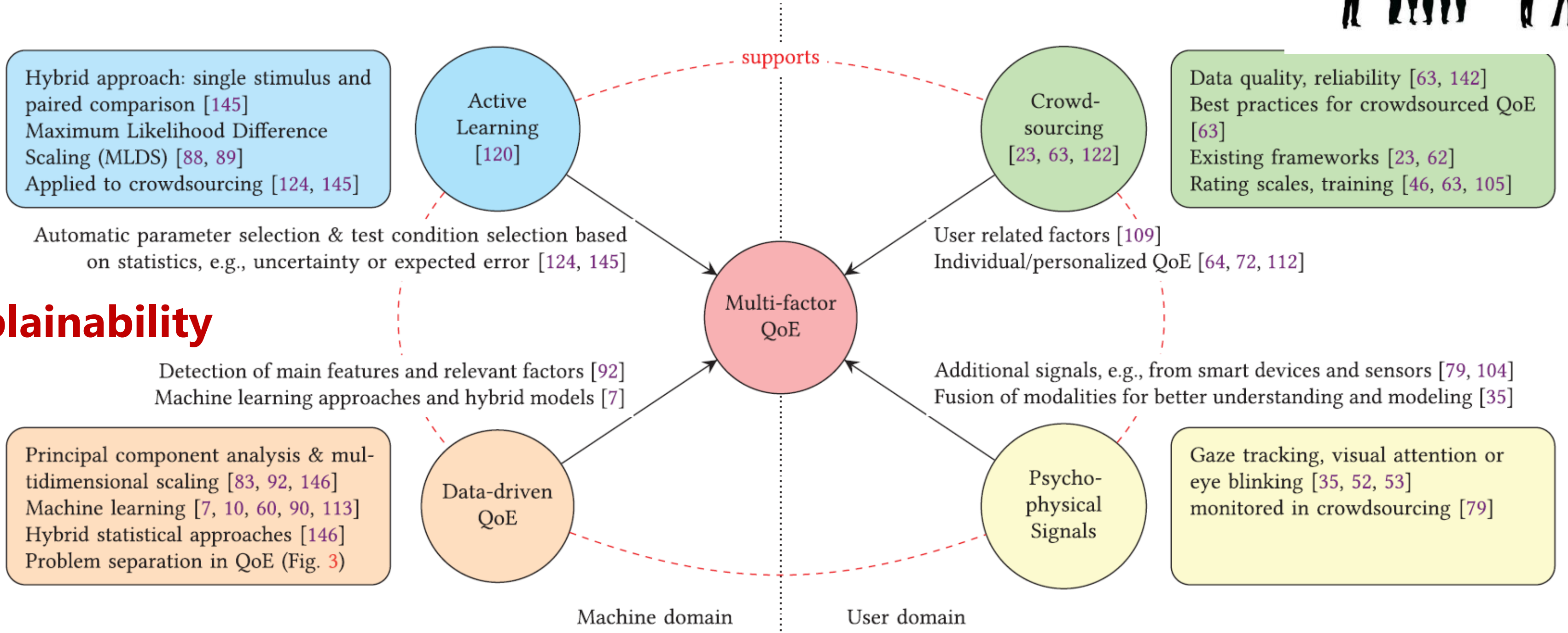
- Results are comparable to VMAF and other state-of-the-art metrics

TABLE V

PERFORMANCE COMPARISON, DATABASES W/O FRAMERATE VARIATION.

| Metric | RMSE | Pearson | Spearman | Kendall | $R^2$ Score |
|---|---|---|---|---|---|
| P.1204.3 | **0.400** | **0.962** | **0.948** | **0.804** | **0.874** |
| VMAF | 0.531 | 0.880 | 0.889 | 0.721 | 0.774 |
| BRISQUE | 0.653 | 0.815 | 0.838 | 0.653 | 0.660 |
| NIQE | 1.009 | 0.432 | 0.445 | 0.301 | 0.187 |
| PSNR | 1.109 | 0.131 | 0.682 | 0.531 | 0.017 |
| SSIM | 0.956 | 0.520 | 0.761 | 0.569 | 0.270 |
| MS-SSIM | 0.896 | 0.599 | 0.752 | 0.563 | 0.358 |
| ADM2 | 0.580 | 0.855 | 0.874 | 0.698 | 0.731 |
| VIFP | 0.757 | 0.736 | 0.756 | 0.562 | 0.542 |

# QoE Models: Discussions




**Explainability**

Skorin-Kapov, Lea, et al. "A survey of emerging concepts and challenges for QoE management of multimedia services." ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM) 14.2s (2018): 1-29. https://doi.org/10.1145/3176648

# Part 2: QoE in Systems

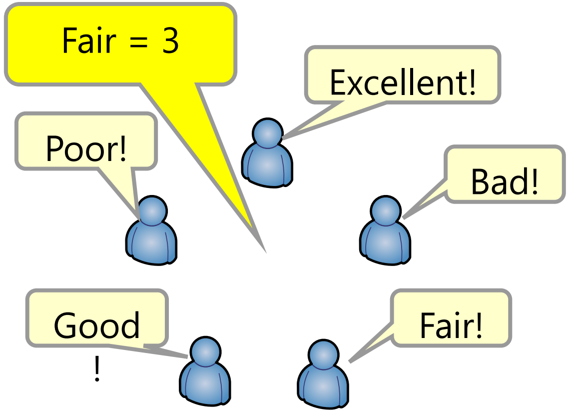
Notion of QoE in systems. Fundamental relations and mathematical models. QoE Fairness.

# QoE Beyond the MOS

-20°   80 °

Ø

On average, it's fine!
Still, you're in pain!



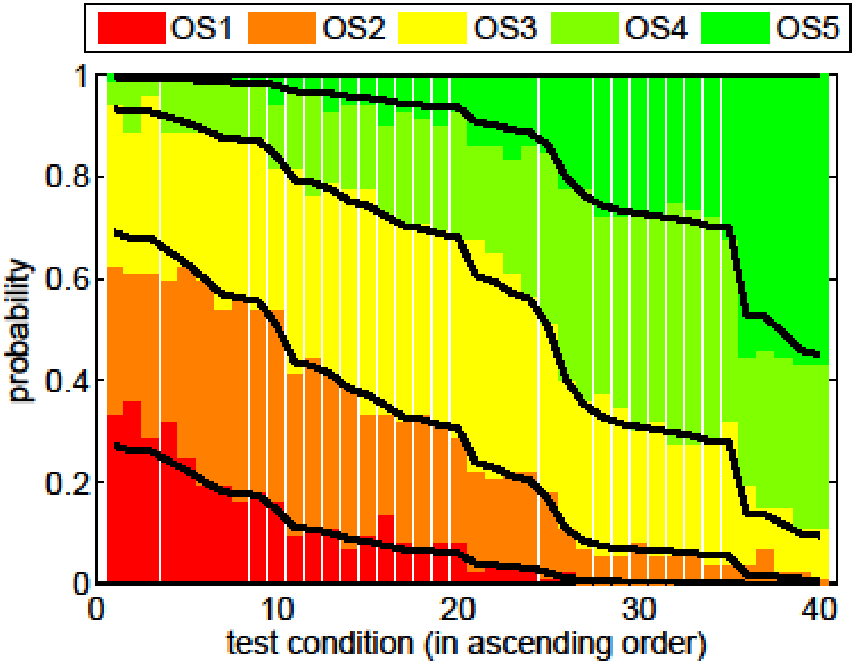

Ø

On average, it's fine!
Still, some suffer!

# Distribution of User Ratings

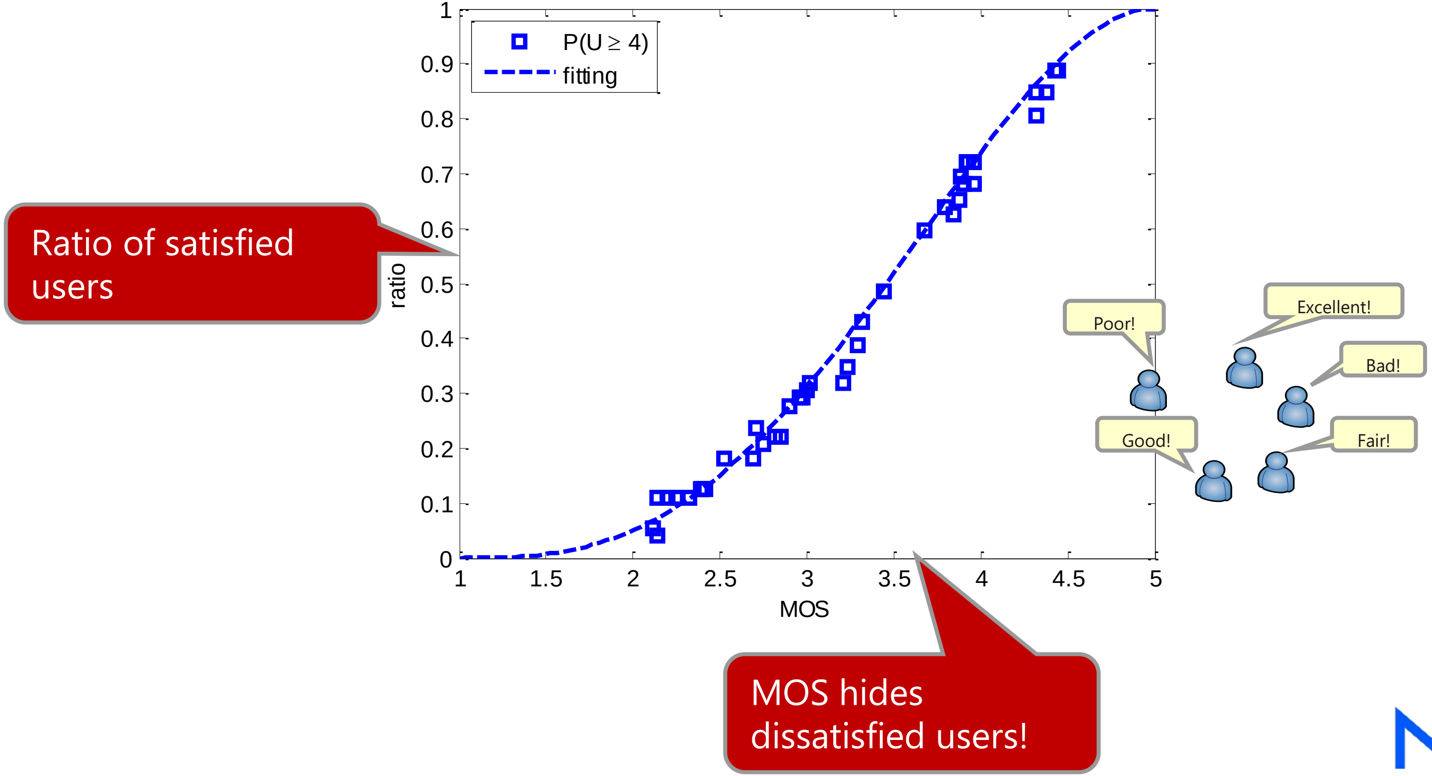
- For each test condition, we observe a distribution of user ratings (random variable)

- Contains complete information



# QoE Metric: Ratio of Users Rating Good or Better (GoB)

- Result of subjective test with $N$ users for a test condition

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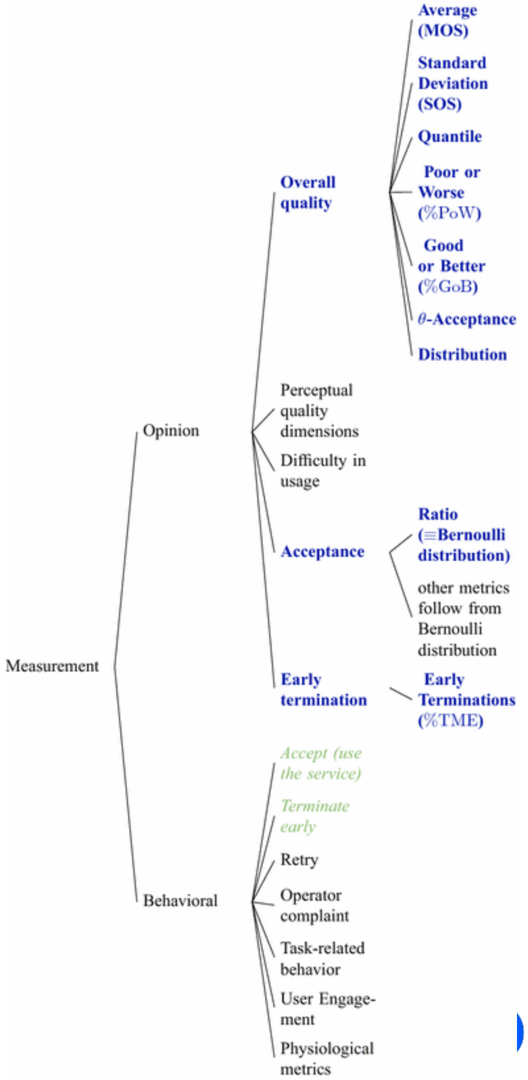
# QoE Metrics

- **MOS**: average user rating for one test condition
- **SOS**: user diversity for that test condition
- **%GoB**: the percentage of users rating Good-or-Better (%GoB)
- **%PoW**: the percentage of users rating Poor-or-Worse (%PoW)
- **Quantile**: user rating of fraction of (satisfied, dissatfied) users
- **Probability distribution**: complete information

- **SOS parameter:** quantifies user rating diversity

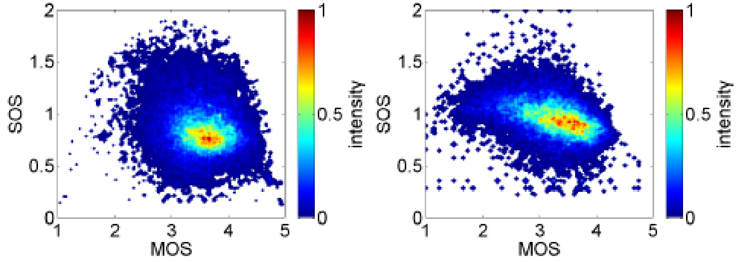




Hoßfeld, Tobias, Poul E. Heegaard, Martín Varela, and Sebastian Möller. "QoE beyond the MOS: an in-depth look at QoE via better metrics and their relation to MOS." Quality and User Experience, no. 1(2) (2016). https://doi.org/10.1007/s41233-016-0002-1

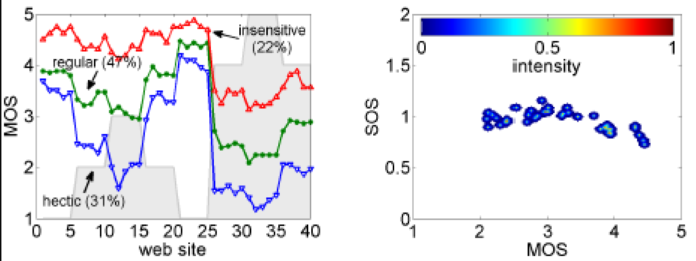
# User (Rating) Diversity

- User rating diversity expressed as standard deviation
  - Example 1: movie ratings
  - Example 2: QoE user ratings




(a) Internet Movie Database IMDb (b) MovieLens Data Set

**Fig. 1:** User rating histograms for movies from two different datasets




(a) MOS for user types (b) Nature of ratings

**Fig. 2:** User ratings as observed in a web traffic experiment

Hoßfeld, T., Schatz, R., & Egger, S. “SOS: The MOS is not enough!”. QoMEX 2011. https://doi.org/10.1109/QoMEX.2011.6065690

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# SOS Hypothesis

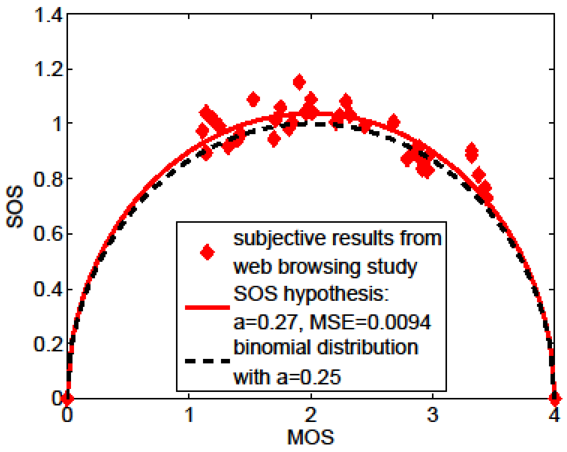
- Standard deviation of opinion scores: SOS

- **SOS parameter a**
  - quantifies user diversity for one application
  - relates SOS and MOS $x$
  - SOS hypothesis (for 5-point scale)

$$S^2(x) = a(5-x)(x-1)$$

  - SOS parameter $a$ is scale independent

- Single SOS parameter for one QoE experiment and particular application



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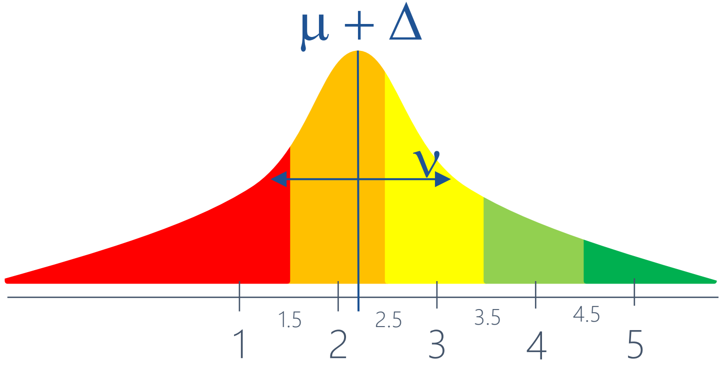
# User Rating Modeling

- User scores can be modeled by a normal random variable

$$Q_{c,u} = \mu_c + \mathcal{N}(\Delta_u, \nu_u)$$




  - $\mu_c$ = *true quality* of condition ***c***
  - $(\Delta_u, \nu_u)$ = bias and inconsistency of user ***u***

- Better representation of population scores that empirical distribution

- Included in ITU-T P.910

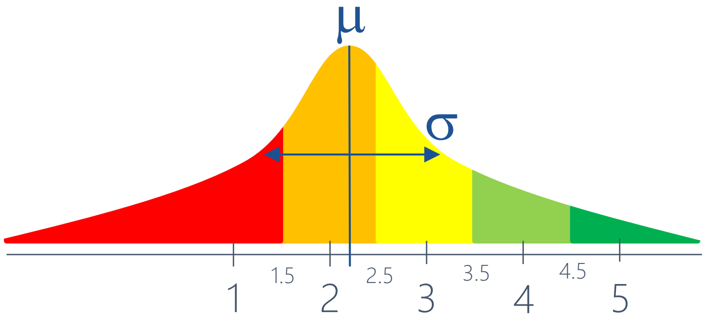

Li, Z., Bampis, C. G., Janowski, L., & Katsavounidis, I. (2020). A Simple Model for Subject Behavior in Subjective Experiments. Electronic Imaging, 32, 1-14. https://doi.org/10.48550/arXiv.2004.02067
Nawała, J., Janowski, L., Ćmiel, B., Rusek, K., & Pérez, P. (2022). Generalized Score Distribution: A Two-Parameter Discrete Distribution Accurately Describing Responses From Quality of Experience Subjective Experiments. IEEE Transactions on Multimedia. https://doi.org/10.1109/TMM.2022.3205444

# Theoretical derivation of the SOS Hypothesis

- The distribution of scores of a single condition is normal

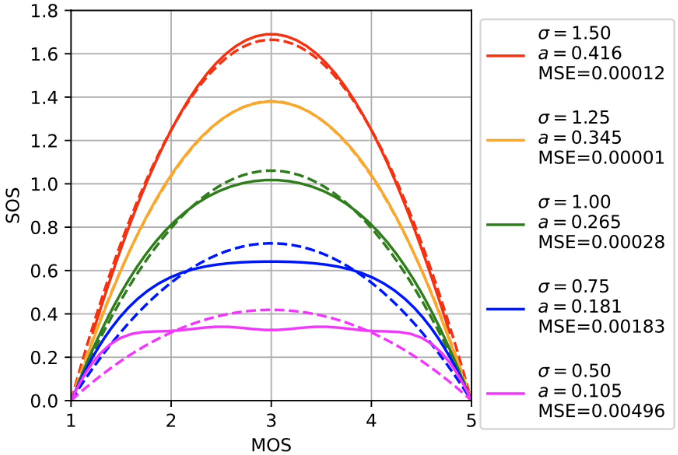
$$Q_c = \mathcal{N}(\mu_c, \sigma)$$

  - Variance is constant for all conditions
  - Equivalent to the SOS hypothesis




- Empirical relationship between parameters

$$\sigma = 3.01a + 0.2$$

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# Dicussion: QoE Metrics for which Use Case?

- Getting an idea how parameters influence the user perception
- Evaluation of a service or system with many users
- Comparison of codecs, configuration parameters, …
- …

# Dicussion: QoE Metrics for which Use Case?

- Getting an idea how parameters influence the user perception of a single user

| Use Case | Best QoE Metric(s) to Use | Why? |
|---|---|---|
| **Remote Driving** | Acceptance rate + Poor-or-worse rate | Safety-critical ➔ Anything "poor" is unacceptable. |
| **XR Telemeeting** | MOS + Good-or-better | Immersion and comfort are subjective and personal. |
| **First-Responder Support** | Poor-or-worse + Acceptance rate | Mission-critical ➔ Zero tolerance for poor connections. |
| **AI-driven Web** | Good-or-better + MOS | User satisfaction with AI interaction and response quality. |

- How to go beyond a single user? Evaluation of a service or system with many users?

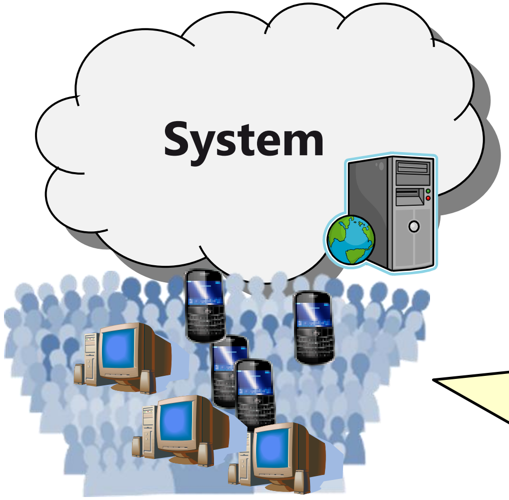
# System QoE: Fundamental Relationships

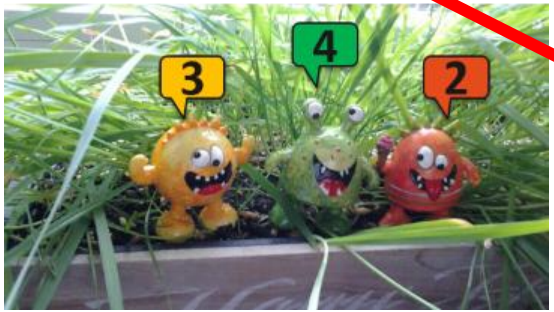
Hoßfeld, T., Heegaard, P. E., Skorin-Kapov, L., & Varela, M. (2019, June).
Fundamental relationships for deriving QoE in systems. QoMEX 2019.
https://doi.org/10.1109/QoMEX.2019.8743339

# User Centric Evaluation

- Proper sampling, annoying for users
- User bias (neg. feedback only)
- Viable for service providers

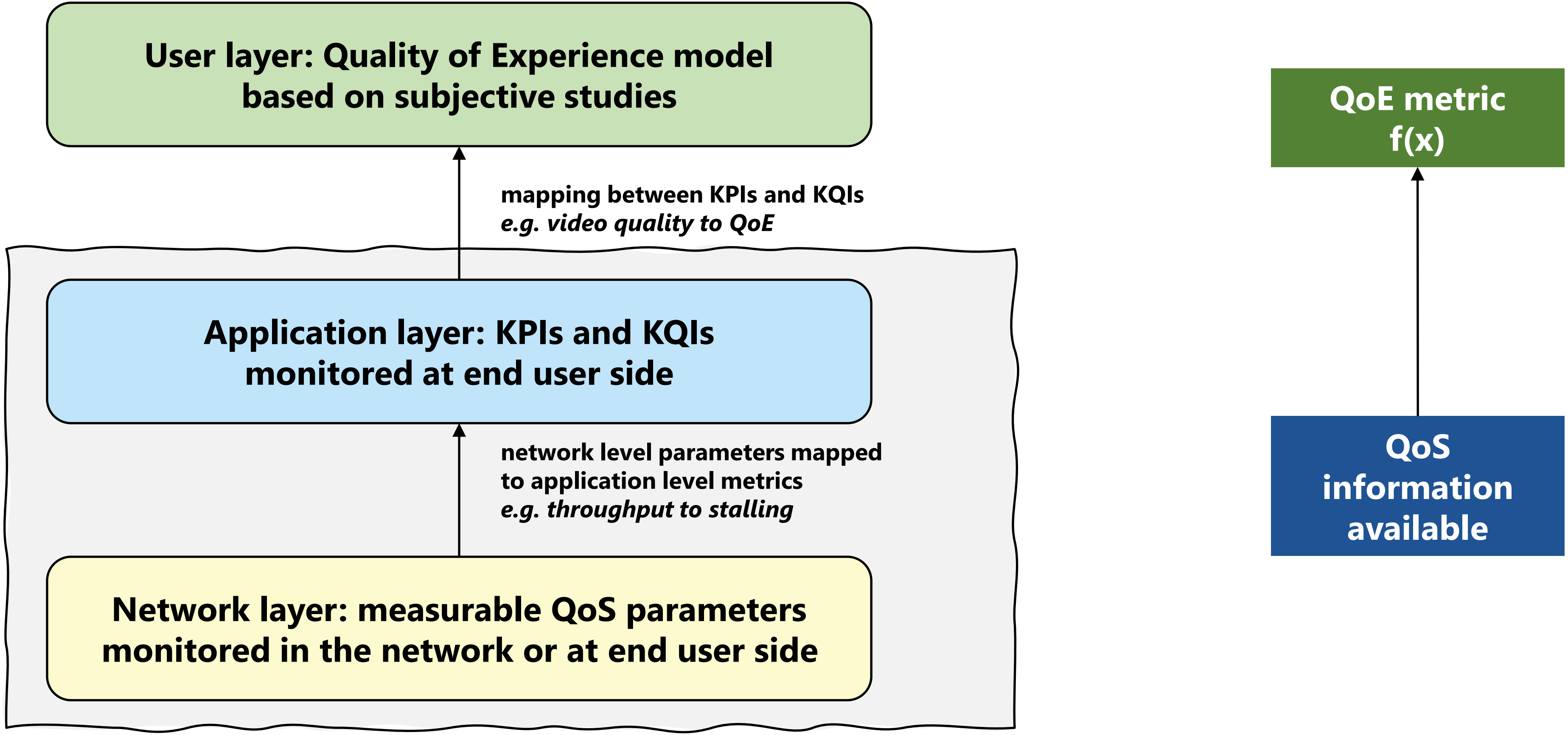
DIFFICULT



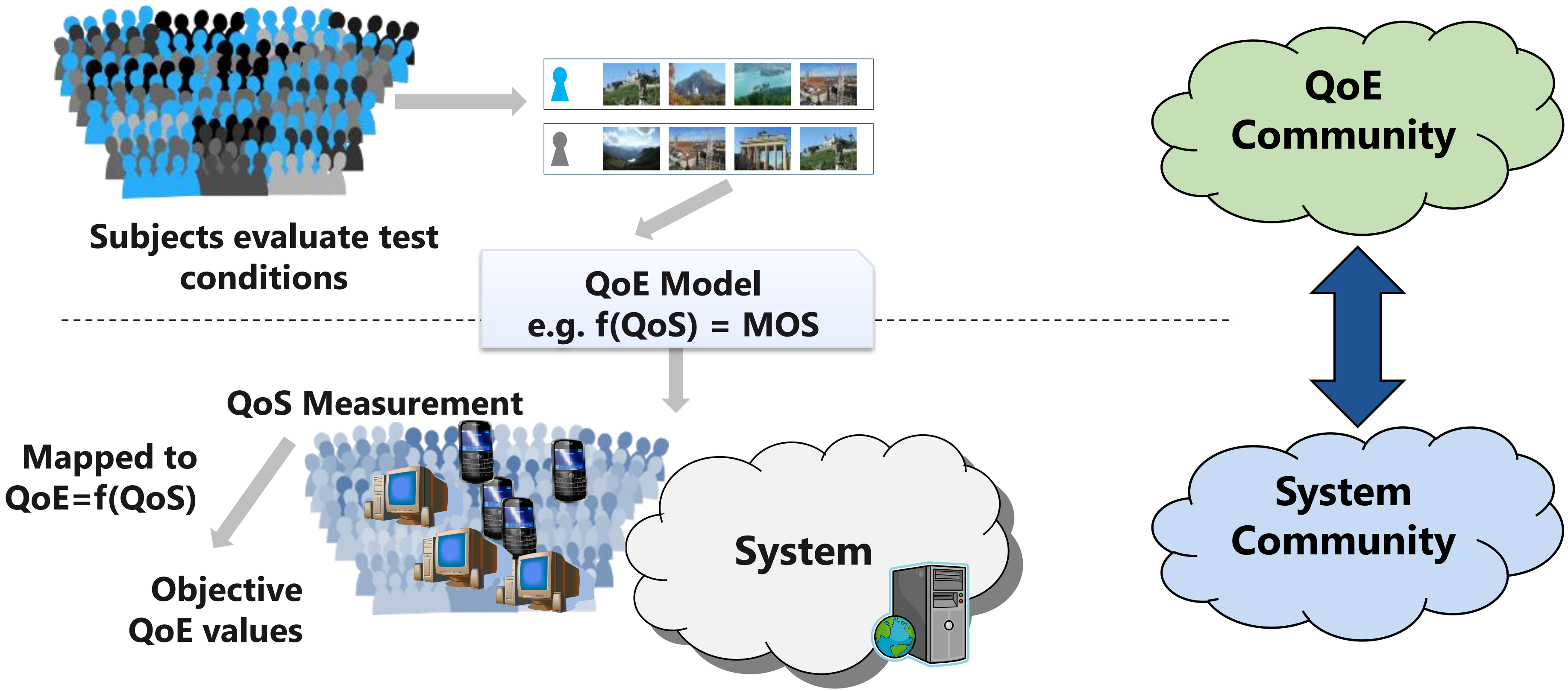




User feedback:
"What is your QoE?"

# Passive QoE Monitoring



# System QoE


Subjects evaluate test conditions
QoE Model
e.g. f(QoS) = MOS
QoS Measurement
Mapped to QoE=f(QoS)
Objective QoE values
System
QoE Community
System Community

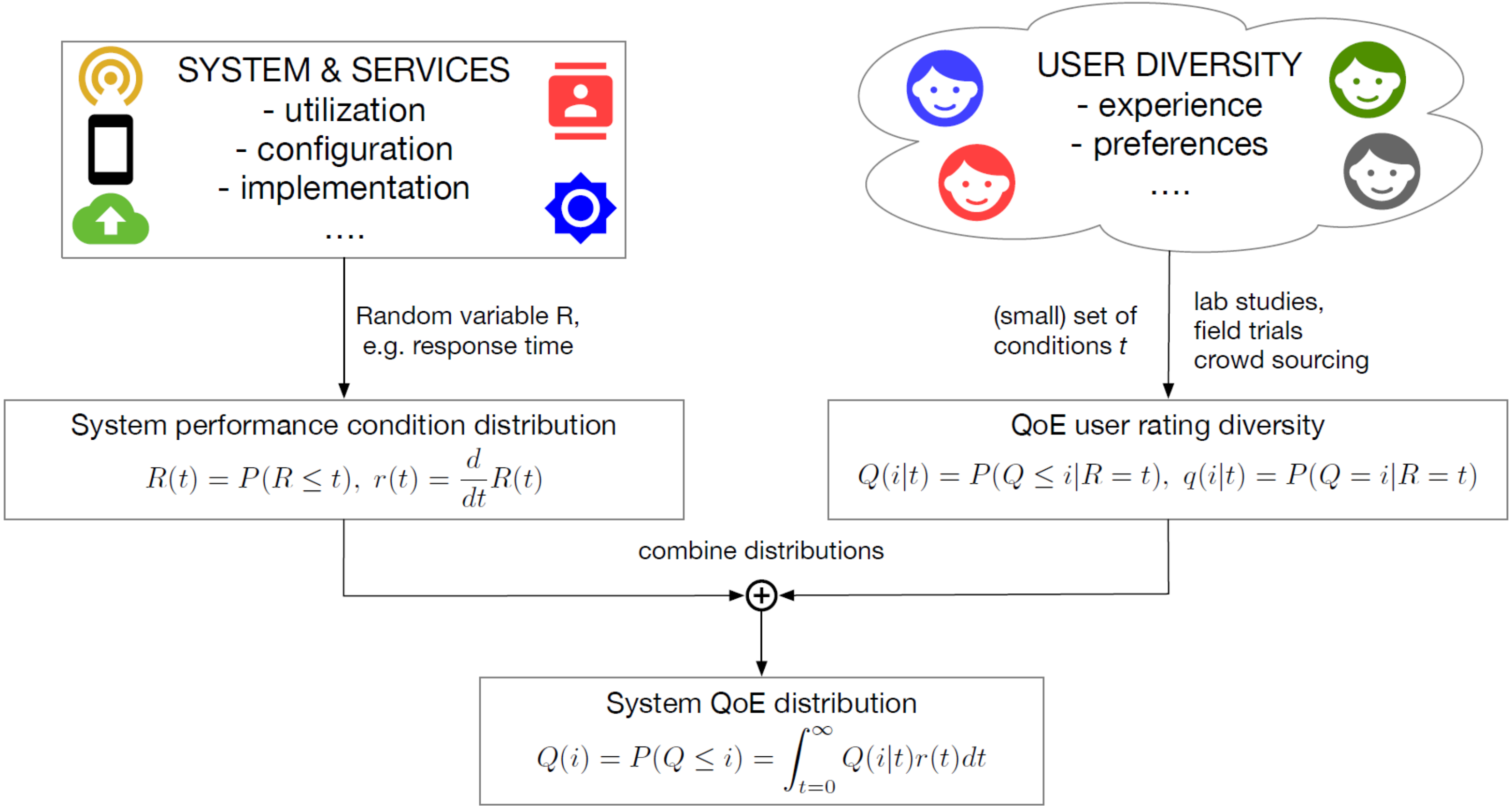
# System QoE

- System QoE is the expected QoE $E[Q]$ in a system
  - with QoS conditions $R$ (r.v.) and
  - MOS function $f(t)$, mapping the QoS $t$ to a MOS value $f(t)$

System QoE $\quad E[Q] = E[f(R)]$

- *Note:* Jensen's inequality for general function $f$: $E[f(R)] \neq f(E[R])$
  - Only for linear function $f(t) = mt + c$:
    $E[f(R)] = E[mR + c] = mE[R] + c = f(E[R])$

# Framework for System-Centric QoE



# Fundamental Relationship: Expected QoE

**System-centric QoE**
***Q*** (random variable, rv)

**QoE *Q|t* derived in subjective study** (rv)

**System response *R*** (rv)

$$
\begin{aligned}
\mathrm{E}[Q] &= \sum_{i=0}^{n} i q(i) = \sum_{i=0}^{n} i \int_{t=0}^{\infty} q(i|t) r(t) dt \\
&= \int_{t=0}^{\infty} r(t) \sum_{i=0}^{n} i q(i|t) dt = \int_{t=0}^{\infty} r(t) \mathrm{E}[Q|_t]\, dt \\
&= \int_{t=0}^{\infty} r(t) f(t) dt = \mathrm{E}[f(R)] = \mathrm{E}[M] \qquad (7)
\end{aligned}
$$

**MOS**

**MOS mapping function *f***

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# Fundamental Relationship: Expected QoE

**Expected system QoE and expected MOS.** The expected system QoE is equal to the expected MOS, $\mathrm{E}[Q] = \mathrm{E}[f(R)] = \mathrm{E}[M]$

$$\mathrm{E}[Q] = \mathrm{E}[f(R)] \neq f(\mathrm{E}[R])$$

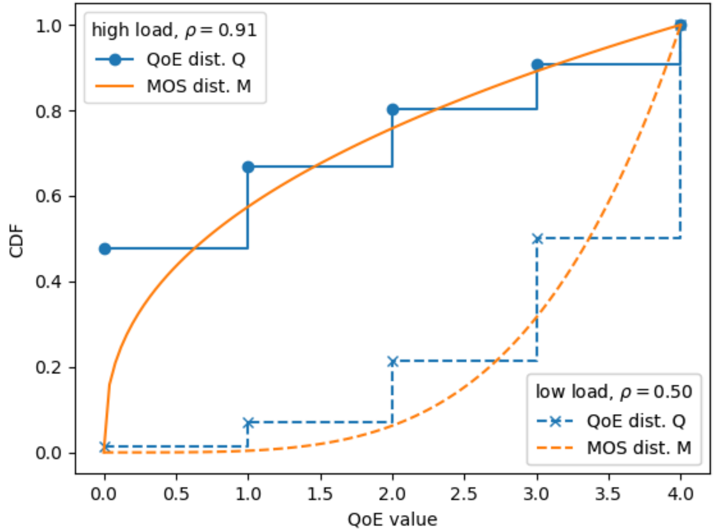
**Jensen's inequality**. If $f(t)$ is a convex function, the mapped MOS value of the average response time, $f(\mathrm{E}[R])$, is smaller than the expected MOS $\mathrm{E}[f(R)]$

$$f(\mathrm{E}[R]) \leq \mathrm{E}[f(R)] = \mathrm{E}[M] = \mathrm{E}[Q] \qquad (9)$$

# Example: Web Page Loading QoE

- QoE distribution
  - users experiencing different QoS conditions (random variable $X$)
  - user rating diversity (also for same conditions)
  - QoE of all users in the system (r.v. $Q$)
    (here: discrete rating scale from 0 to 4)

**QoE Distribution != MOS distribution**




- MOS mapping: f(x) is a continuous function mapping page load time to MOS
- MOS distribution $M = f(X)$: apply MOS mapping to QoS distribution $X$

# Fundamental Relationship: Good-or-Better (GoB)

$$
\begin{aligned}
GoB[Q,\alpha] = P(Q \geq \alpha) &= \sum_{i=\lceil k \rceil}^{n} P(Q=i) \\
&= \sum_{i=\lceil k \rceil}^{n} \int_{t=0}^{\infty} q(i|t) r(t) dt = \int_{t=0}^{\infty} r(t) \sum_{i=\lceil k \rceil}^{n} q(i|t) dt \\
&= \int_{t=0}^{\infty} r(t) GoB[Q|_t, \alpha] dt = \int_{t=0}^{\infty} r(t) g(t) dt \\
&= \mathrm{E}[g(R)]
\end{aligned}
$$

**GoB mapping function *g***

- Often: only MOS mapping functions available, e.g. *f(page load time)=MOS*
  → metrics like GoB cannot be derived for system centric QoE
- Other measures like GoB, quantiles, etc. require mapping function from subjective studies → report entire distributions in subjective tests

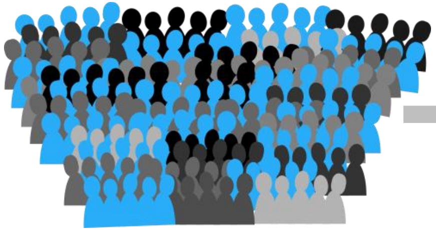
# QoE Fairness

Notion of QoE Fairness. Issues with existing fairness metrics.

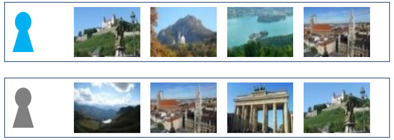
Suggested QoE Fairness Index.

Hoßfeld, T., Skorin-Kapov, L., Heegaard, P. E., & Varela, M. (2018). A new QoE fairness index for QoE management. Quality and User Experience, 3, 1-23.
https://doi.org/10.1007/s41233-018-0017-x

# QoE Fairness



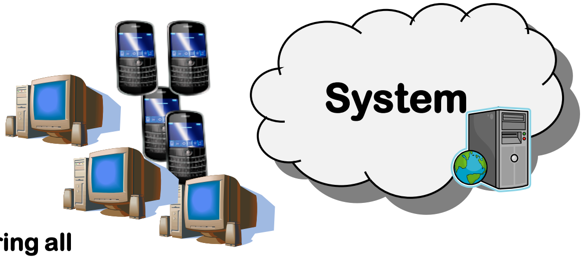
Subjects evaluate test conditions
e.g. on a 5-point scale.



QoE Metrics

QoE Model
e.g. f(QoS) = MOS

QoS Measurement



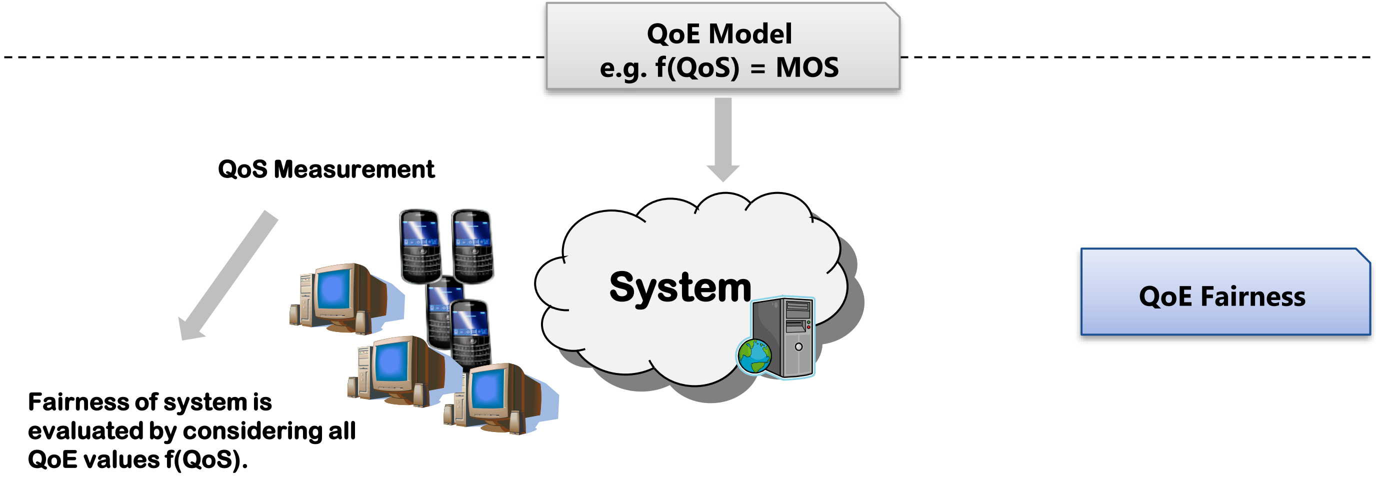

QoE Fairness

Fairness of system is
evaluated by considering all
QoE values f(QoS).

**How to define and
calculate QoE fairness?**

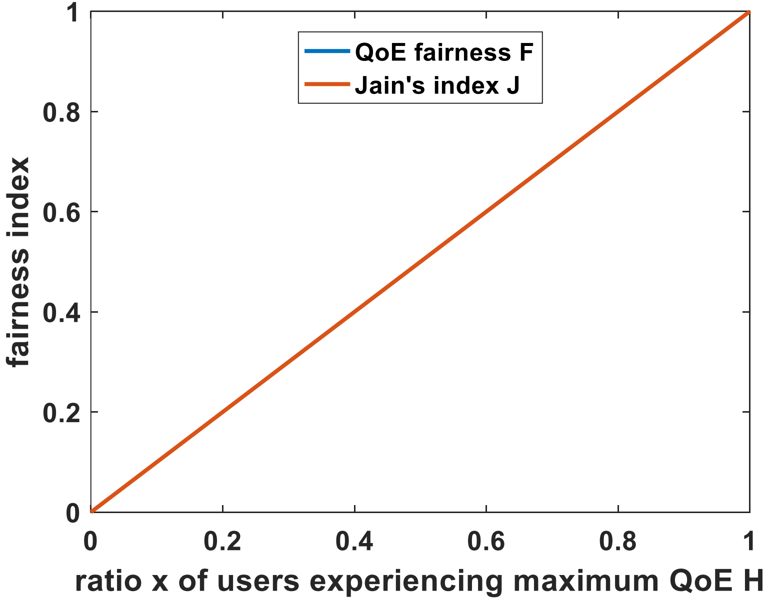
# QoE Fairness

- How to define and objectively calculate QoE fairness?
- It is not about user rating diversity!
- Fairness of the system concerning objective QoE scores, e.g. consider the average user = MOS mapping f(QoS)



# For which x is the system maximal unfair?

- In the system
  - x% of users experience maximum (best) QoE: $\boldsymbol{H = 5}$
  - 100-x% of users experience minimum (worst) QoE: $\boldsymbol{L = 1}$



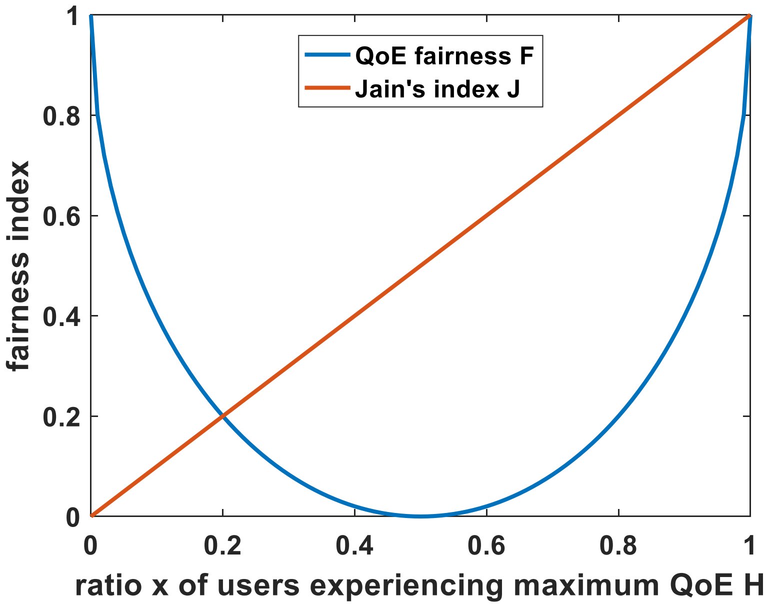

Jain's fairness index

$$J = \frac{1}{1+c^2} = \frac{E[Y]^2}{E[Y^2]}$$

- Coefficient of variation: only useful for **ratio scales**
  - Requires **natural zero point**
  - No meaning on interval scale

# For which x is the system maximal unfair?

- In the system
  - x% of users experience maximum (best) QoE: $\boldsymbol{H} = \mathbf{5}$
  - 100-x% of users experience minimum (worst) QoE: $\boldsymbol{L} = \mathbf{1}$



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# Definition of QoE Fairness Index

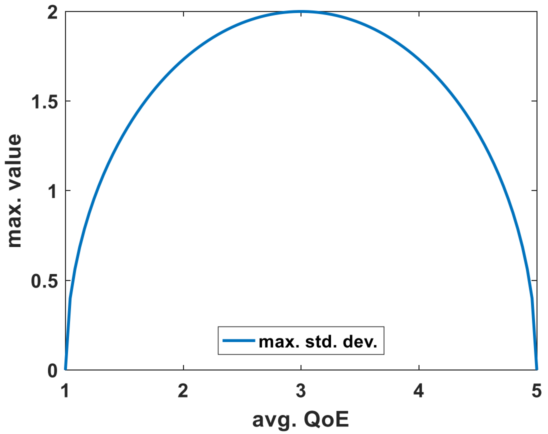
- QoE model maps QoS parameters x to QoE in $[L; H]$
  $Q: x \mapsto y = Q(x) \in [L; H]$
  - E.g. $Q(x)$ is the MOS value on a 5-point scale, $L = 1, H = 5$

- In a system with $n$ users, QoE values are random variable $Y$

- Maximum standard deviation of $Y$
  $\sigma_{max} = \frac{1}{2}(H - L).$

- Fairness index

$$F = 1 - \frac{\sigma}{\sigma_{max}} = 1 - \frac{2\sigma}{H - L}$$

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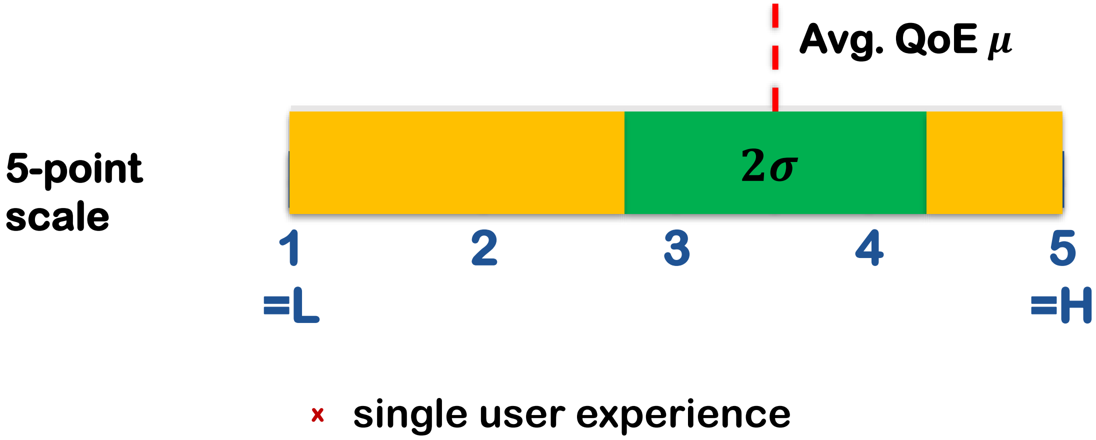
# Illustration

$$F = 1 - \frac{\sigma}{\sigma_{max}} = 1 - \frac{2\sigma}{H - L}$$



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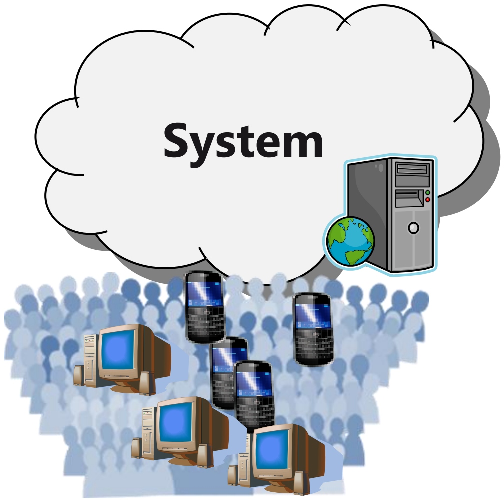
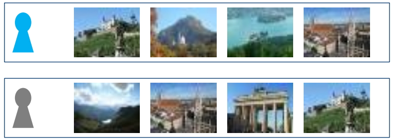
# Discussion

- What is required to quantify system QoE? Fundamental relationship
- What is your system? On which time-scales? …
- Which QoE model? Which QoE metric? …



**QoE Model**

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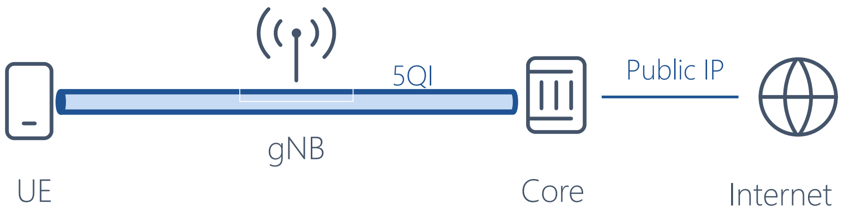
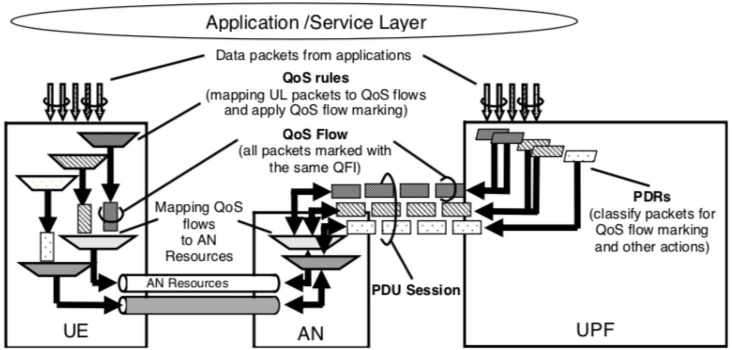
# Part 3: From QoE Research to Operation

Towards QoE management for CAPs and CSPs. Control loops between stakeholders. Guidelines to handle QoE in telecommunication networks: from research to operation.

# 5G QoS Model

- Simplified

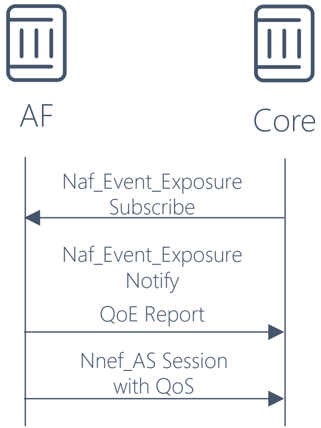


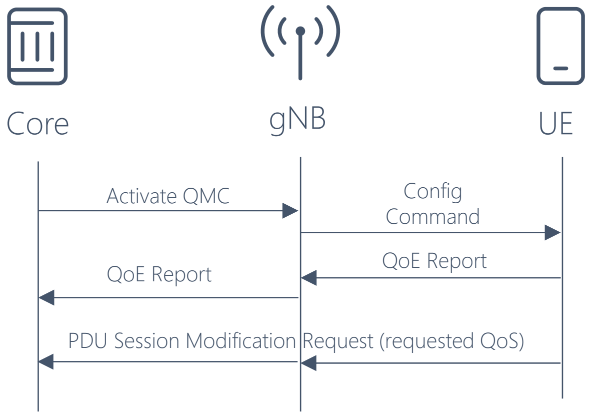




- Each data connection has a **QoS profile (5QI)**:
  - Priority Level
  - Packet Delay Budget
  - Packet Error Rate
  - Guaranteed Bit Rate (some profiles)
- 5G-network-wide (UE to Core)
- **Enforced by the network**

# QoE Measurements and Requested QoS

- 3GPP specifies methods for QoE measurements collection from the AF and the UE.
- Requests for specific QoS handling and segregation of service data flows can be done from the AF and the UE.

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# "QoE Metrics": To be more precise "KQIs"

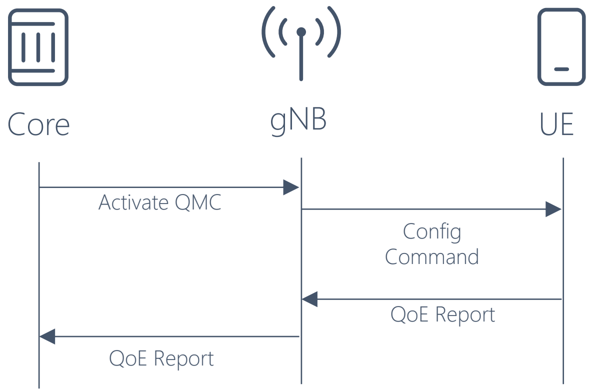
Quality DASH [26.247]
- List of Representation Switch Events
- Average Throughput
- Initial Playout Delay
- Buffer Level
- Play List
- MPD Information
- Playout Delay for Media Start-up
- Device information

VR [26.118]
- Based on DASH QoE (all metrics apply to VR also)
- Comparable quality viewport switching latency
- Rendered viewports
- VR device information

MTSI [26.114]
- Corruption Duration
- Successive loss of RTP packets
- Frame rate
- Jitter duration
- Sync loss duration
- RTT
- Average codec rate
- Codec information
- Call setup time

# QoE Measurement Collection (QMC) framework

- TS 28.405 (SA5) defines QoE Measurement Collection control:
  - **Management based** activation (from Network Management to RAN)
  - **Signalling based** activation (through Core Network to RAN) (supported as per TS 38.300)
- RAN visible QoE (RVQoE): QoE Measurements are sent "in clear" from the UE to gNB:
  - Buffer Level
  - Playout Delay for Media Startup
- **Not widely used**. In practice, QoE measurement is basically done at pilot deployments / network dimensioning.

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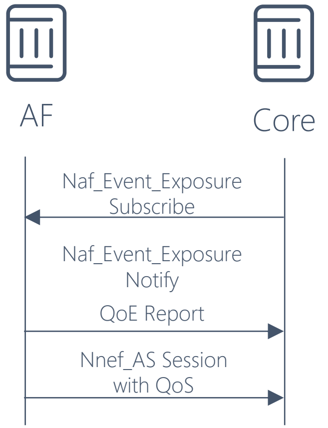
# Event Exposure Service by Applications

Data collection is done through event exposures including [TS 29.517]:




AF application events exposed by AF:

- Service Experience information for an application:
    - MOS with upper and lower values of the rating score
    - Time window
    - IP traffic filter
- UE mobility information;
- …

UE application events exposed via Data Collection AF:

- Media Streaming QoE metrics;
    - 3GP-DASH QoE Report [26.247]
    - virtual reality media the report [26.118]
- Media Streaming Consumption reports;
- …

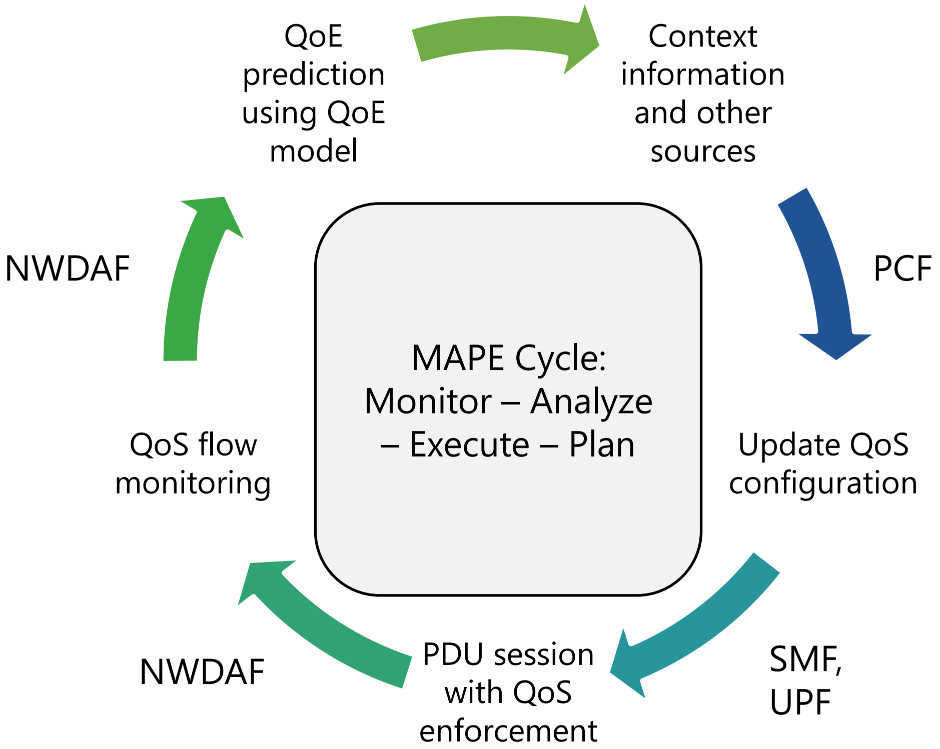
# Control Loops

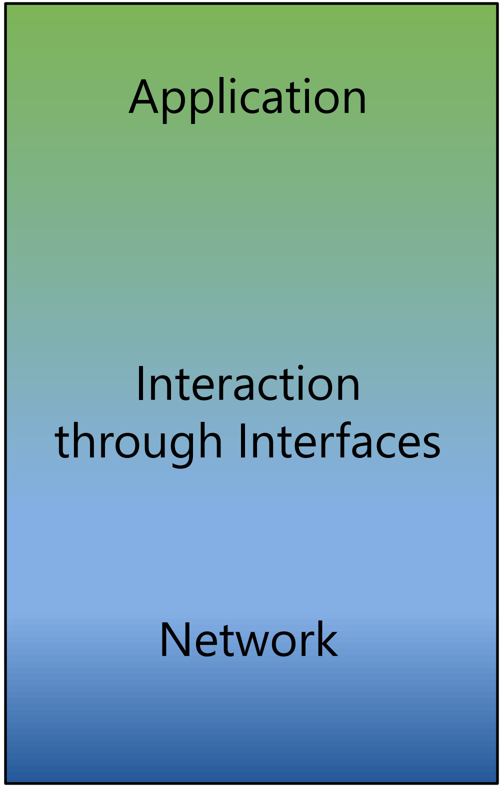
QoE-Aware E2E Management through Integrated Control Loops

# Key Problem: Information Asymmetry

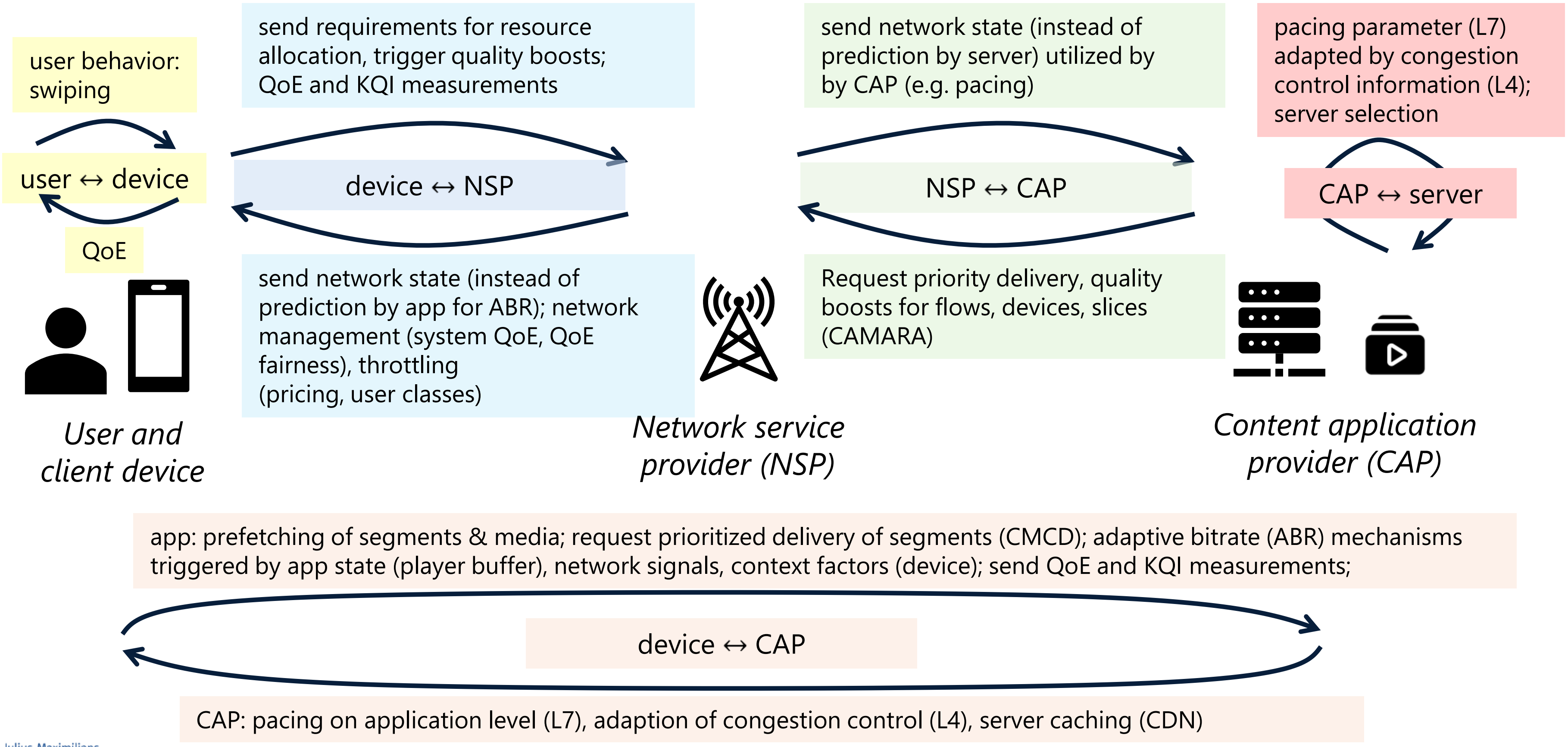
| Aspect | Network Service Providers (NSPs) | Content and Application Providers (CAPs) |
|---|---|---|
| Role in the Ecosystem | Manage network infrastructure, traffic routing, and bandwidth allocation. | Develop and deliver digital services such as streaming, gaming, and cloud applications. |
| Challenges Due to Information Asymmetry | Lack visibility into application-layer requirements, leading to inefficient traffic management and potential misallocation of resources. | Operate without direct knowledge of network congestion, latency variations, or available bandwidth, leading to inefficient adaptive strategies. |
| Impact on QoE | May impose rigid traffic policies without understanding specific application needs, potentially degrading user experience. | Must estimate network conditions, sometimes resulting in unnecessary buffering, redundant data transmission, or lowered quality. |
| Optimization Strategies | Implement traffic shaping, network slicing, and prioritization strategies to optimize resource use. | Use adaptive bitrate streaming, error correction, and congestion-aware algorithms to improve QoE. |
| Proposed Solutions for Cooperation | Establish open APIs for real-time traffic insights, enhance QoS reporting, and collaborate on common performance metrics. | Integrate with NSPs via real-time network analytics, optimize traffic flows, and adopt standardized performance metrics. |
| Regulatory Considerations | Subject to net neutrality and anti-discrimination regulations; require compliance with fair traffic management policies. | Encouraged to comply with fair-use policies, avoid excessive traffic generation, and ensure non-discriminatory content delivery. |

# QoE Management in 6G: MAPE Cycle

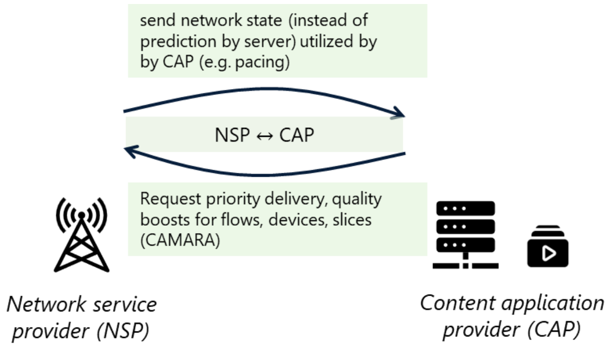


# Control Loops



# CAMARA Project and QoE Enhancement




- CAMARA (Linux Foundation) harmonizes network APIs across global telecom operators.
- **Quality-On-Demand (QoD) API**
  - enables app developers to request stable latency or prioritized throughput
  - abstracts telecom complexity
  - e.g., CDNs dynamically adjust resources via QoD for better QoE

- Challenges
  - Integrating QoD APIs into existing systems
  - Mapping QoS to QoE is nonlinear and context-dependent (content, device, user behavior)

- Other CAMARA APIs
  - **Device Information APIs:** Real-time connectivity and network status insights.
  - **Edge Cloud Service APIs:** Dynamic edge cloud discovery, traffic optimization, and deployment management (VMs or containers).

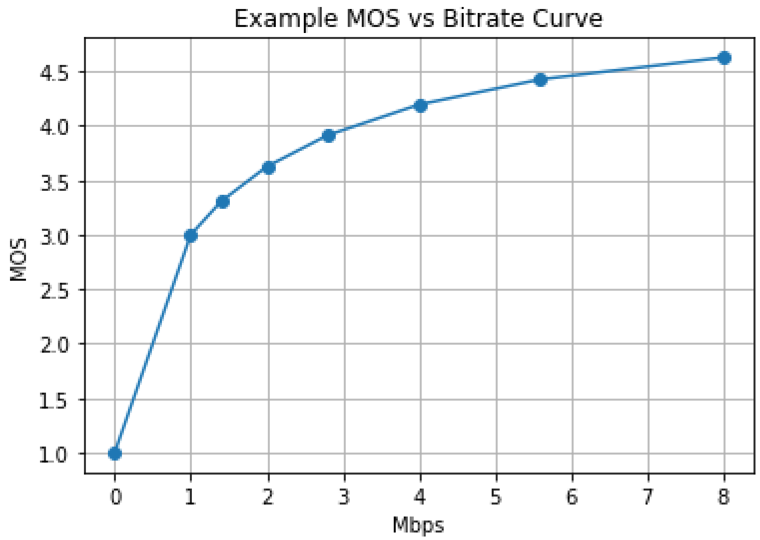
# Examples: CAMARA QoD

- CDNs utilize QoD APIs to enhance video streaming QoE by dynamically adjusting network resources to prevent video buffering and enhance streaming quality
  - T. Tran, D. Gageot, C. Neumann, G. Bichot, A. Tlili, K. Boutiba, and A. Ksentini, “On the benefits and caveats of exploiting quality on demand network apis for video streaming,” in NOSSDAV ,24.
  - T. Tran, D. Gageot, C. Neumann, G. Bichot, A. Tlili, K. Boutiba, and A. Ksentini, “On demand bandwidth boost: Improving video streaming over cellular networks with network apis,” in MHV ,24

- QoD-based optical Network-as-a-Service (NaaS) platform that dynamically allocates network resources for cloud-based virtual reality (VR) gaming
  - H. Rahimi, L. Gifre, R. Vilalta, R. Munoz, H. Yu, Y. Wang, R. Cai, and Y. Chen, “An open-source and standards-based network-as-a-service platform for cloud vr gaming,” in NetSoft 2024
  - H. Rahimi, L. Gifre, R. Vilalta, R. Munoz, H. Yu, Y. Wang, R. Cai, and C. Janz, “Enabling quality-on-demand and service differentiation on a novel network-as-a-service platform using slicing technology for control and management of optical networks,” in CNSM 2024

# Example: QoE-aware Scheduling

- 5 second segments
- 20-second videos
- 6-segment buffer
  - Policy: download next content
- 3 users, 20 mbps of shared link
- ABR policy
  - If empty -> x10 priority (QoE-enabled only)
  - If buffer < 3, download lowest quality
  - Otherwise use BW estimation to select quality
- 1000x 5-min simulations

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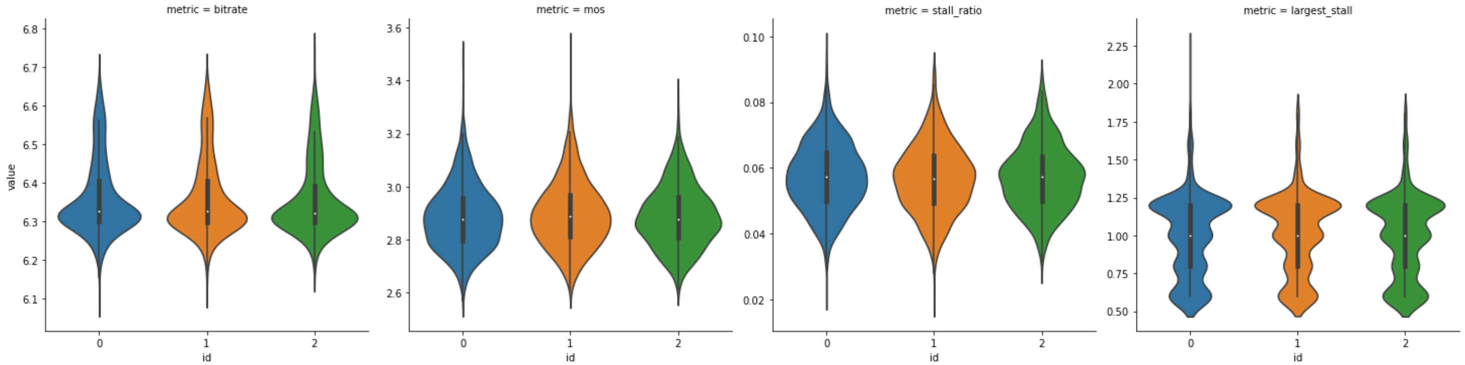
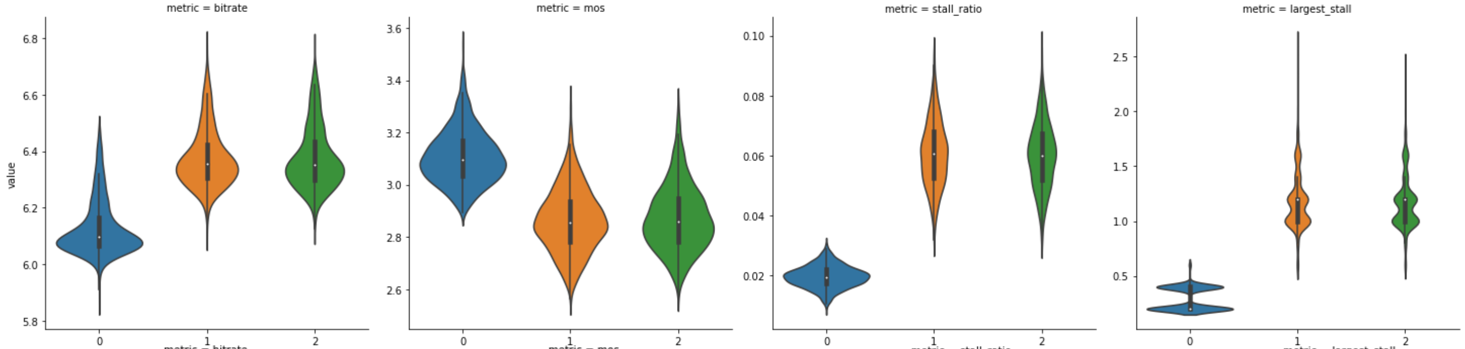
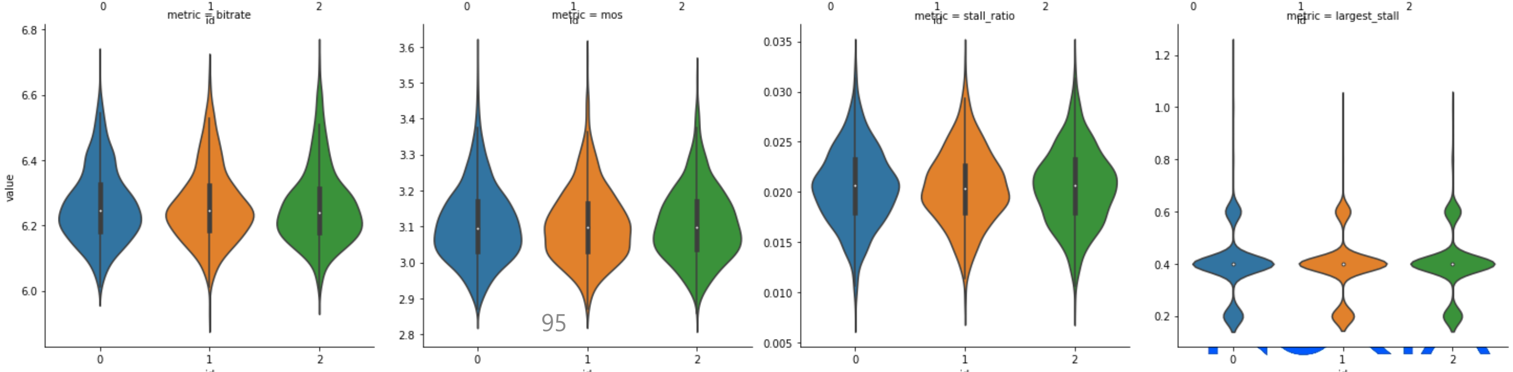
N=3
NQoE=0




N=3
NQoE=1




N=3
NQoE=3

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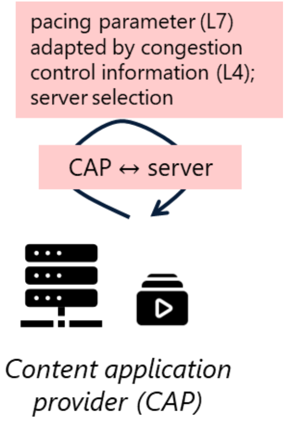
# Server Pacing and ABR Integration for Video Streaming




- Traditional streaming causes bursty traffic
  ➔ packet loss, delays, and unfair bandwidth use.
- Idea of application-informed pacing system for QUIC
  - letting ABR algorithms set maximum packet rates.
  - jointly optimizes video quality and pacing rate.
  - smooths traffic, reduces network strain, and improves user experience.

- Example: Sammy Algorithm and Netflix Production Results
  - 61% reduction in peak chunk throughput
  - 35% fewer retransmissions
  - 14% lower Round-Trip Time (RTT)
  - VMAF stays similar with and w/o Sammy

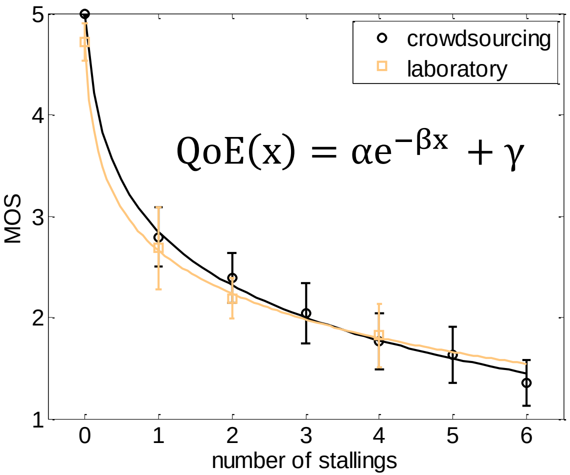
B. Spang, S. Kunamalla, R. Teixeira, T.-Y. Huang, G. Armitage, R. Johari, and N. McKeown, "Sammy: Smoothing video traffic to be a friendly internet neighbor," ACM SIGCOMM 2023 https://doi.org/10.1145/3603269.3604839

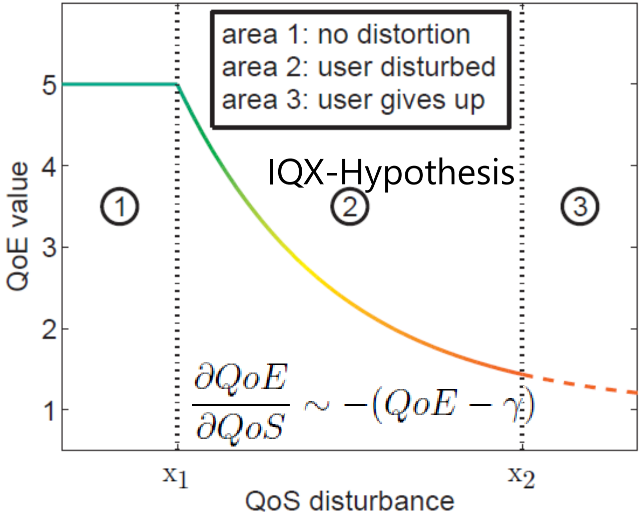
# What is the influence of stalling on YouTube QoE?

- Small number of interruptions strongly affect YouTube QoE

➔ Provider (i.e. content and network provider) **must avoid stalling**

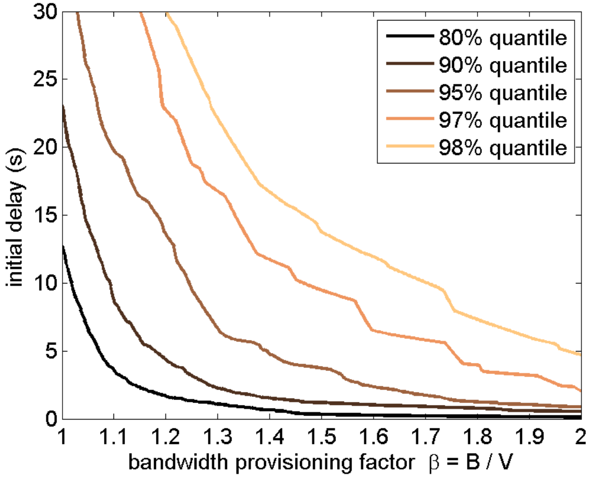
| | | |
|---|---|---|
| 5 | Excellent | Imperceptible |
| 4 | Good | Perceptible |
| 3 | Fair | Slightly annoying |
| 2 | Poor | Annoying |
| 1 | Bad | Very annoying |



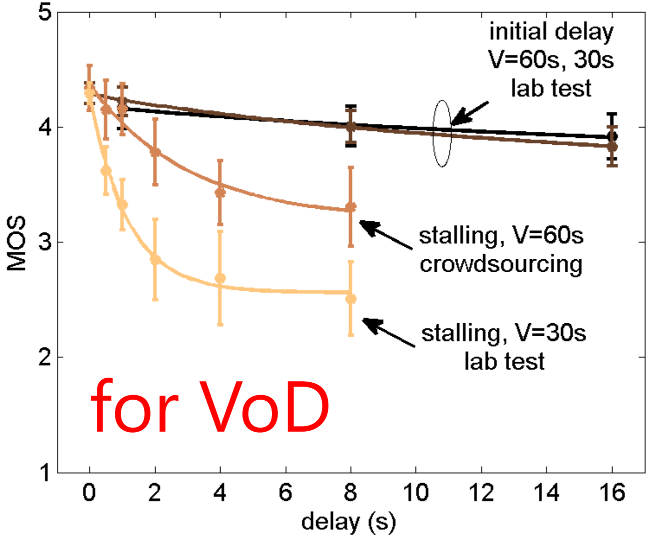



# Provider: In Case of Insufficient Resources?

User QoE




Operator costs




*User and client device*

*Content application provider (CAP)*

app: prefetching of segments & media; request prioritized delivery of segments (CMCD); adaptive bitrate (ABR) mechanisms triggered by app state (player buffer), network signals, context factors (device); send QoE and KQI measurements;

device ↔ CAP

CAP: pacing on application level (L7), adaption of congestion control (L4), server caching (CDN)

- Delivering videos with about 120% of video bitrate as “rule of thumb”

# GUIDELINES TO HANDLE QOE IN TELECOMMUNICATION NETWORKS

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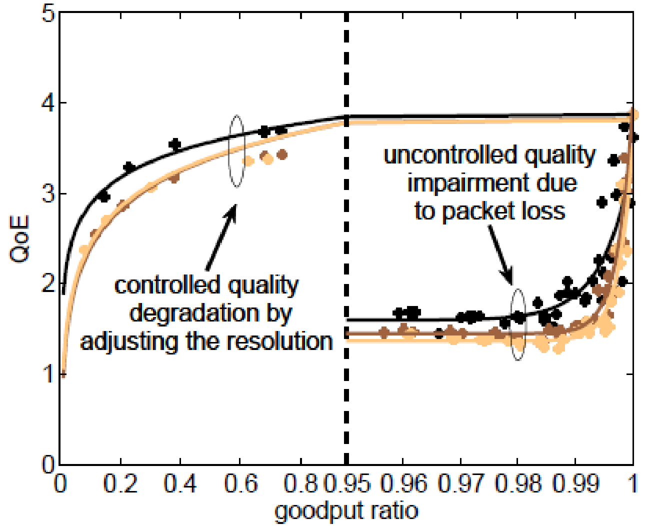
# QoE Provisioning – Delivery Hysteresis




- Different impacts of
  - a) provisioning and
  - b) success or failure

  in delivery on QoE

- **QoE Provisioning-Delivery Hysteresis** captures the phenomenon where controlled resource reductions (provisioning) impact QoE far less severely than uncontrolled delivery failures (e.g., congestion losses).
  - QoE differences between a) resource limitation and
  - b) service disruption effects.

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# Guidelines to handle QoE in telecommunication networks

YES,

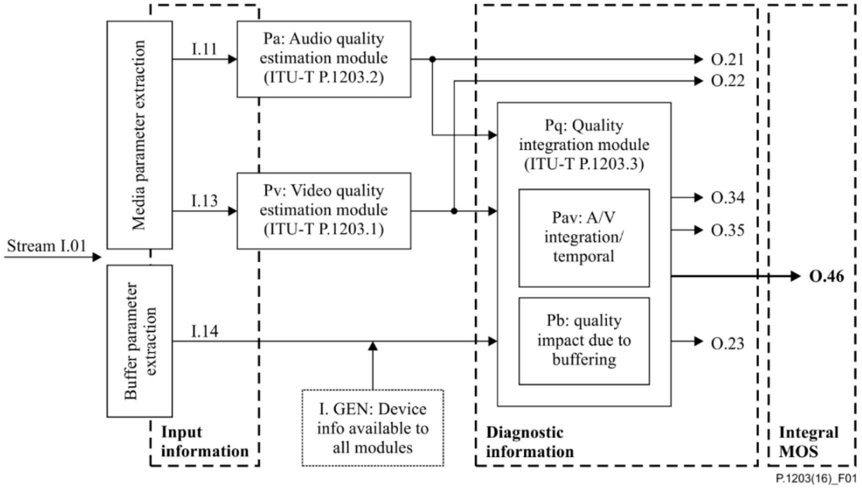



**Figure 1 – Building blocks of the ITU-T P.1203 model**

BUT...

[Tond24]

| Metric M | Metric weight w | Metric values | (ACR) Score (ACRS) |
|---|---|---|---|
| M1: Latency | w1 (0.5) | 50ms | 5 |
| | | 90ms | 4 |
| | | 120ms | 3 |
| | | 130ms | 2 |
| | | 150ms | 1 |
| M2: PER | w2 (0.1) | 10e-7 | 5 |
| | | 10e-5 | 4 |
| | | 10e-4 | 3 |
| | | 10e-3 | 2 |
| | | 10e-2 | 1 |
| M3: PLR | w3 (0.1) | V1 | 5 |
| | | V2 | 4 |
| | | V3 | 3 |
| | | V4 | 2 |
| | | V5 | 1 |
| M4: Jitter | W4 (0.1) | V1 | 5 |
| | | V2 | 4 |
| | | V3 | 3 |
| | | V4 | 2 |
| | | V5 | 1 |
| M5: Avg DR | W5 (0.2) | V1 | 5 |
| | | V2 | 4 |
| | | V3 | 3 |
| | | V4 | 2 |
| | | V5 | 1 |

$$Aggregate\ score\ (AS) = \sum_{i=1}^{5} w_i * ACRS$$

# Design principles to build simple models from the state of the art

- A QoE model must be complete (cover any use case)
- Simple models are preferred
- When we say "QoE" we mean "user-reported QoE"
- QoE is the bridge between QoS and technology acceptance
- Users are robust in judging QoE on ACR scale
- User ratings have ~10% uncertainty
- QoE scores follow a normal distribution with constant variance (this is R scale)
- Context dependency can be approximated by linear mapping (in R scale)
- Single-dimension QoS-to-QoE can be approximated with simple models (in R scale)
- Multi-modal and multi-party QoE can be modeled as independent contributions

# A QoE model must cover all possible use cases coherently

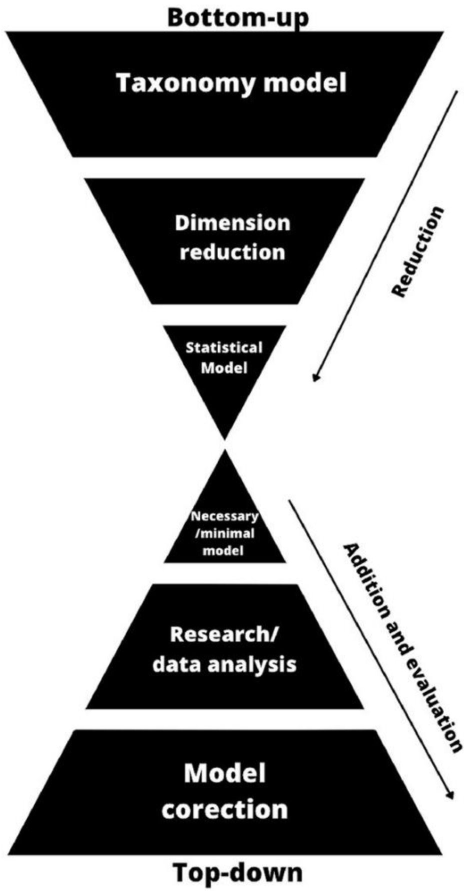
| Category | Type | Example | Usage | Paid |
|---|---|---|---|---|
| Traditional 3GPP Applications | Messaging | SMS and MMS | Business/Personal | Yes |
| | Voice | CS Voice, VoLTE, VoNR and VoWIFI | Business/Personal | Yes |
| Connected Application | Web Browsing | News, eLearning, shopping | Business/Personal | Unlikely |
| | Social Media | X, Facebook, Instagram | Personal | Unlikely |
| | Internet of Things | Wearables, Connected home | Business/Personal | Likely |
| | Online Gaming | Massively multiplayer online games | Personal | Unlikely |
| Real-time Communications (RTC) | Conferencing | WhatsApp, Skype, Zoom, Teams, etc. | Business/Personal | Unlikely |
| | Voice OTT | | | |
| | Messaging | | | |
| Streaming Media | On demand Video/Music | Netflix, Spotify, YouTube, etc. | Personal | Likely |
| | Short form video | TikTok, Instagram Reels | Personal | Unlikely |
| | Live Video/Broadcasting | Live Events (Sport, Music, etc.) | Personal | Likely |
| Immersive Applications | Cloud Gaming | Nvidia, Xbox, Luna, PlayStation, etc. | Personal | Likely |
| | Augmented and Virtual Reality | Industrial Applications | Business | Private |
| File Transfer | Backup, Upgrades and Transfers | Dropbox, Windows Update, SpeedTest, etc. | Business/Personal | Likely |

# Simple models are preferred

- Parsimony: predict as much as possible with as few assumptions and variables as possible

- Top-down model:
  - Emphasize causal relationships among variables
  - Structure QoE experiments
  - Facilitate investigation of causal links

- More info: [Kon24]



# When we say “QoE” we mean “user-reported QoE”

We define **user-reported QoE** as the quantification of the impact of a system on user delight or annoyance, through self-report, behavioral, or psychophysiological studies.

This impact can be caused by the application, network, or hardware and is moderated by the usage context.

Services working as designed have “perfect QoE” → Resource (e.g. bandith) limits impair QoE → QoE as cost function for QoE management

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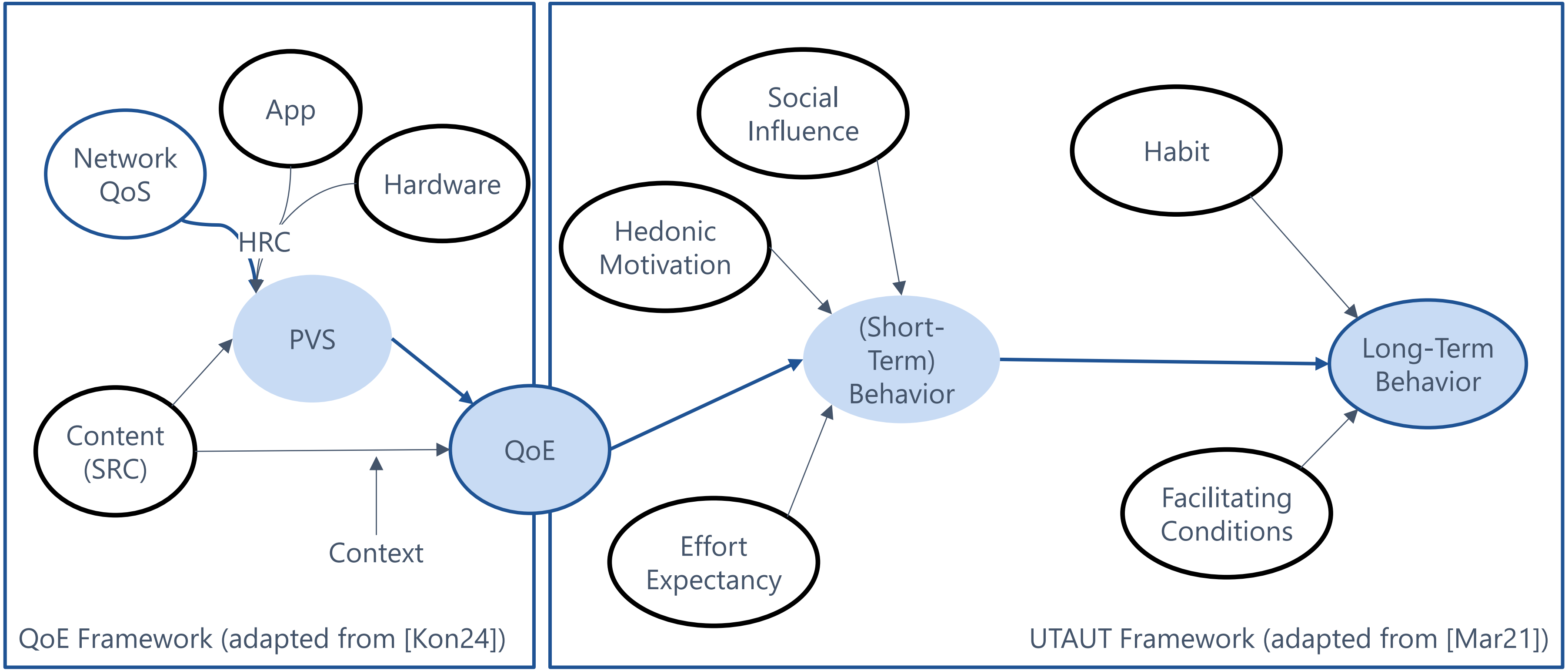
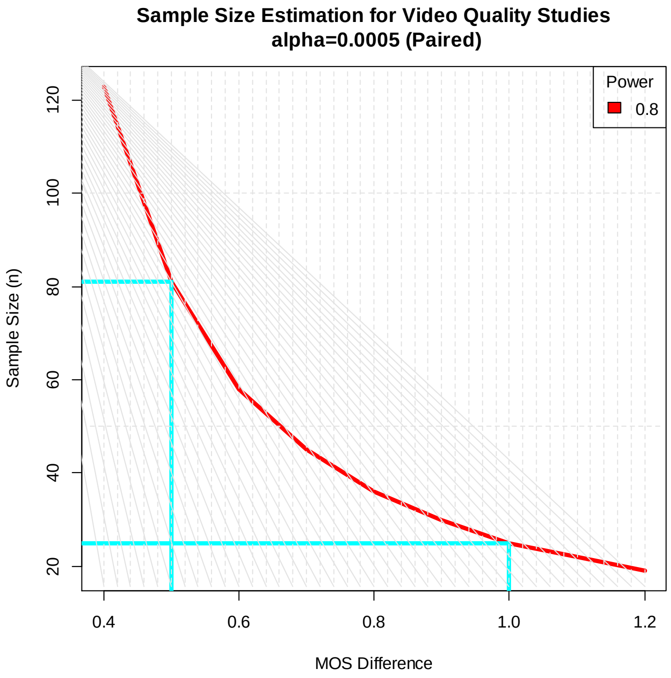
# QoE is the bridge between QoS and technology acceptance



# People are robust in judging the quality on ACR scale


# User-reported QoE metrics have ~10% uncertainty

- Considering a typical case with N=25, and given sigma values around 1, standard error of the mean would be around 0.2, which means confidence intervals about +/- 0.4 around each MOS score (before any adjust for multiple comparisons), which is 10% of the scale spread.




Doing 100 comparisons (~10 points pairwise) requires ~80 samples to discriminate 0.5 MOS differences [Brun17]

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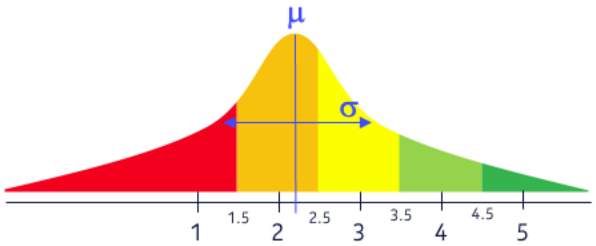
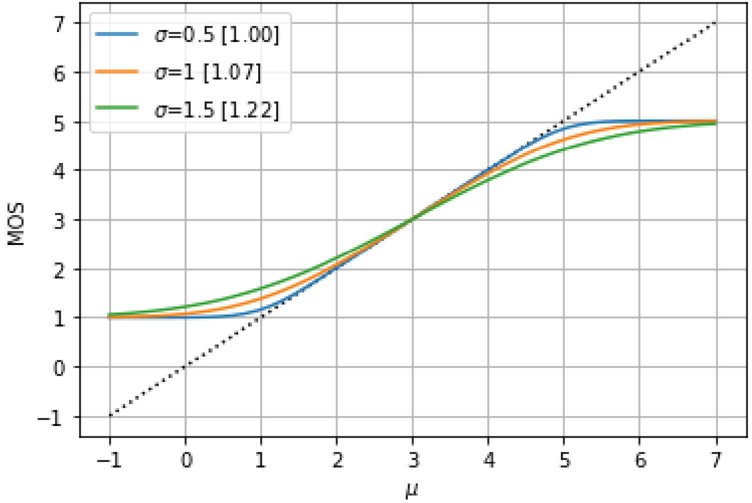
# QoE scores follow a normal distribution with constant variance




$$o_{ie} = \mu_{ie} + \sigma_{ie} X \approx \mu_{ie} + \sigma_e X$$

$$MOS_{ie} = \sum_{j=1}^{5} j P_{je} = 5 - \sum_{j}^{4} E\left(\frac{j + 0.5 - \mu_{ie}}{\sigma_e}\right)$$

- Opinion scores depend on PVS $i$ and context $e$ (there is no “absolute MOS”)
- Constant variance = SOS hypothesis
- MOS, GoB, PoW... obtained from the model



# Context dependency can be approximated by linear mapping in the Transmission Rating scale

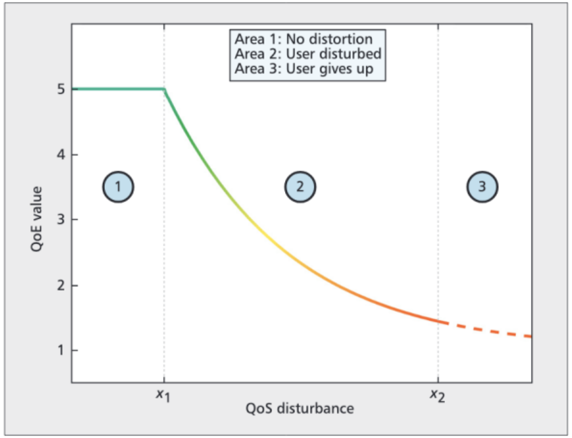
- Linear mapping of quality scores obtained in different contexts $e$ and $e'$ [Per23]:
$$\mu_{e'} = a\,\mu_e + b$$

- Define "reference context" => context-less scores "Transmission Rating" scale ($R$):
$$\mu_e(R) = a_e R + b_e$$

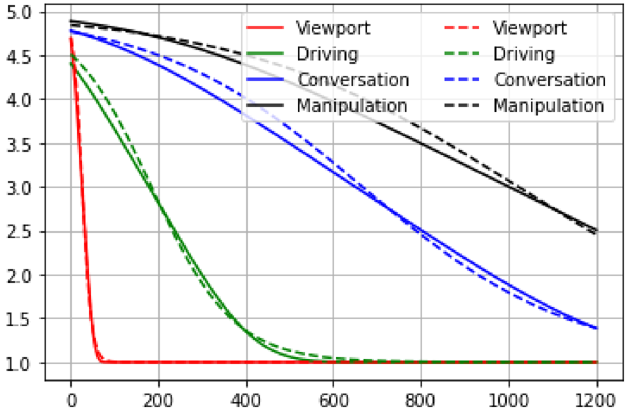
- The original R scale in the E-model ITU-T G.107, where R is roughly equivalent to the attenuation, in dB, of the speech level in analog calls, see [Cav76, Mar31].

# One-dimension QoS-to-QoE can be approx. with simple models

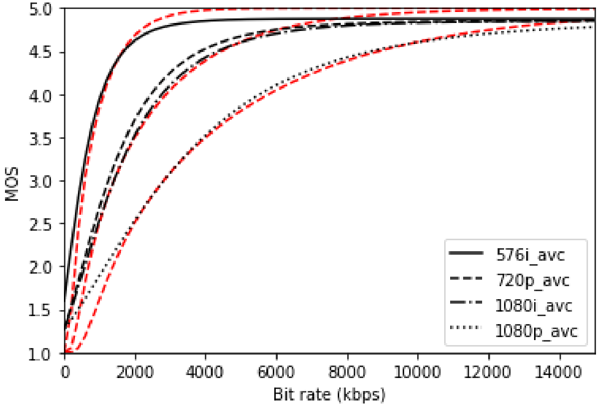
Simple function + Perceptual & Acceptance thresholds + MOS-from-R mapping




Generic QoS-QoE shape
[Fied10]




R = delay(ms)
vs [Cort23]




R = log(bitrate)
vs ITU-T G.1701

- $MOS(R)$ creates logistic shape
- $MOS(R_a) = 3.0, \;\; MOS(R_p) = 4.5$

# Multi-modal and multi-party opinion scores can be modeled as independent contributions

- We can ask people to rate the qualities of different media streams both together and separately

- Media streams can have separate qualities which can be manipulated in experiments separately

- Model can be established by combining single stream qualities

$$MOS(X_1, X_2, \ldots, X_n) = F\big(MOS(X_1), MOS(X_2), \ldots, MOS(X_n)\big)$$

- Effect of impairments in the same media stream is additive in the transmission rating scale [Osa92, Moll00].

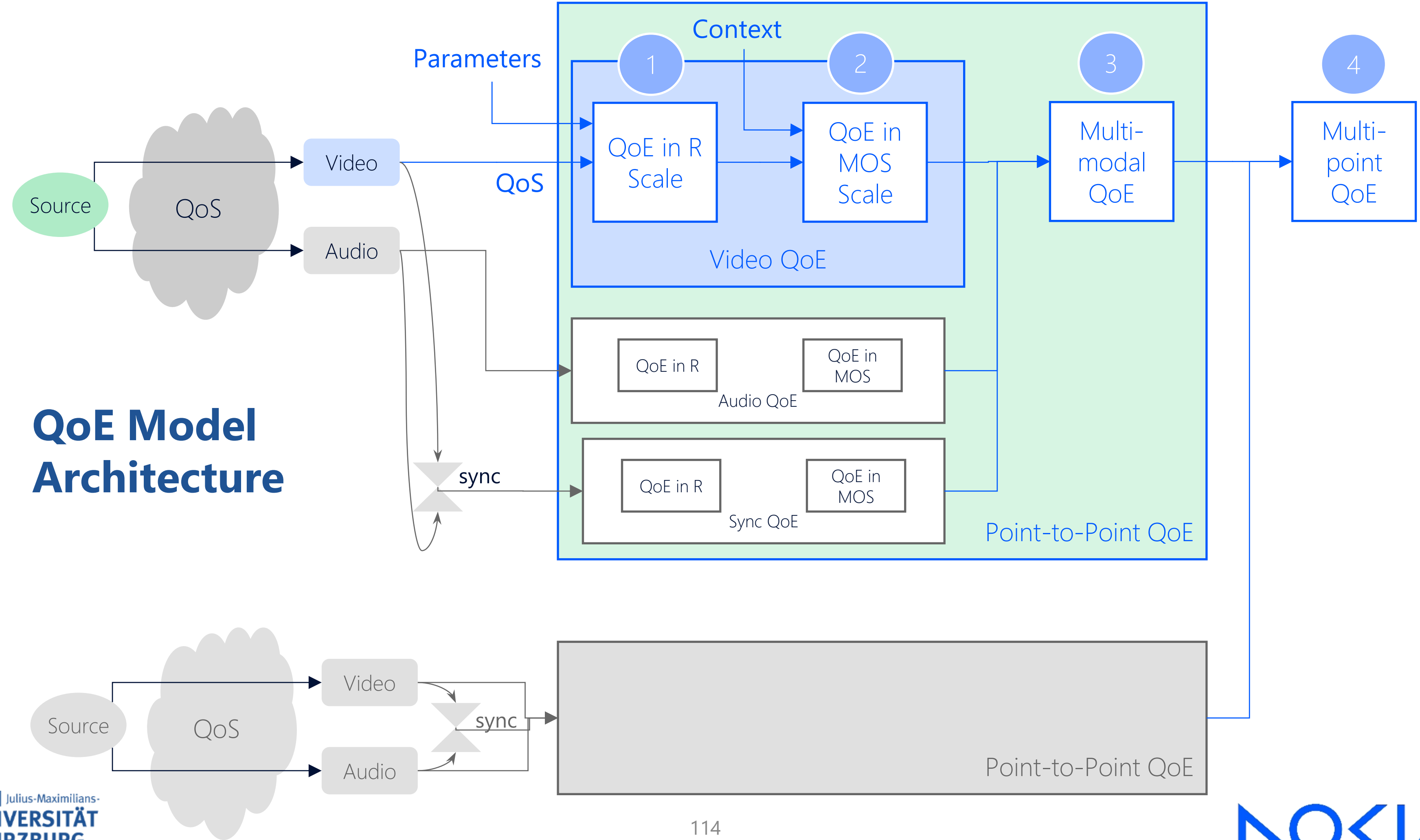
- Effect of video and audio quality integration is multiplicative on the MOS scale [Han04, Pin11, Min20].

# Based on these principles…

- A QoE model must be complete (cover any use case)
- Simple models are preferred
- When we say “QoE” we mean “user-reported QoE”
- QoE is the bridge between QoS and technology acceptance
- Users are robust in judging QoE on ACR scale
- User ratings have ~10% uncertainty
- QoE scores follow a normal distribution with constant variance (this is R scale)
- Context dependency can be approximated by linear mapping (in R scale)
- Single-dimension QoS-to-QoE can be approximated with simple models (in R scale)
- Multi-modal and multi-party QoE can be modeled as independent contributions

**…let’s build a QoE model**

# QoE Model Architecture

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# Computation of MOS for each stream

1. If MOS/R model available (e.g. VMAF), use it.
2. If needed, adapt context

   Computation of μ(R) is a linear transformation:

   $$\mu = \frac{\mu_p - \mu_a}{R_p - R_a}(R - R_a) + \mu_a$$

   Where $R_p$ and $R_a$ are the perception (e.g. MOS=4.5) and acceptability (e.g. MOS=3) thresholds of R.

3. If no model, create simple one
   - QoS to QoE mapped
     – In R domain, not in MOS domain.
     – Simple functions (linear, exponential, logarithmic...).
   - R to MOS
     – Based on acceptance and perception thresholds.
     – Strongly dependent on the context and on the content.

# Aggregation of individual scores

- Aggregation of multi-modal and multi-source QoE is done with a weighted Minkowski mean:

$$M_{p(x_1,\dots,x_n)} = \left(\frac{\sum_{i=1}^{n} w_i x_i^p}{\sum_{i=1}^{n} w_i}\right)^{\frac{1}{p}}$$

- When p=0, it is equal to the weighted geometric mean

$$M_{o(x_1,\dots,x_n)} = \left(\prod_{i=1}^{n} x_i^{w_i}\right)^{1/\sum_{i=1}^{n} w_i}$$

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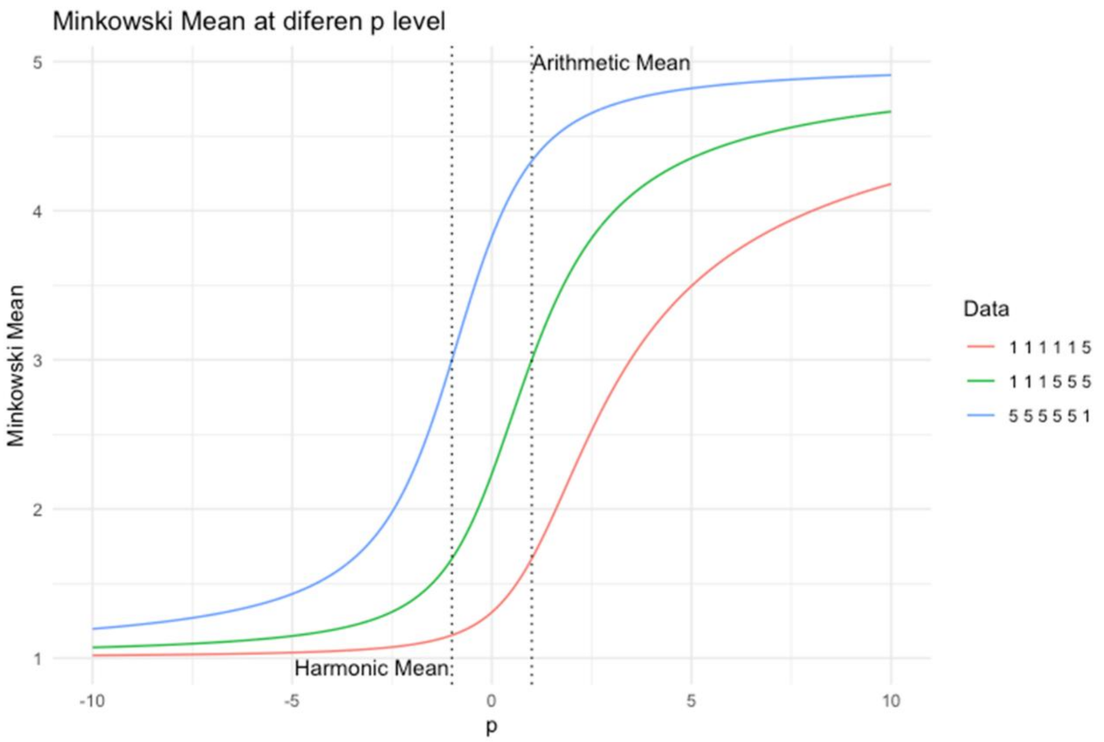
# Weighted Minkowski Mean

- *p* determines how the lowest scores contribute to general QoE score.

- With low p value only one low score can make the model prediction low, even if the rest of the qualities are acceptable.



# Calibrating model parameters

- Subjective assessment tests done for each module independently. This way, subjective tests will manipulate the bare minimum number of independent variables to obtain a result.

- Subjective tests should use using ITU-T P.910.

- ITU-T P.910 defines the FOWR protocol, which allows a small number of users (4 to 6), which may be experts, to perform an assessment, and repeat the test 4 or 5 times in different days.

# Model provides instant QoE for a single user (= receiver)

- Pooling across different users → System QoE
  - See [Hoss20].

- Pooling along time → account for recency, peak effects, etc.
  - See [Seu13]
  - But also: asking QoE at the end is not a neutral decision!, see [Ord22]

# Key advantages

- Explainable
  - All parameters are understandable by design
  - MOS model as proxy for other QoE parts

- Modular
  - Integrate good models with 1st order approximations
  - Each module is optimized independently
  - Re-use of already done work

- Actionable
  - Contribution of each media stream is handled separately

# QoE models in practice - bibliography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# Part 4: VQEG Whitepaper on QoE Management and Open Discussions (20min)

Participation and joint efforts: VQEG Whitepaper.

Open discussions.

# VQEG – A Brief History

- Formed in 1997 to advance the field of video quality assessment

- Closely related to ITU-T and ITU-R study groups
  - ITU-T SG9 (Broadband cable & TV)
  - ITU-T SG12 (Performance, QoS and QoE)
  - ITU-R WP6C (Programme production and quality assessment)

- Historically, a primary focus on:
  - Creation of test plans to develop and validate objective quality metrics
  - Particular focus on defining the scope and subjective test methodology
  - Statistical techniques for assessing model performance
  - → recommending approaches/models to be standardized by ITU-R/ITU-T

- Today: open discussion fórum between academia and industry

# What is great about VQEG

- Free to join — no membership fees
- No strict or complicated rules
  - Consensus is often reached without lengthy voting procedures
- Simple organization and hierarchy
  - Chairs & co-chairs for different projects
  - Anyone can propose or contribute a new project
- Highly interactive meetings
  - Anyone can present their ideas
  - Focus on discussion time
- Not a commercial venue
  - No sales talks, no commercial advertising
- Mixture between academia and industry

# VQEG 5GKPI Working Group

- Goals:
  - Defining use cases for video in 5G
  - Studying QoE aspects for video in mobility and industrial scenarios
  - Identifying the relevant network KPIs and application-level video KPIs (e.g. picture quality, A/V sync, …)
  - Building open datasets for algorithm testing and training
- Recent highlights:
  - ITU-T Technical Report GSTR.5GQoE (2022): Specific QoE requirements and required performance and features from the network

# Current Focus: towards 6G

## Current status: missing visibility

- Operators are missing visibility on content quality
- CAP lacks visibility on network status

## Use cases: today and future

- Today: streaming + video calls
- Future: XR, tele-operation…

## What can VQEG do?

Identify relevant QoE-QoS activities (ITU-T, VQEG, NGMM, TIP, IETF, 3GPP…)

Organize colaboration between operators – content providers - vendors

Agree on a common language for QoS and QoE in networks

Propose an approach to model QoS/QoE relation

Define a framework for QoE management

# VQEG Whitepaper on QoE Management in Communication Networks

Pablo Pérez, François Blouin, Kjell Brunnström, Pablo Rojo, Marta Orduna, Ioannis Katsavounidis, Balu Adsumilli, Neil Birkbeck, Theo Karagioules, Emir Halepovic, Jesús Folgueira, Luis Miguel Contreras, David Lindero, Werner Robitza, Michele Zorzi, Federica Battisti, Sara Baldoni, Alexander Raake, Rakesh Rao R, Tobias Hoßfeld, Narciso García, Kamil Koniuch, Markus Fiedler, et al., *in preparation*.

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# Vision

- More efficient end-to-end video delivery
- Identify and solve the problems seen by the customers
- Ecosystem win-win approach CAP/CSPs/Users
- Overcome lack of trust and enhance cooperation among stakeholders
- North Star: Develop QoE/QoS models and framework for QoE management in 5G-advanced/6G.

# Issues and Gaps

- **CAP Perspective**
  - Determining Network State: Capacity/Congestion → Leads to stalls, poor ABR choices.
  - Predicting Network Dynamics: Variability → Stalls, retransmissions, data waste.
  - Understanding Subscriber Context: Data plans/limits → Potential overage or unnecessary throttling.
- **Opportunities via exchange**: Improved bandwidth estimation, better ABR tuning, optimized prefetching/buffering, efficient data usage.

- **CSP Perspective**
  - Diverse Requirements: Complexity in policy design, mapping QoS fairness to QoE fairness.
  - Lack of QoE Information: Limits utility of QoS frameworks (e.g., 3GPP QCI), relies on inaccurate inference.
  - Lack of Real-Time QoE Feedback: Missed opportunities for proactive optimization beyond basic KPIs.
- **Opportunities via Exchange**: Targeted QoS/QoE policies, accurate traffic handling, informed network monitoring/tuning , real-time QoE-aware actions.

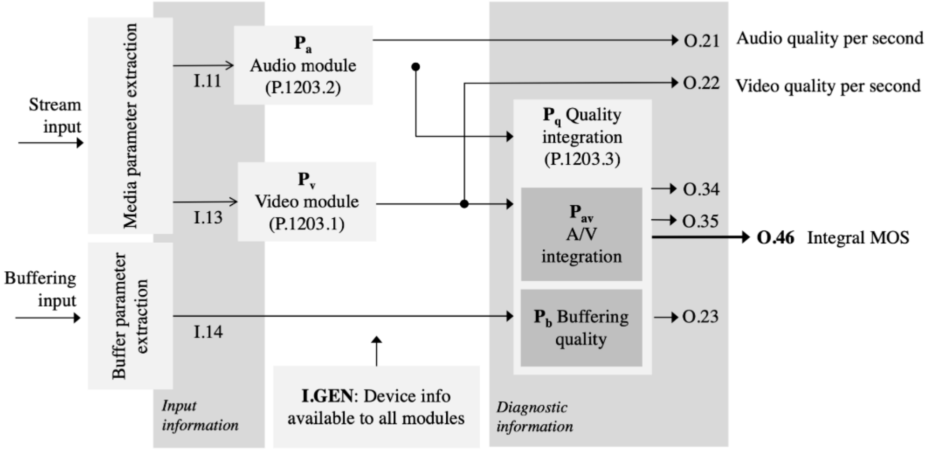
# Layered Approach

| Layer | Information |
|---|---|
| **System Layer** | **System QoE:** QoE of a group of users of a particular service or system<br>**System QoE Metrics**: Expected system QoE, System GoB, System PoW, QoE Fairness |
| **Layer 8: User Layer** | QoE scores based on<br>- subjective ratings (**self-reported QoE**), e.g. MOS = average of opinion scores, e.g. GoB = Prob(„Good-or-better“) or<br>- QoE models (**modeled QoE**) mapping KQIs and KPIs to modeled QoE metrics, e,g. MOS = function(KQIs, KPIs) |
| **Layer 7: Application Layer** | Key Quality Indicators (**KQIs**), for example,<br>Video streaming: rebuffering ratio, video quality, reception ratio<br>Web browsing: page load times, speed index |
| **Layer 1 – 4: Network Layers** | Key Performance Indicators (**KPIs**): measures on physical (L1), link (L2), network (L3), transport layer (L4) and potentially aggregated into KPIs<br>L4: TCP goodput or throughput, and variability thereof (i.e. jitter)<br>L3: IP packet loss ratio<br>L2: Collision Rate, Frame Error Rate<br>L1: Signal-to-Noise Ratio (SNR) |

# Proposed Framework – Shared State Table

- Scope:
  - Video (short/long form)
  - Conferencing/interactive services
- Core Idea: Logical shared view of QoS/QoE status between CAP & CSP.
- Mechanism:
  - Maintains continuous state (potentially divergent views of same params like BW).
  - One-way updates on state changes (more efficient than request/response).
  - Implementation potential: Side-channel, metadata exchange (e.g., via NWDAF).

**Leverage existing models** for semantics: e.g., use ITU-T P.1203 structure as a template for needed information types like "per-second video quality".



# General Components & Shared Metrics

- Common QoE components across services:
  - Media Fidelity (visual/audio quality)
  - Media Delivery Continuity (stalls, freezes, drops)
  - Media Delay & Interactivity (latency, responsiveness, startup)

**CAP Provided**

- Current Quality (Video/Audio/Stall scores)
- Cost Function (Rate-Distortion curve, Qmin/Rmin, Qmax/Rmax)
- Metadata (codec, bitrate, …).

⟷

**CSP Provided**

- Network State (Congestion level, ECN)
- Subscriber Entitlement (Policy Rate Limits)

# Discussion

- Which are the main benefits of adopting a common QoE management approach between CAPs / CSPs?
- Which are the barriers or limitations that may prevent it to succeed? How to overcome them?
- Which are the use cases and scenarios that should be covered?
- Would you like to join VQEG ☺?

# Quality of Experience in Telecommunications: theory, fundamentals, application guidelines

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