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Quality of Experience in Networking

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Thanks giving to many colleagues

- *The material presented in these slides is partiallty taken from the work done by Dr. Raimund Schatz @FTW*

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Outline

- **What is QoE?**
  Origins, definitions, differentiation from QoS
- **How to measure QoE?**
  How to assess QoE with(out) users?
- **How do QoS and QoE relate to each other?**
  Fundamental relationships, results from existing studies
- **What does QoE mean in the context of Web traffic?**
  Quality in the context of web browsing, file downloads, etc.
- **Other Applications of QoE**
  Cloud QoE, QoE in YouTube, QoE Monitoring, QoE @smartphones

Background: From QoS to QoE

A Brief History of Service Quality

- Early definitions of Quality-of-Service (QoS)
  - *"collective effect of service performance which determines the **degree of satisfaction of a user** of the service"* [ITU-T Rec. E.800, 1994]
  - *"used to define the network's **capability to meet the requirements of users** and applications"* [Kilkki, 1999]
- 10 years later…
  - *"ability of the network to **provide a service at an assured service level**"* [Soldani, 2006]
  - *"capability of a network to provide better service to selected network traffic … **described by the following parameters: delay and jitter, loss probability, reliability, throughput and delivery time**"* [Markaki, 2007]

→ A slow shift from a user to a technology focus …

From Quality of Service ...

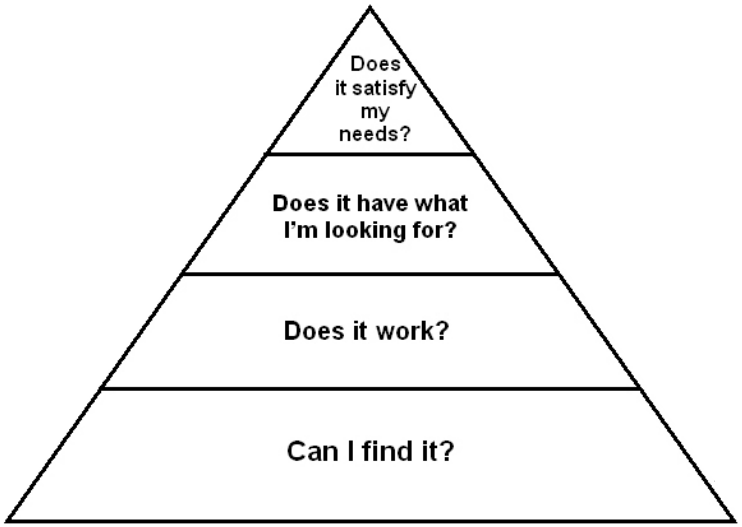
- Observation: original notions of QoS strongly refer to user perception

- However: since then, work on QoS has focused more on **technical performance parameters** than service quality itself

JITTER BIT-RATE

DELAY PACKET LOSS PACKET-ERRORS = QoS = Quality?

BUT: does this approach adequately reflect the needs of end-users (= us)?



… towards an Anti-Copernican Revolution!

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Quality:

= *"Result of appraisal of the perceived composition of the service with respect to its desired composition."* (ITU-T Rec. P.851, 2003, following Jekosch, 2000, 2005)

→ Requires perception and judgement (by someone)!

Industry force: intensifying competition in communication service markets

→ Customer perception and judgement becoming increasingly important!

Resulting insight:

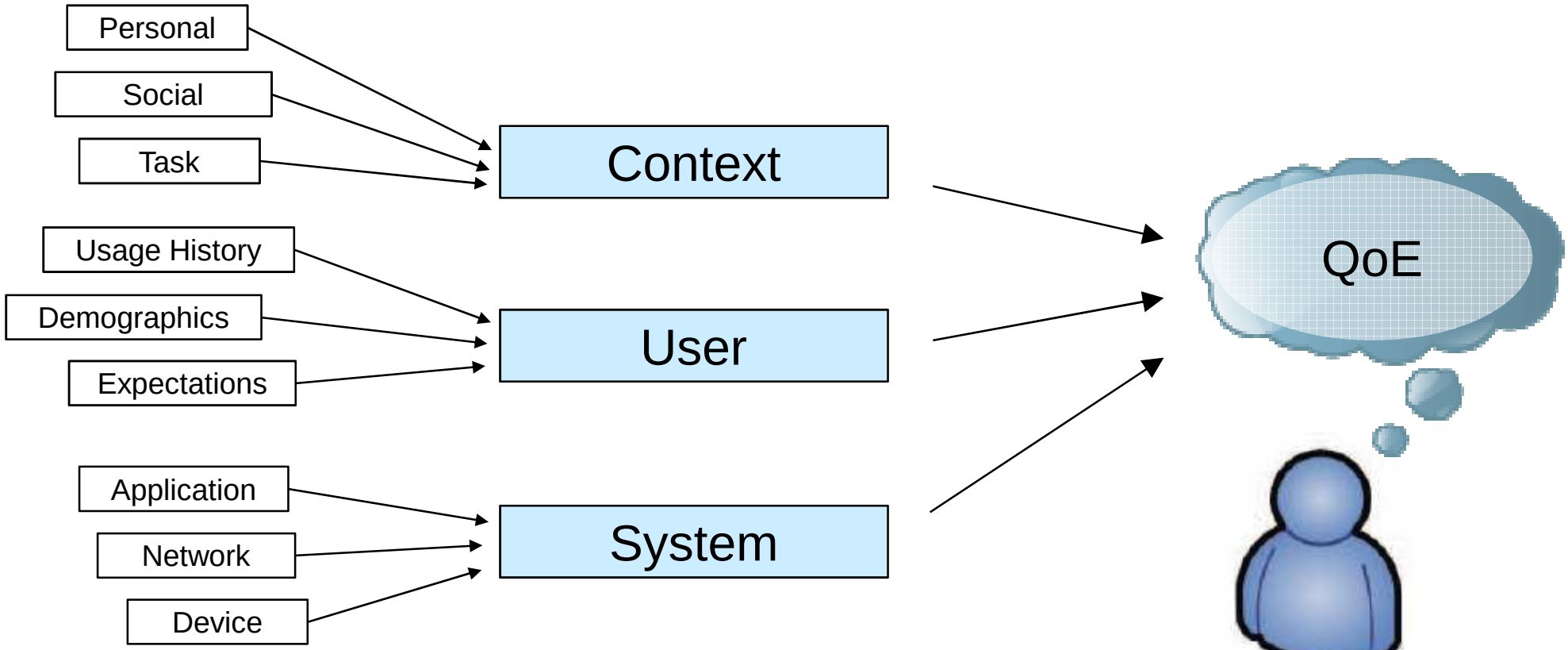
Sometimes it pays off to consider the **human being** as center of the universe …

→ **Perceived QoS, end-user QoS, etc.**

→ **Quality of Experience (QoE)**

QoE: ITU-T Definition (most widely used)

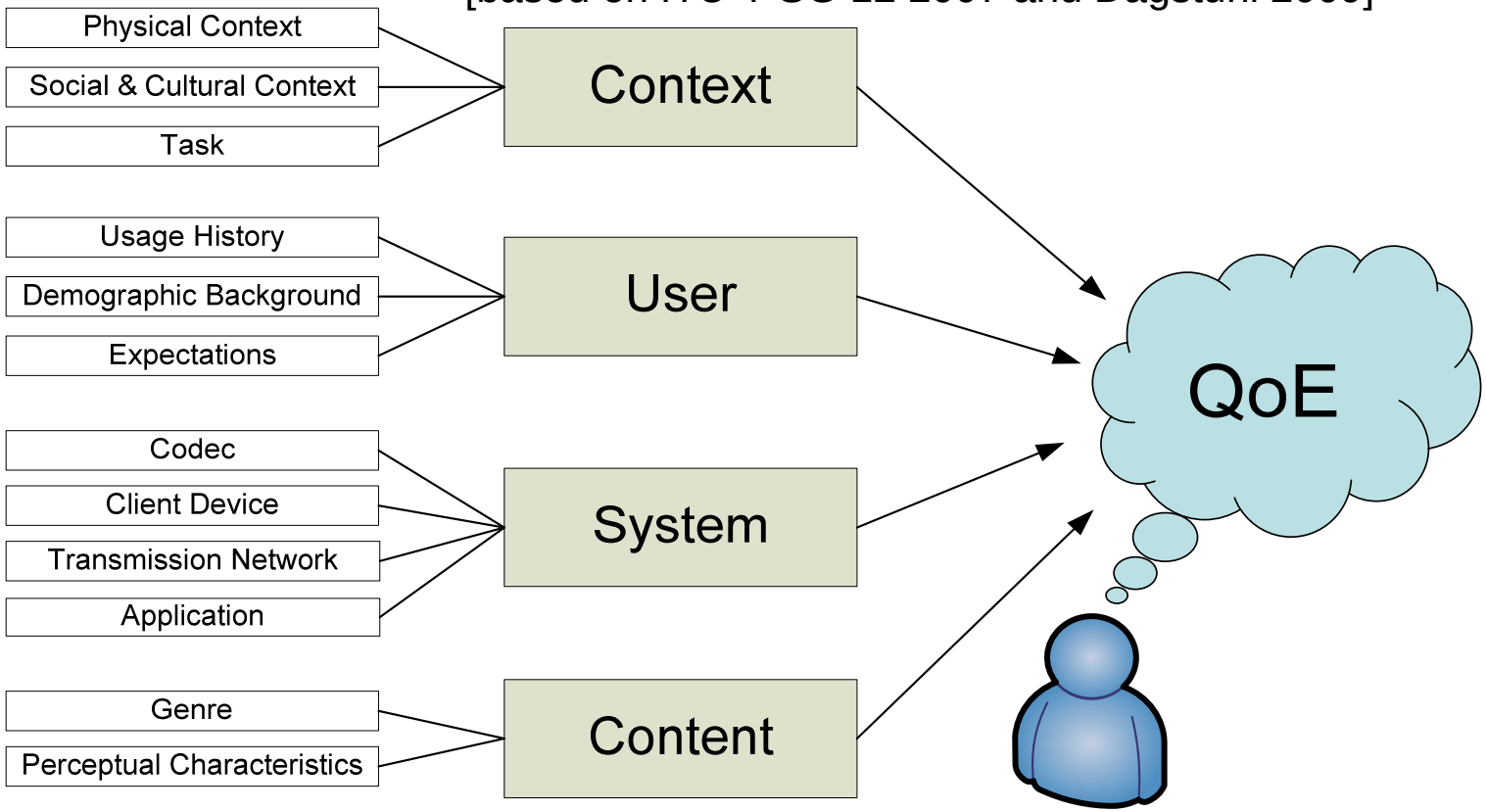
"Overall acceptability of an application or service as perceived subjectively by the end-user …
… includes the complete end-to-end system effects …
… may be influenced by user expectations and context."
[ITU-T SG 12, 2007]



BUT: Has some weaknesses → Scientific community not satisfied …

QoE: A More Evolved Definition

"Degree of delight 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."
[based on ITU-T SG 12 2007 and Dagstuhl 2009]



Still not satisfying → Evolution still in progress …

Distinguishing QoE from QoS

QoS

- **Technology –driven**: focuses on the physical elements of the experience, essentially the network notably bit-rate, loss rate, jitter, delay, etc.
- Involves the user – if at all - only at a **basic, common level**, notably in his/her anatomical dimension as an end-point of a delivery chain
- Mostly only one **single quality dimension** is typically involved, e.g. signal fidelity
- No usability, no utility, no emotions

QoE

- **User-driven**: takes into account **more quality dimensions**, notably associated to the user (e.g. preferences, emotions, personal needs, goals), device/user interface and context (social, environmental)
- Targets complex, **end-to-end** systems/services where the users play a major role in shaping the experience
- QoE assessment needs to be **multi-dimensional and multi-sensorial**
- Effectiveness, efficiency, utility
- Service usable? Useful? Evokes emotions?

QoS vs. QoE: Typical Measures

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QoS

- Bandwidth
- Bit Rate
- Delay
- Jitter
- Loss Rate
- SNR, PSNR
- …

QoE

- Responsiveness, Promptness
- Interactivity
- Availability
- Resilience
- Task completion
- Acceptability
- Fatigue, Tiredness
- Satisfaction
- Delight, Annoyance
- Joy
- …

The Field: QoE Research & Applications

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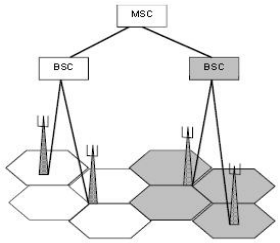
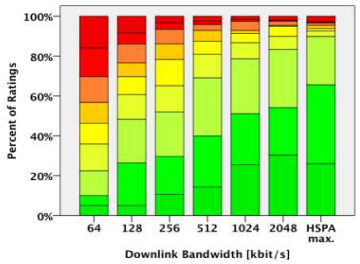
Analyze

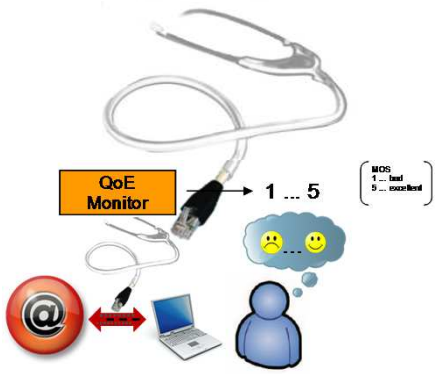
Predict

Control

- Fundamental relationships and data on quality perception
  - QoE as f(System, User state, Content, Context)
  - Law of Weber-Fechner, IQX Hypothesis, etc.
- Guidelines for
  - Network planning and parametrization
  - Application, service or algorithm design
- QoE Models and Metrics for
  - Predicting QoE based on technical measurements
- QoE Measurement/Prediction Systems for
  - Monitoring and documenting health of system/network based on user-centric KPIs (e.g. picture quality)
- QoE-centric Network Management in order to
  - Ensure optimal end-user experience in economic ways
  - Distribute resources fairly among users







From QoS to QoE: Summary

QoE …

- … is a broad multidisciplinary field of growing interest
- … is about appraising services (and their delivery) from the user's perspective → a holistic and user-centric approach towards quality

BUT:

- QoE is a subjective, multi-faceted concept that lacks precise boundaries
- There is still no generally agreed (or: 100% satisfying) definition of QoE – including what it is and how to measure it.
- Human quality perception is highly complex, subjective and context-dependent

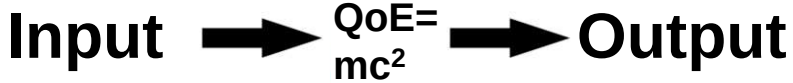
→ These issues turn QoE measurement into a challenge!

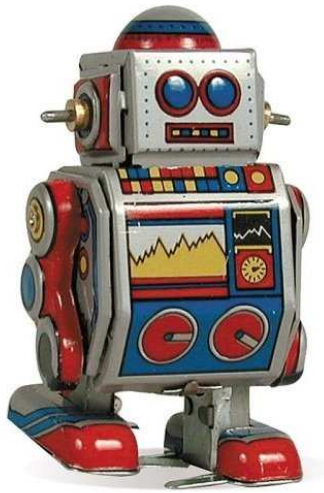
Measuring QoE

How to Measure QoE?

- Subjective QoE Assessment
  - Based on end-user involvement
    - Subjective measures: e.g. user opinion, ratings
    - Objective measures: e.g. task performance, behavior

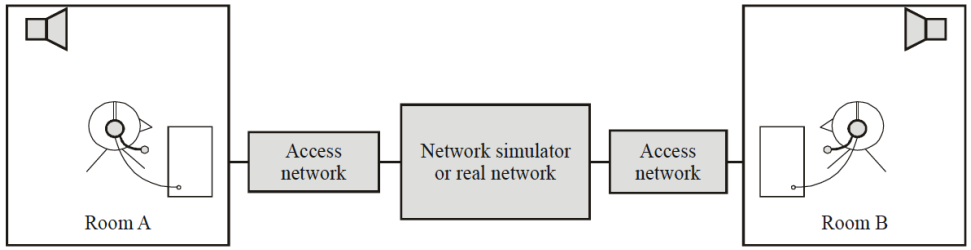
- „Objective“ QoE Prediction
  - Based on analytical/statistical models
  - Translate input parameters to estimated QoE





Subjective Testing: Degrees of Freedom

- Variables
  - Which ones to manipulate, control, observe or ignore?
    → Avoid unintended influences from QoE factors on results
- Subjects
  - Naïve or Expert?, N=?
- Instructions
  - Which questions to ask subjects and how
  - Training
- Presentation
  - Single or double stimulus, sequential or simultaneous?
- Grading scale
  - Numerical, Categorical? MOS?



→ Methodologies are rooted in several disciplines: HCI, UX, Quality assessment Psychology, Sociology, etc.

Key Subjective Measure: MOS

- **M**ean **O**pinion **S**core
- Widely used in many fields:
  - Politics/Elections
  - Marketing/Advertisement
  - Food industry
  - Multimedia

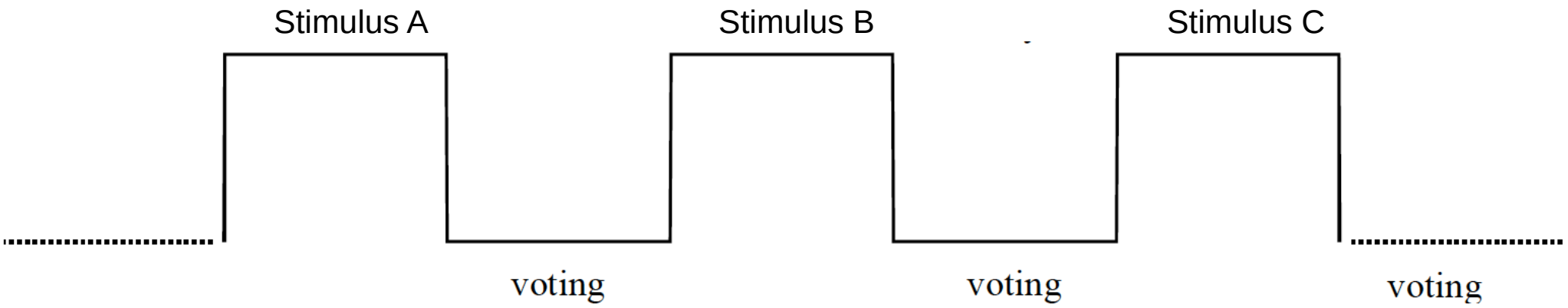
MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

- MOS = The likely level of satisfaction with a service or product as appreciated by an average user
  - Example question: “How would you rate the audio quality of this clip?”
- Challenge: test design that generates reliable and reproducible results
  - Implementation more complex and difficult that it seems *a priori* (WYAIWYG problem: what you ask is what you get)

Scaling: ACR (Absolute Category Rating)

- Discrete
- Single stimulus
- Multiple dimensions addressable
- Usually 5-point scale, but can also be 7-, 9-, or 11-point

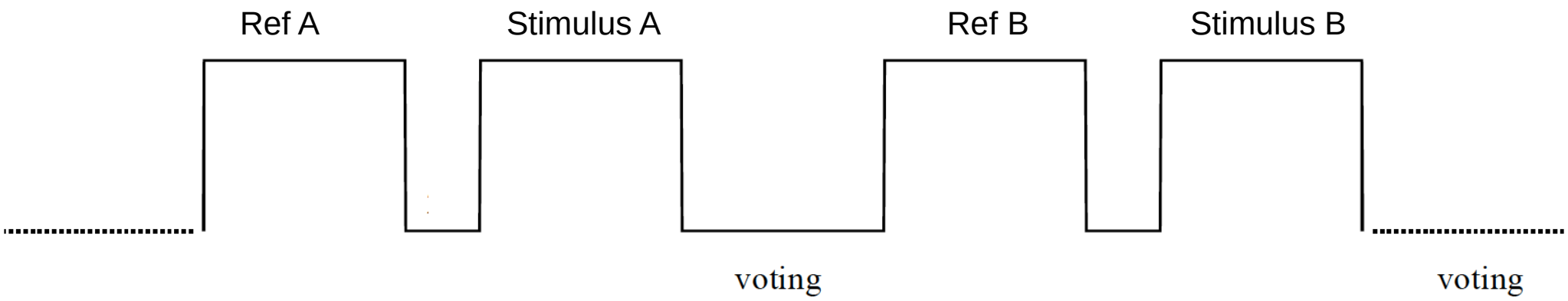
ACR	
5	Excellent
4	Good
3	Fair
2	Poor
1	Bad



Scaling: DCR (Degradation Category Rating)

- Discrete
- Paired Comparison → Relative
- Reference vs. processed sample
- Highly sensitive

DCR	
5	degradation is not perceivable
4	degradation is perceivable but not annoying
3	degradation is slightly annoying
2	degradation is annoying
1	degradation is very annoying



MOS Data Analysis and Reporting

- Mean Opinion Scores (MOS) and confidence intervals

$$MOS_j = \frac{\sum_{i=1}^{N} m_{ij}}{N}$$

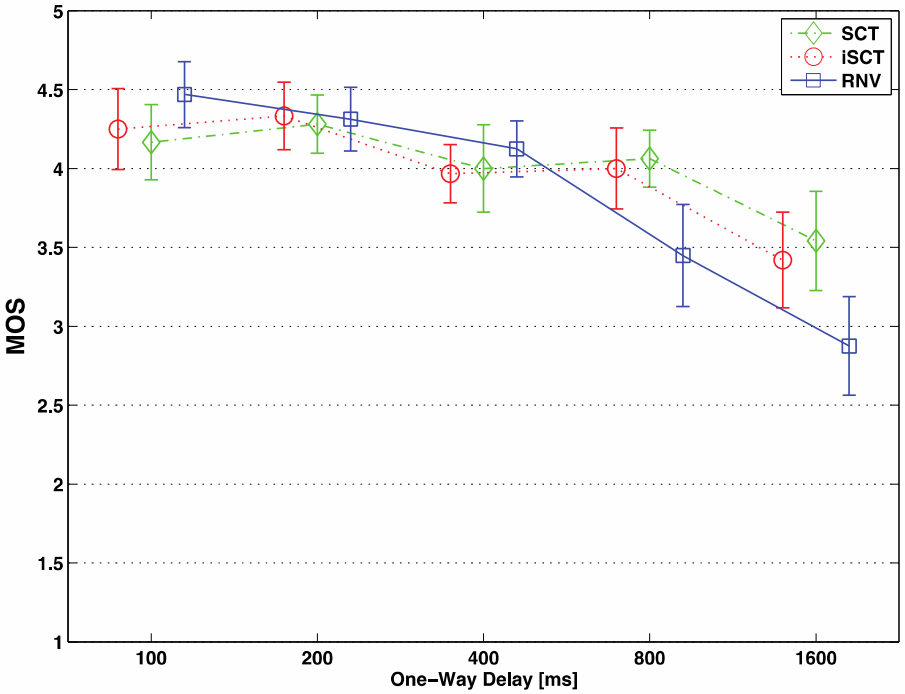
$$CI_j = Z \cdot \frac{\sigma_j}{\sqrt{N}}$$

m_{ij} = score by subject *i* for test condition *j*.

N = number of subjects after outliers removal.

Z = z-value for required confidence level (1.96 for 95%).

σ_j = standard deviation of the scores distribution across subjects for test condition *j*.

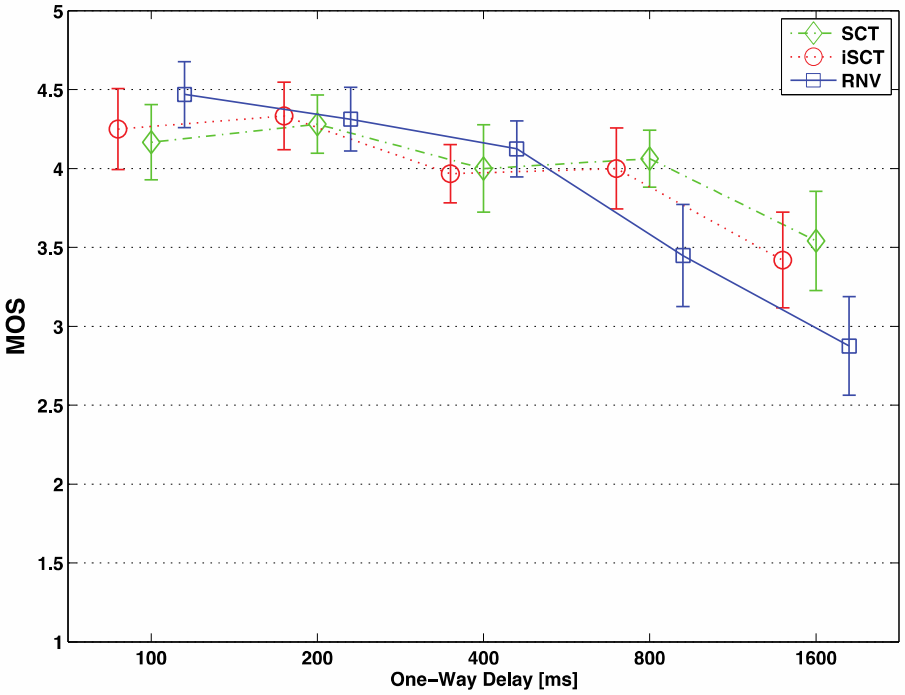


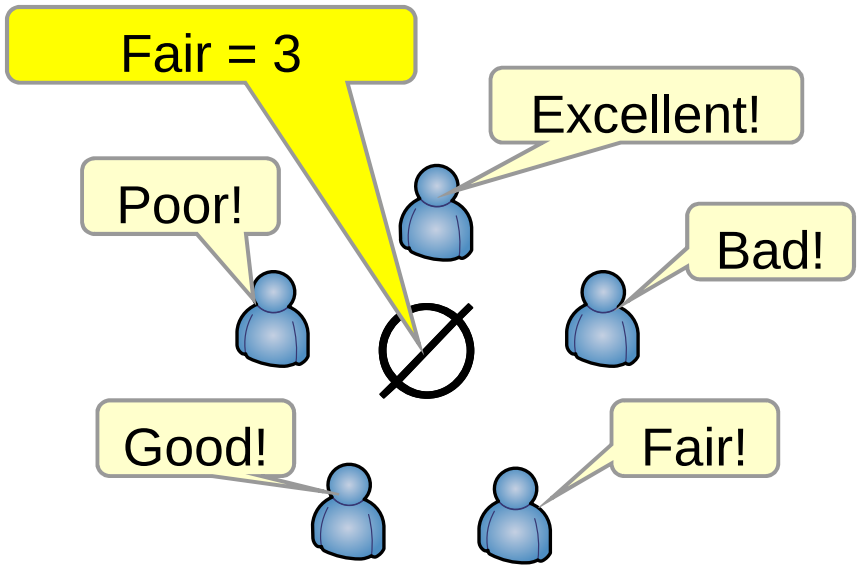
MOS Data Analysis and Reporting, ctd.

Note: MOS by itself only reports an *average* opinion

BUT: subjects seldom all rate the same

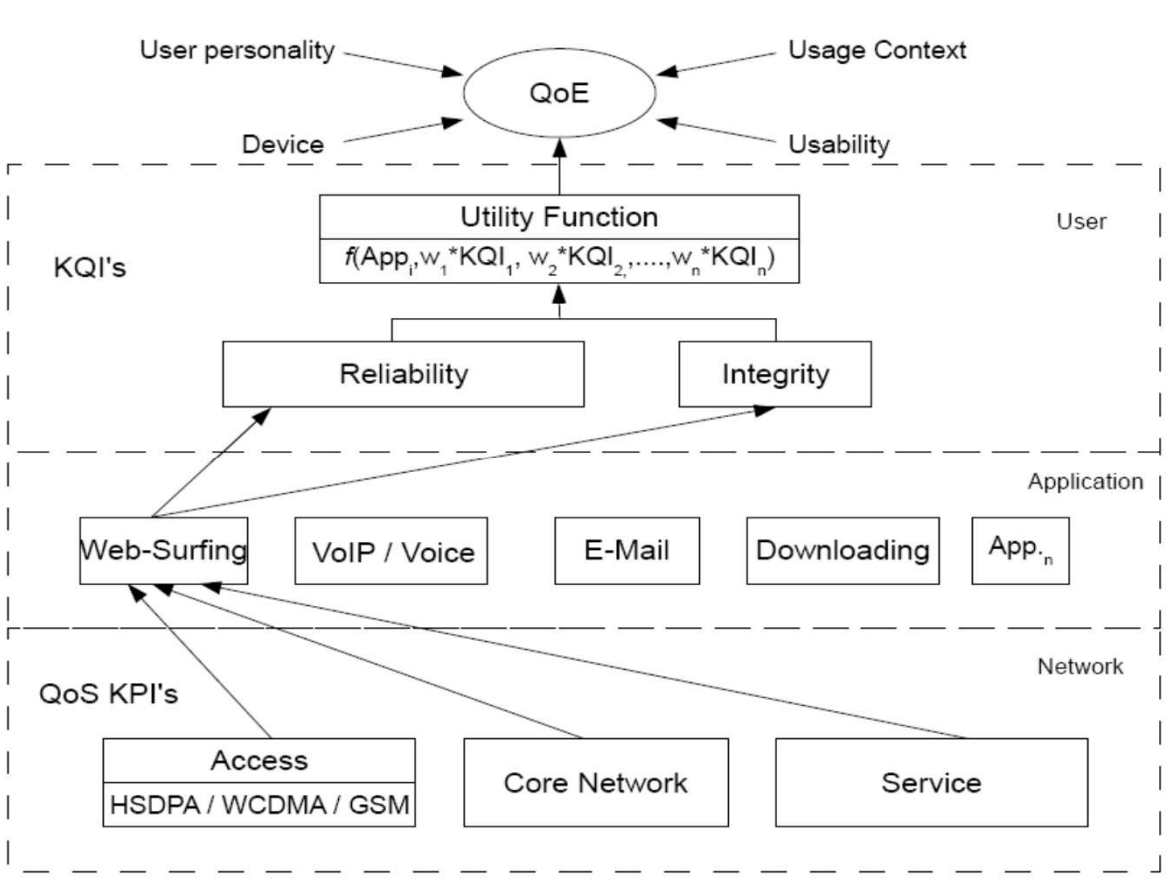
→ don't forget to analyze and report user opinion <u>diversity</u> (e.g. via confidence intervals, histograms, CDFs, user group segmentation)!





From Experimental Data to QoE Models

QoE typically requires a cross-layer approach:



Research Process

Extensive User Studies

Application Log Analysis

Traffic Analysis

Signal-based

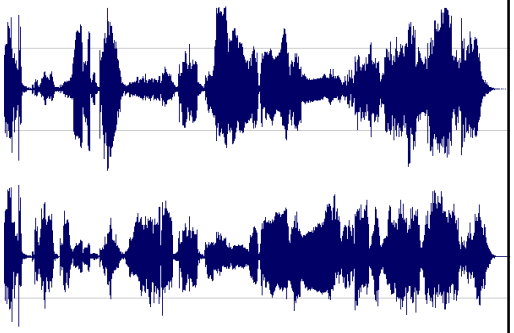
Parameter-based

QoE Model

Bit-stream

Packet-layer

Model Types, Example: Voice Quality



- Signal Based Models (e.g. PESQ)
  - **Process actual audio signal**
    (often: comparison of source and received sample)
  - Pros: codec independent, accurate
  - Cons: complex, DPI
- Parameter-based Opinion Models (e.g. E-Model)
  - Speech quality estimated on basis of **selected parameters**
  - Pros: low complexity, estimates also conversational quality
  - Cons: simple models, lower accuracy
- Packet Layer Models (e.g. PSQA)
  - **IP Packet-level/QoS information**
  - Pros: excellent quality estimation, real-time operation possible
  - Con: requires large bodies of training data, application & network-dependent, often a black box (PSQA)

Measuring QoE: Summary

- QoE measurement always involves end-user perspective
- Either direct involvement of users or codified as models
- MOS as central QoE measure (but not the only one!)
- QoE models can be very complex

→ **Let‘s look at something more simple and generic …**

Generic Relationships between QoS and QoE

What are Generic QoS-QOS Relationships?

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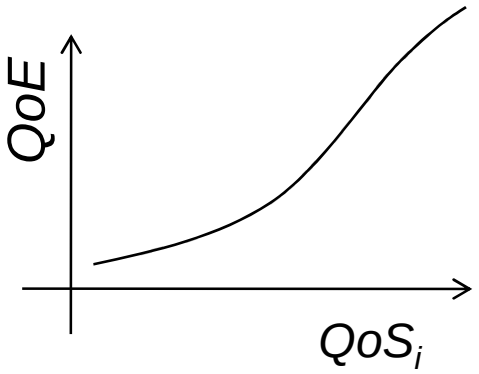
Analytical Models:

- QoE modeling data = results from questionnaires, observations, measurements
- Typically several impact factors: *QoE = f(QoS$_1$, QoS$_2$, …)*

Generic Relationships:

- We focus on **one impact factor at a time**: *QoE = f(QoS$_i$)*
- Description by partial differential equations
- Generic relationships of the type

$$\frac{\partial QoE}{\partial QoS_i} = g(QoE, QoS_i)$$



Why Dealing with Generic Relationships?

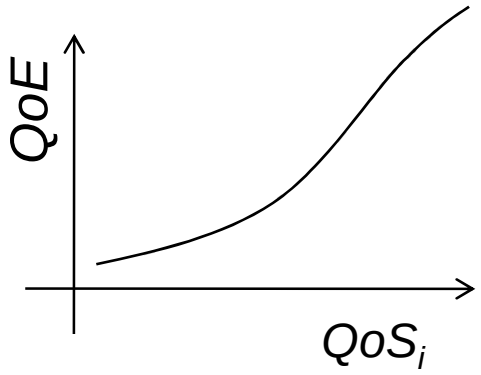
- Reveal fundamental laws regarding QoE perception
- Essential part of the „Science of QoE“
- Often a good match with output of subjective tests (i.e. one instrumented parameter at a time)
- „Mini-models“ → building blocks for more complex models
- They‘re fun!

How to find QoE–QoS relationships?

1. Experiments
   - Subjective tests with users (exposed to controlled QoS stimuli)
   - Alternative: substitute users by QoE models
2. Data collection
   - Subjective: questionnaires, observations
   - Objective: measurements (QoS, traffic features, physiology), model output
3. Data analysis
   - Relationships, thresholds, distributions, trends
   - Curve fitting & regressions, hypotheses

Generic Relationships: Overview

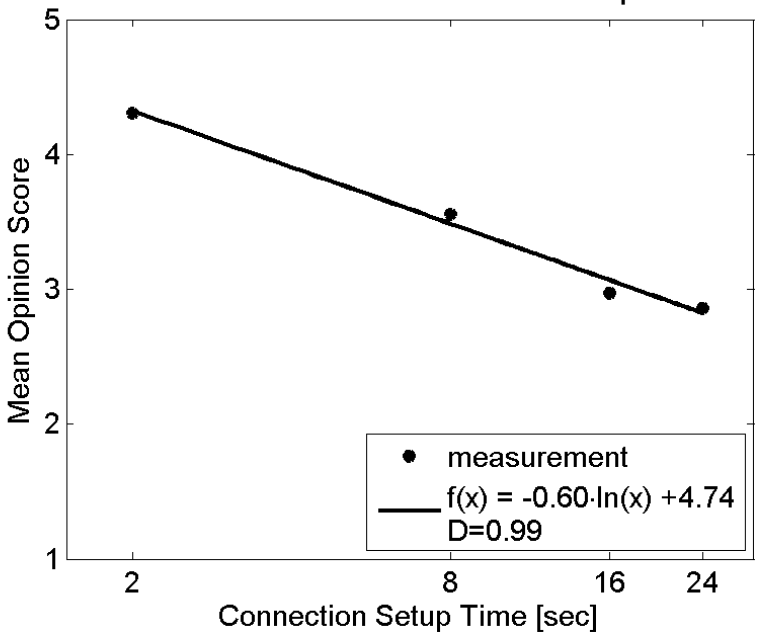
- Typically observed relationships
  - Linear $QoE \propto QoS_i$
  - Exponential $log(QoE) \propto QoS_i$
  - Logarithmic $QoE \propto log(QoS_i)$
  - Power $log(QoE) \propto log(QoS_i)$



- In this lecture we focus on two of the above:
  - Logarithmic → WQL Hypothesis
  - Exponential → IQX Hypothesis

Logarithmic Relationships: WQL-Hypothesis

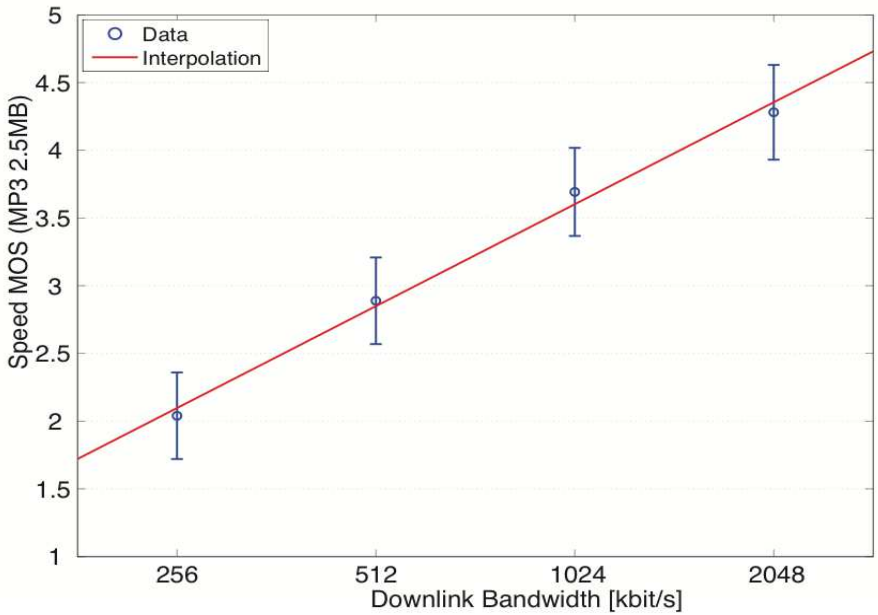
Broadband Connection Setup



Waiting time →

QoE = a+b*ln(t)

File Download



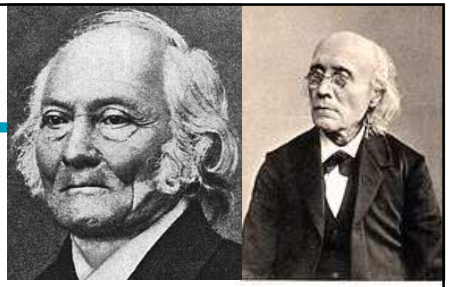
← Waiting time

QoE = a+b*$\log_2$(time)+c*sqrt(size)

Observation: logarithmic dependency between QoS and quality ratings, including connection set ups and file downloads

→ common denominator: **waiting time**

Psychophysics: The Law of Weber-Fechner

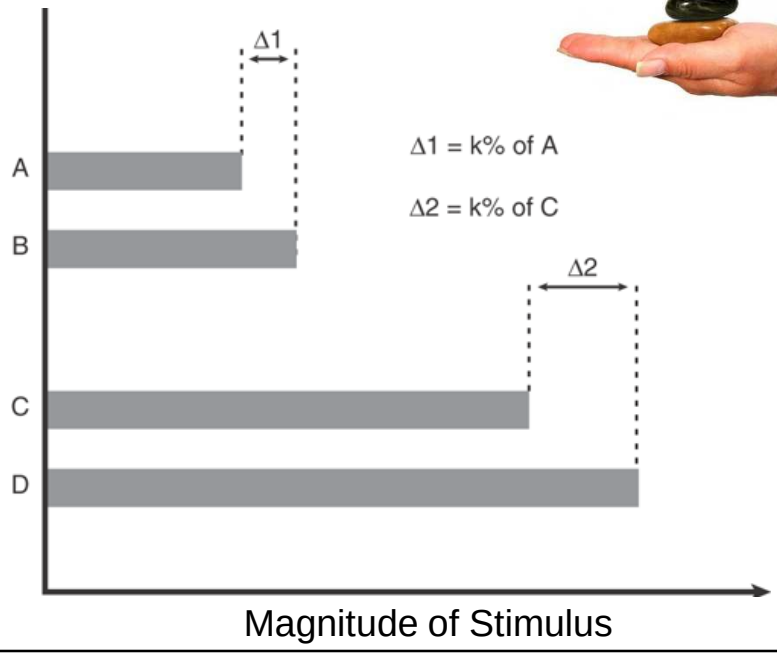


- Published in 1834
- Models relationship between changes of stimulus S and perception P
- Mathematical expressions: $dP = k \cdot \frac{dS}{S} \longrightarrow P = k \cdot \ln \frac{S}{S_0}$
- Key concept: just noticeable differences

  E.g. weighing by hand

  Also applicable to human vision, hearing, smelling, touching, numerical cognition, and …

  ... **time perception**!



See also: Allan (1979), Reichl et al. (2010)

WQL Hypothesis: Derivation & Interpretation

- WQL Hypothesis: “The relationship between **W**aiting time t and its **Q**oE evaluation on a linear ACR scale is **L**ogarithmic”

- Differential equation

$$dQoE = k \cdot \frac{dt}{t}$$ → t is the stimulus

- Derivation of logarithmic solution for WQL hypothesis

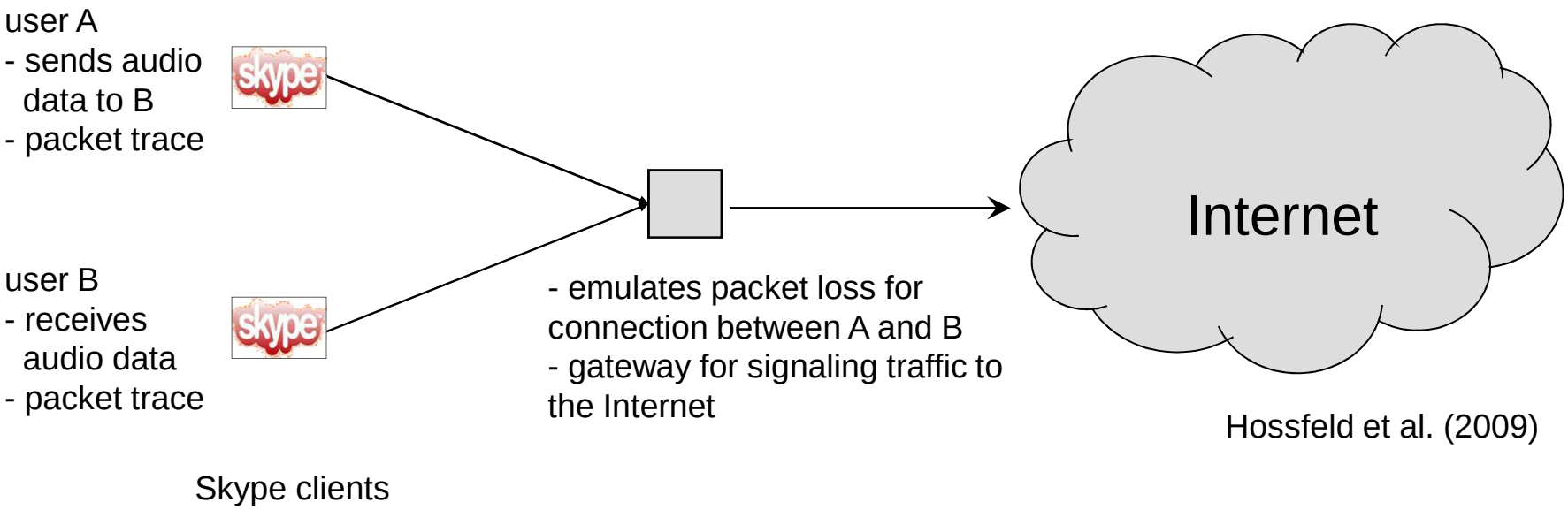
$$QoE = k \cdot \ln \frac{t}{t_0} + c$$ → a+b*ln(t)

- Interpretation:
  - QoE sensitivity dependent on actual stimulus level
  - t as perceived impairment is an f(QoS), e.g. f(downlink bandwidth)

QoS → Stimulus → QoE

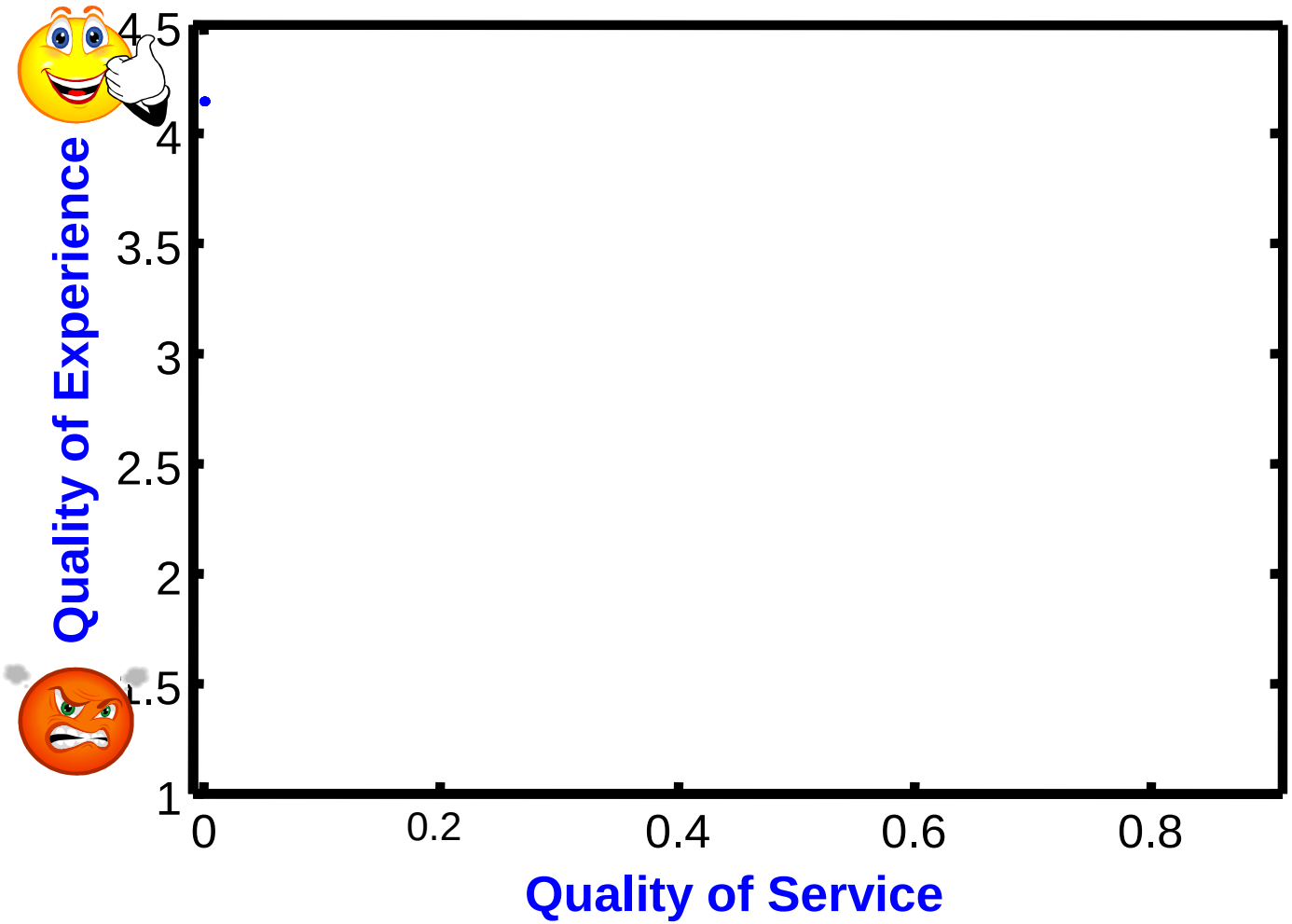
IQX Hypothesis: Measurement Setup

- Scenario: Skype voice telephony (using iLBC codec)
- Packet loss as QoS measure, MOS as QoE measure

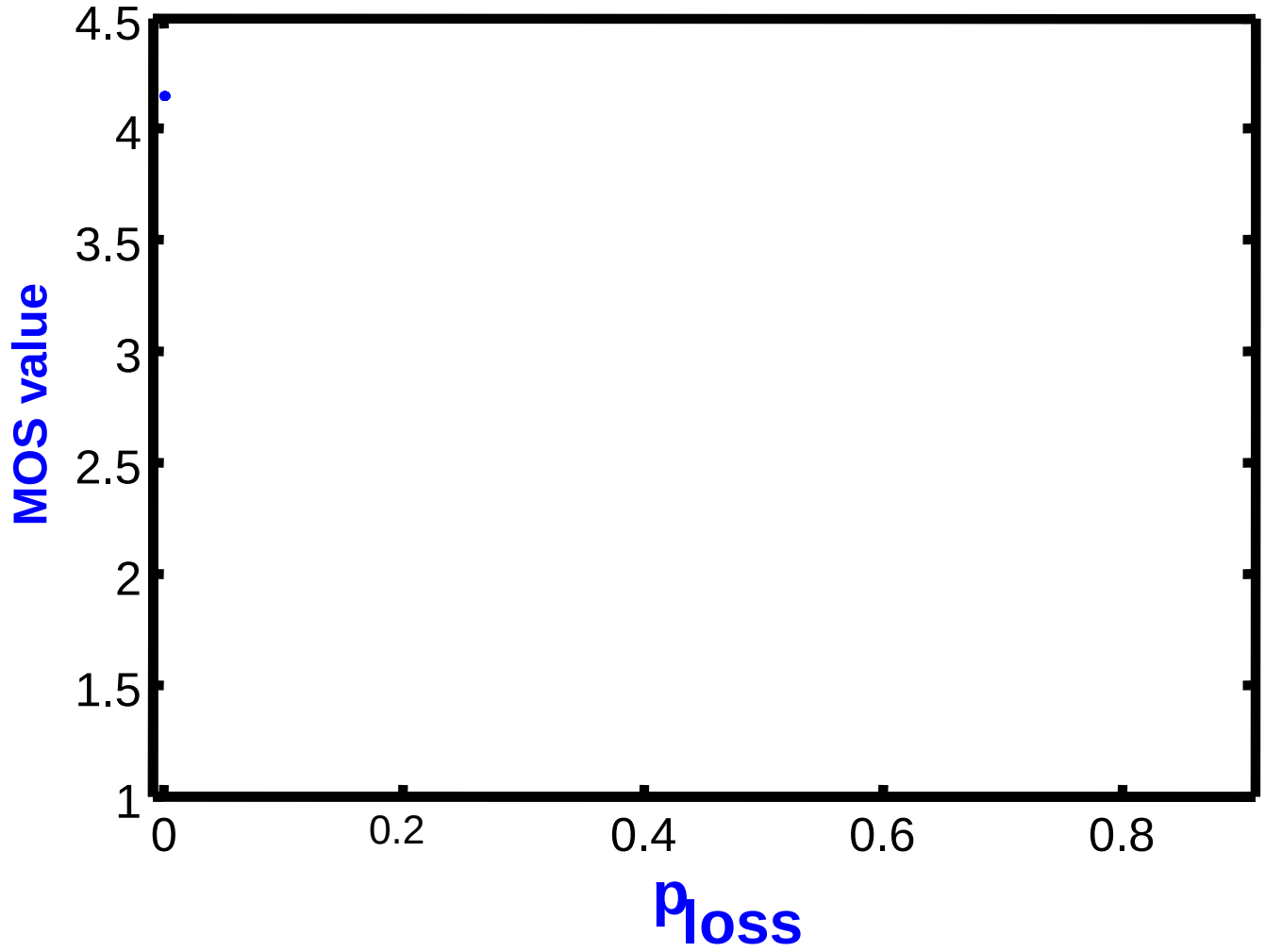


- Impairments from packet loss determined via measurements
  QoE = f(QoS) via PESQ

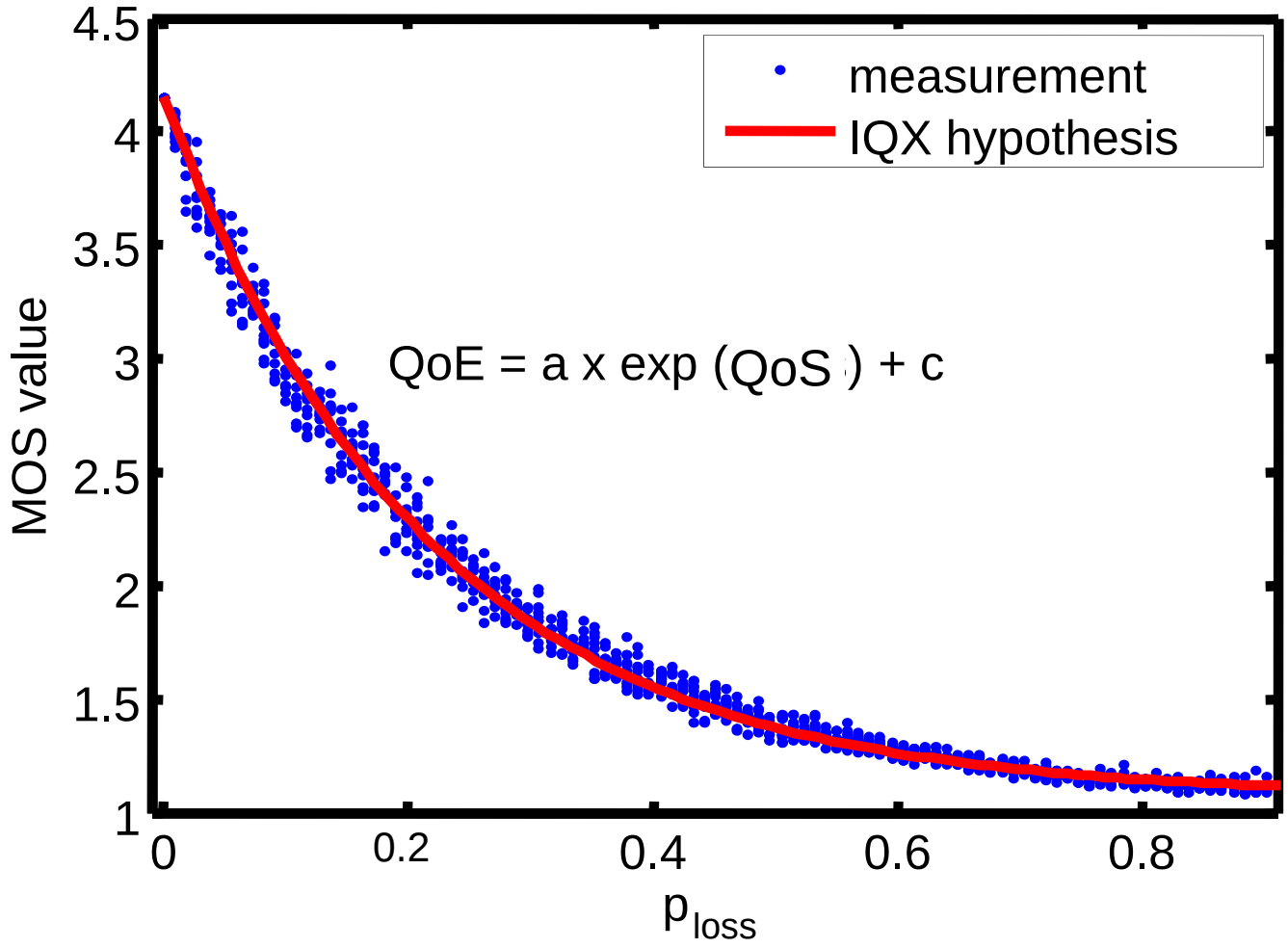
Exponential Relationships: IQX Hypothesis



Exponential Relationships: IQX Hypothesis



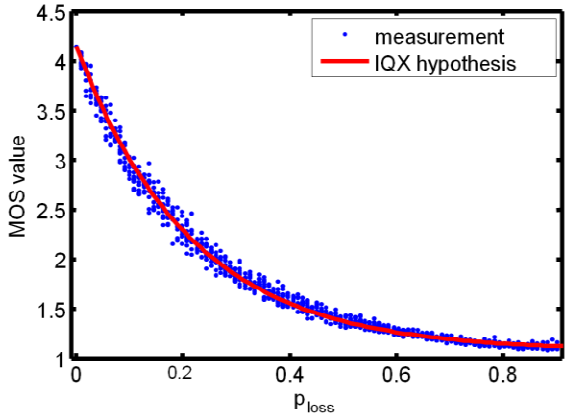
Exponential Relationships: IQX Hypothesis



IQX Hypothesis: Derivation & Interpretation

- Differential equation

$$\frac{\partial QoE}{\partial p_{loss}} = -\tilde{\beta} \cdot (QoE - \gamma)$$



Assumptions:

- QoE sensitivity dependent on actual QoE
- P_{loss} as QoS impairment, perceived stimulus = f(P_{loss})

- Derivation of exponential solution

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

↓ Regression analysis/curve-fitting

$$QoE = 3.0819 \times e^{-4.6446 \times p_{loss}}$$

Generic Relationships: Summary

- Generic relationships as fundamental laws and building blocks
- Applicable to many quality perception phenomena we observe
- Important: the reasoning behind
  → think beyond mere curve-fitting!

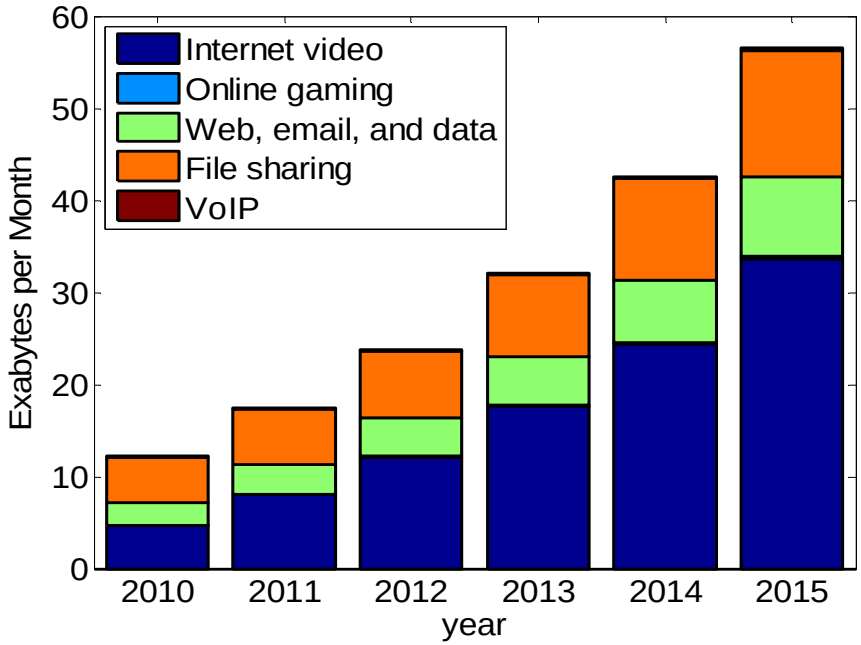
Web QoE

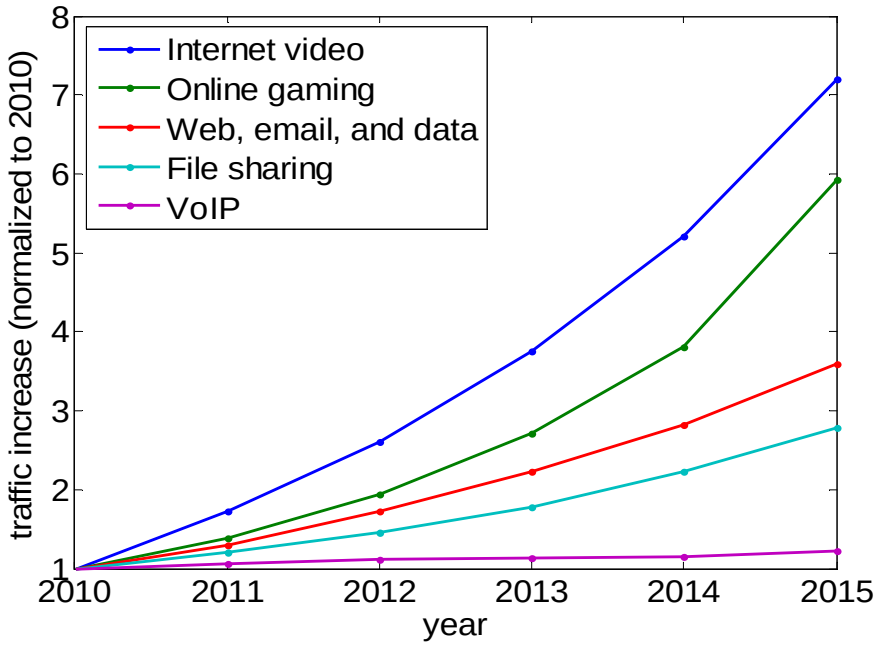
Motivation

- Interactive Data Services

  = Online Video, Web Browsing, Downloads, Cloud Services, etc.

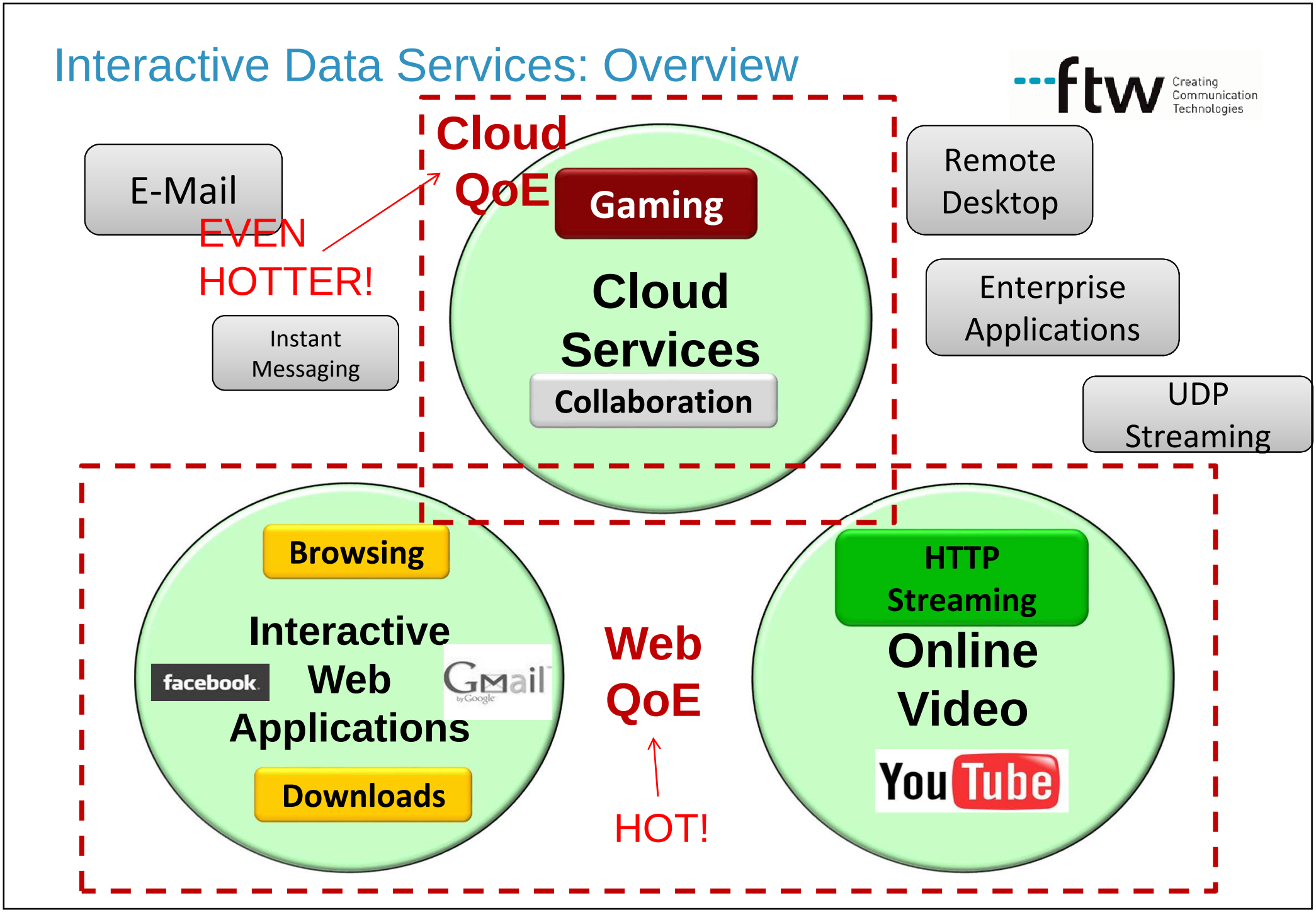
- Why relevant?
  - Constitute dominant internet use cases





Global Consumer Internet Traffic Volume (Forecast).
Source: Cisco VNI 2011.

Interactive Data Services: Overview



Typical Web QoE Issues

- Web Browsing
  - Unavailability of page/site
  - Long waiting time until anything visible happens
  - Slow page rendering/page takes long to load
  - Page feels unresponsive
  - Elements missing or page rendering corrupted

- Online Video (e.g. YouTube):
  - Low quality of content (encoding)
  - Long startup time of playback (= initial delay)
  - Rebuffering, playback stutters (= stalling)
  - Video fails to display at all…

- File Downloads
  - Content corrupted
  - Download progress slow

→ **Most Web QoE issues are related to time-related impairments (latencies, stalling, etc.)**

Web Browsing: QoE Key Issues

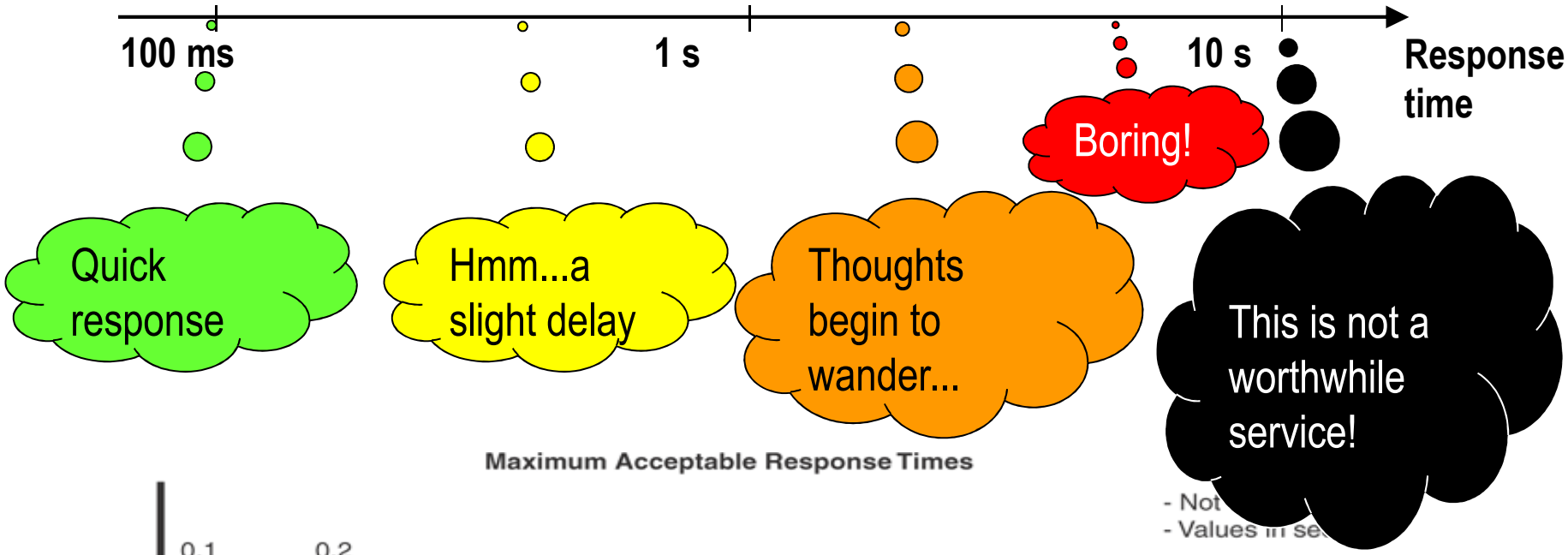
- Key QoE issue: speed and responsiveness

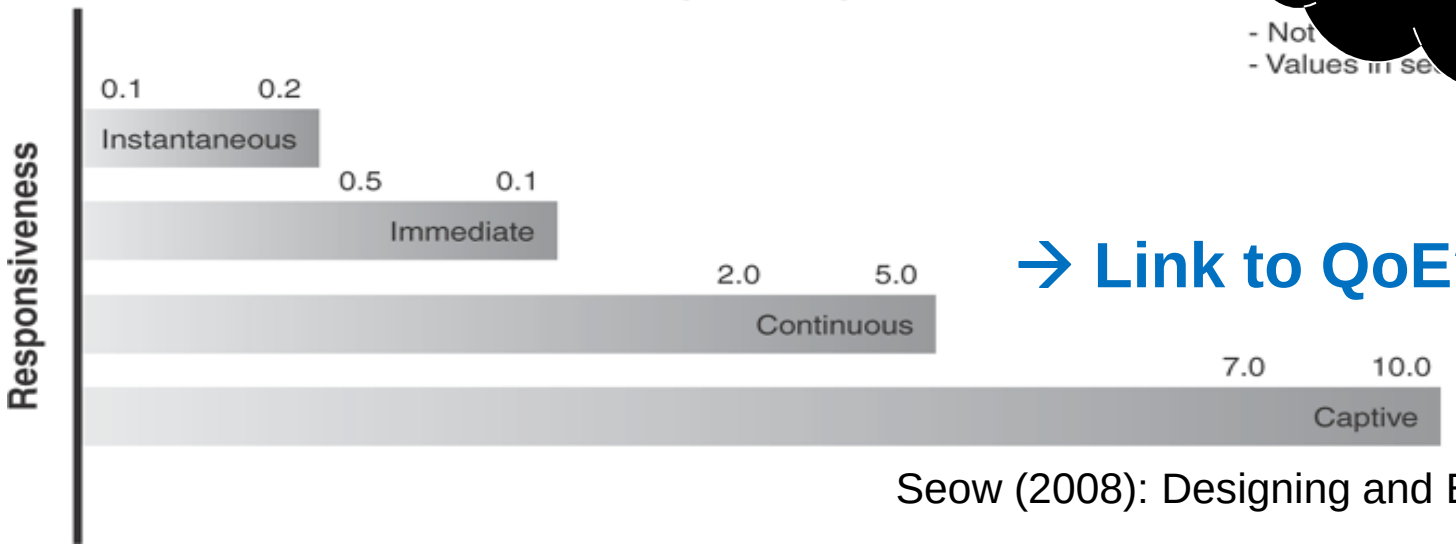
  *"A Web site that fails to deliver its content, either in a **timely** manner or not at all, causes visitors to quickly lose interest, wasting the time and money spent on the site's development."*
  Freshwater Software

  *"Every Web usability study I have conducted since 1994 has shown the same thing: users beg us to **speed up page downloads**."*
  J. Nielsen, "The Need for Speed"

  *"Some users and applications drive the revenue of the business. If the system is **slow**, customers go elsewhere, and transactions or sales are lost forever."*
  P. Sevcik, Business Communications Review

Users' perception of response time





→ **Link to QoE?**

Seow (2008): Designing and Engineering Time

Methods: Web QoE Assessment

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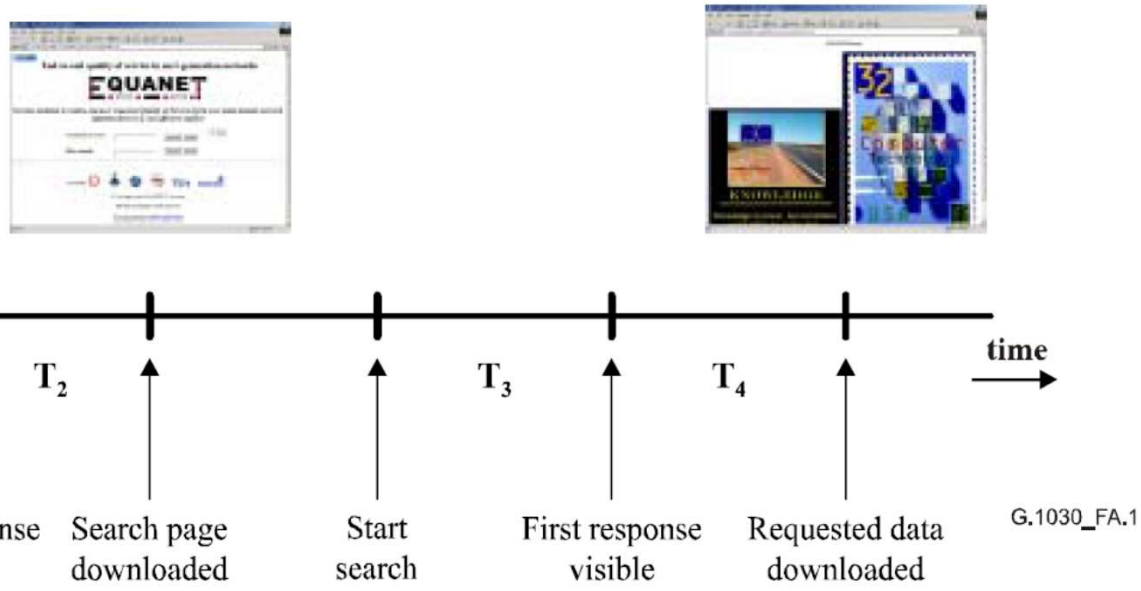
Question: How to assess Web browsing QoE, particularly the impact of speed issues?

How slow can you go?

Web Browsing QoE: Simple Approach

- Web QoE Approach 1: testing simple transactions at constant page-load time (PLT)
  - Users perform very simple web task (query→response)
  - Waiting times Tx = set parameter = independent variable
  - Users provide feedback (e.g. MOS ACR) after each session



Source: ITU-T G.1030

T_1 is the non-interactive response time and was manipulated using Java scripting. T_2 is the non-interactive download time and was manipulated using the network manipulator. T_3 and T_4 are the equivalents for the interactive part. The sum $T_1+T_2+T_3+T_4$ represents the session time.

Test Facilities: The i-Lab @FTW

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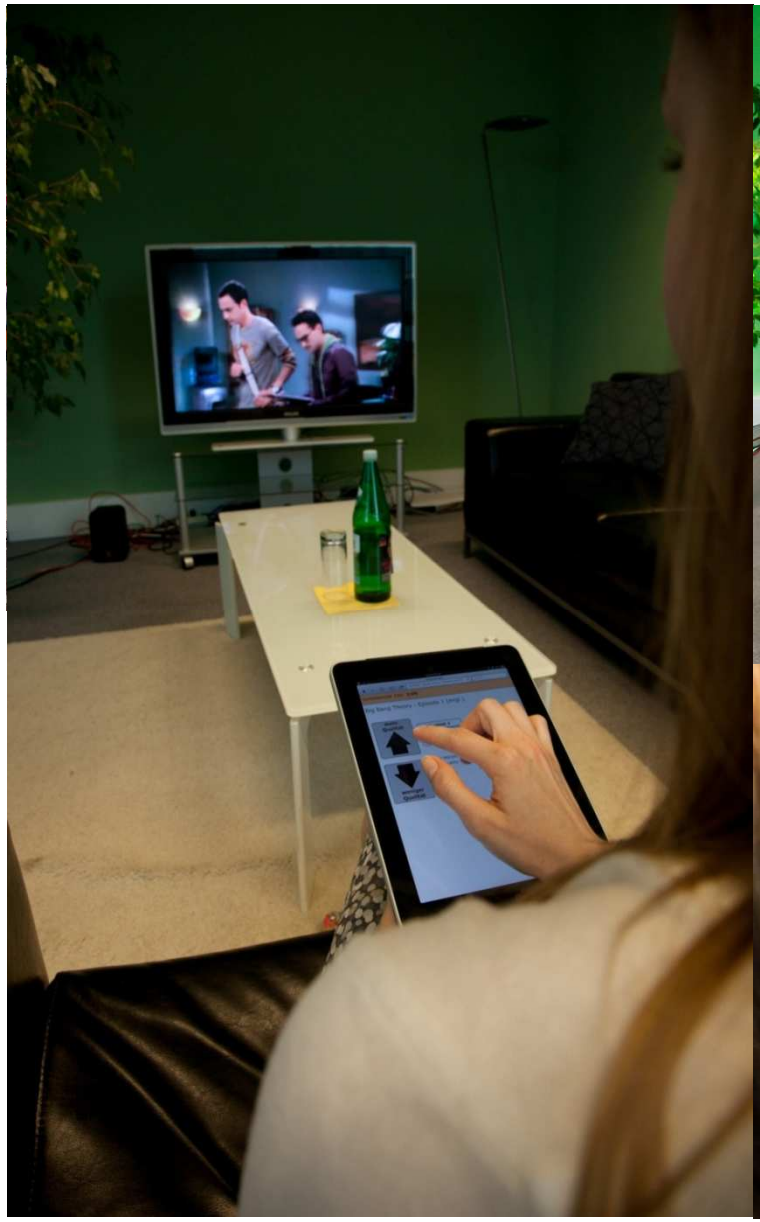
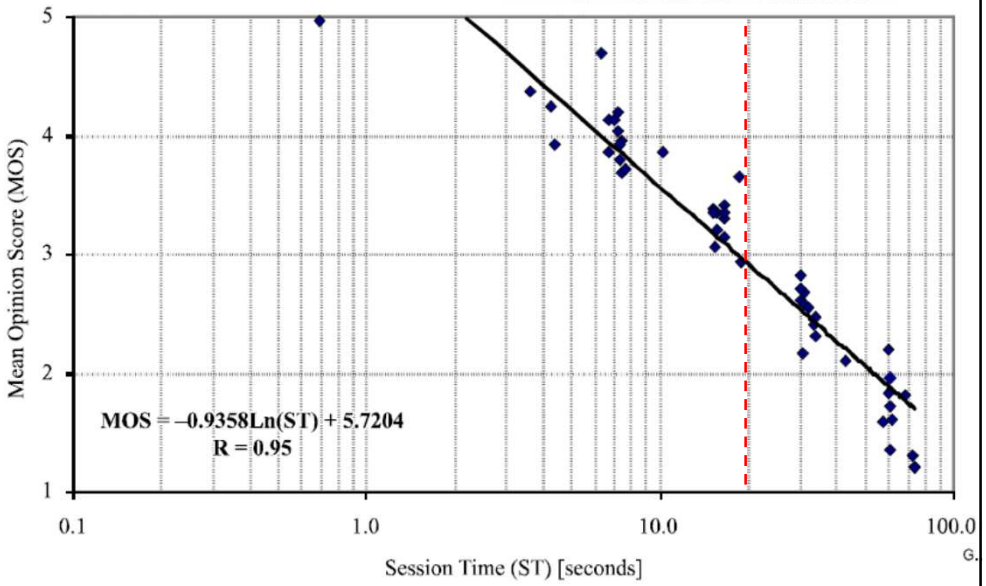
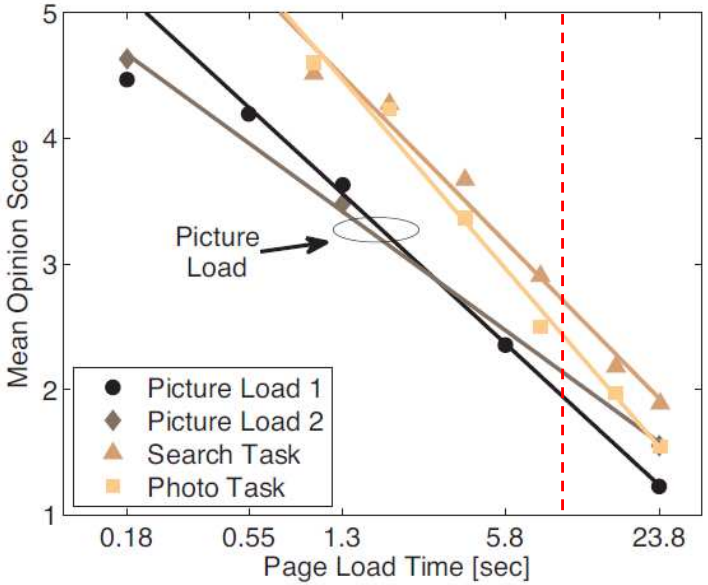


Simple Browsing Tasks: Results

- Results from ITU-T G.1030:
  ST= Sum(waiting times)



- Results from similar experiments at FTW:
  Task: view photos in online album, search queries, all at constant PLT



- Observations:
  - Consistent results, low variability
  - Logarithmic relationships between (page) waiting times and QoE ...

→ **Clear relationship between PLT and QoE**

Beyond Single Web Pages: Flow

- Advantages of simple, transaction-centric approach
  - Studies simple, well-controlled situation → elementary building block
  - Straightforward, consistent test results → reliable & internally valid

BUT: are such results applicable to real world web-browsing and QoE in particular?

- Web surfing is about experiencing a flow of interactions across multiple pageviews

  „Experiencing = an individual's stream of perceptions, interpretations of those perceptions and resulting emotions during an encounter with a system." (Roto 2011)

  → more complex than a simple page view transaction

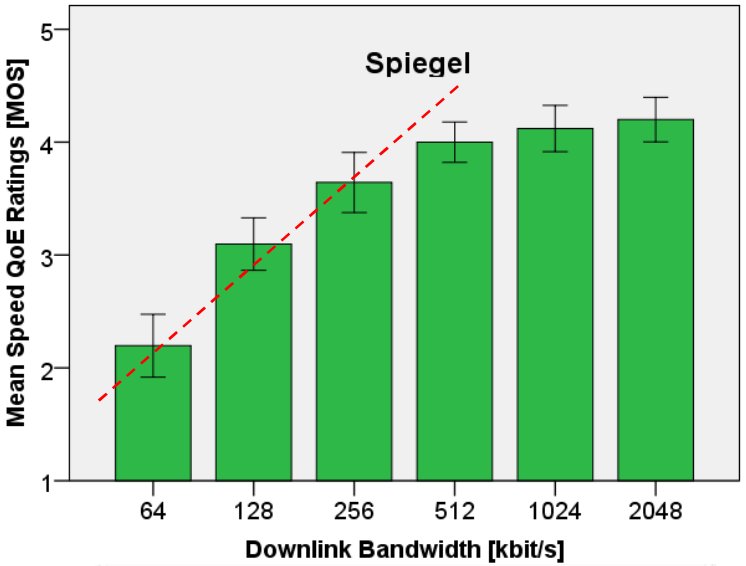
Flow-centric Web QoE Assessment Approach

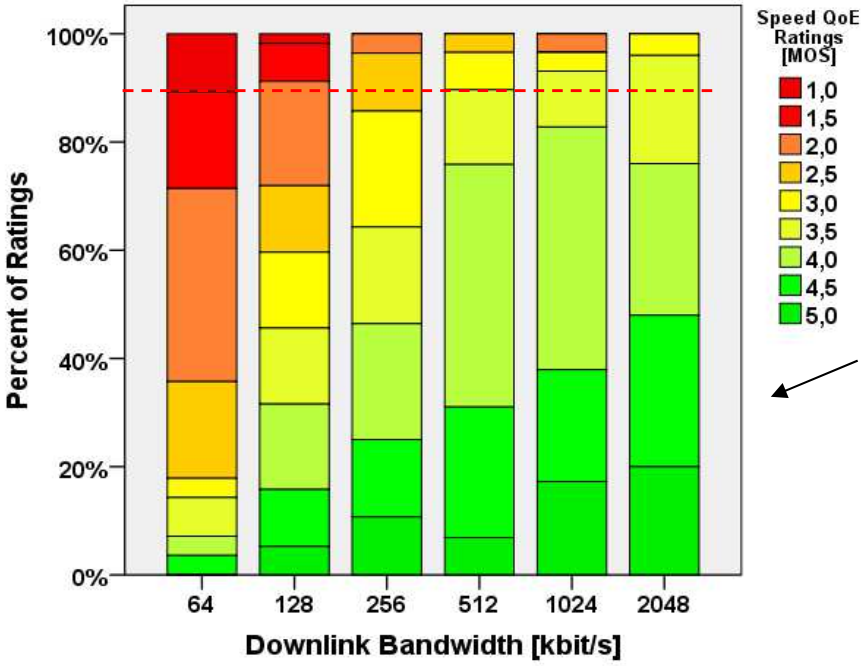
- Test Procedure:
  - Users surf a given website (e.g. spiegel.de)
  - QoS conditions (e.g. delay, max bandwidth) set in background
  - Task: should be not too complicated (to avoid distraction)
  - After e.g. 2-3 minutes, users provide QoE feedback ratings

- Advantages:
  - Highly natural and realistic = high external validity
    → relates better to actual QoE

- Challenges:
  - Test situation not fully under control (user surfing their own path)
  - The retrospective MOS rating related to a whole series of pageviews (at a given QoS level)

Web-browsing QoE: Results Example





Observations:

- Initially, Web QoE increases logarithmically with rising bandwidth

- Saturation around 1-2 Mbit/s

→ **Saturation effects typical for Web browsing** (and for other services)

Note: slope and saturation heavily depend on web page characteristics (weight, complexity)

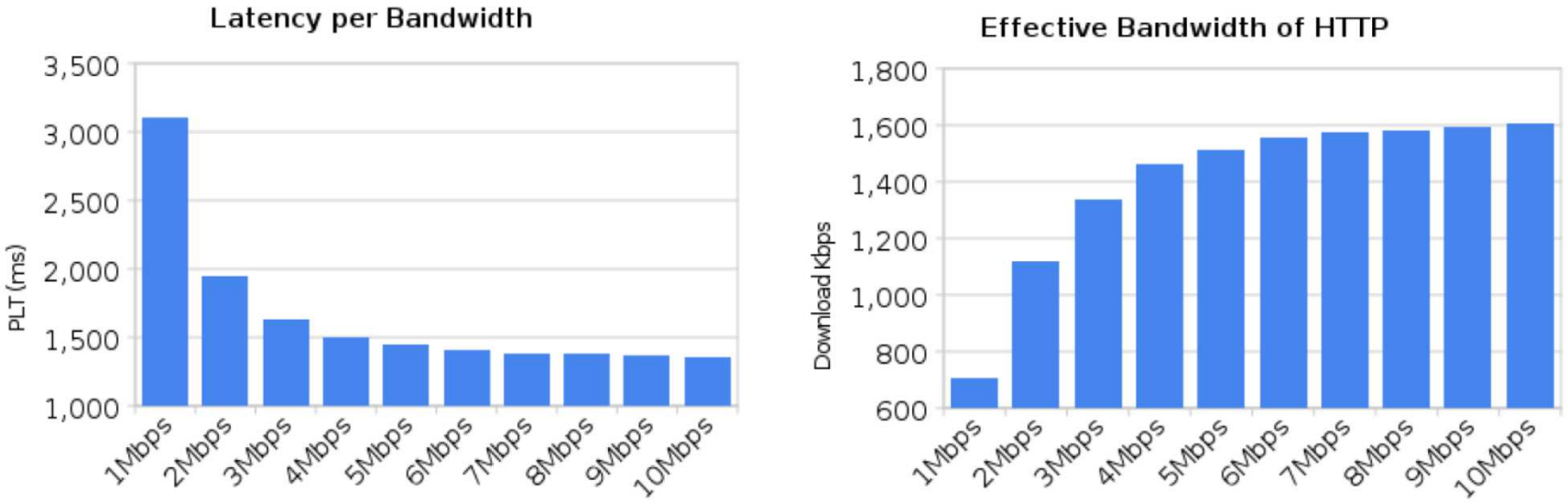
Note: diversity of user ratings reflects diversity in user perception

Web QoE Saturation Effects: Causes

Two causes: technology and user perception

1. Technical saturation: inefficiencies of current protocols

Performance test with Top 25 Websites (Belshe 2010):



→ Bandwidth does not linearly transform into page load time

But: does not fully explain previously observed Web Qoe saturation effect

2. Perceptual saturation: flow & immersion

Actual delivery speed less obvious to users (compared to simple download) due to progressive rendering and interaction with page

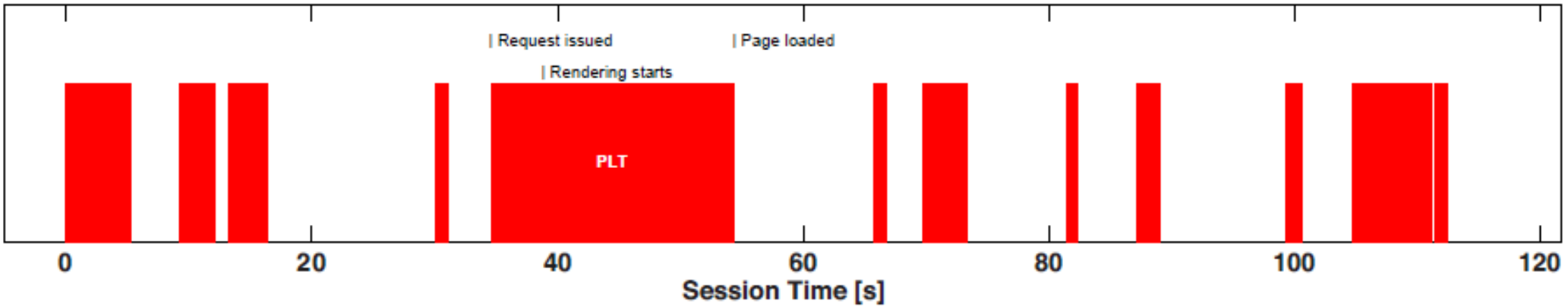
Flow-based Web-browsing: Challenges (1)

Web-browsing in reality is a complex process:

= series of irregularly spaced pageviews with varying page-load times (PLTs)

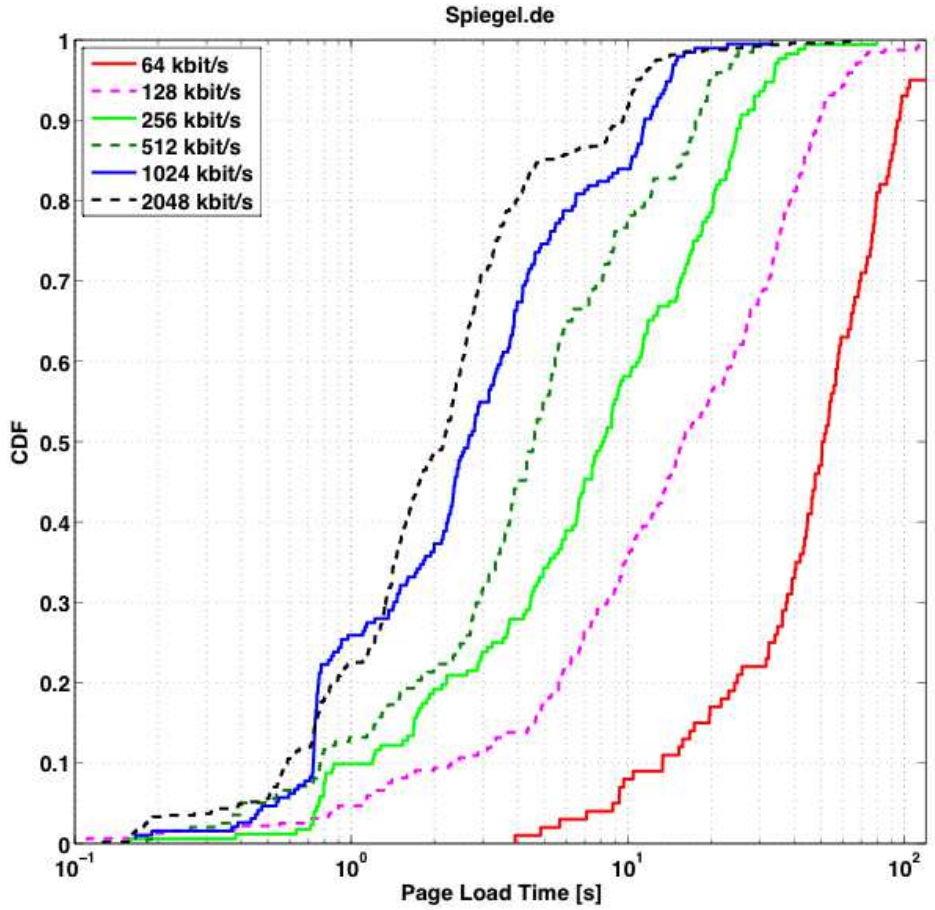
→ Memory effects, etc. come into play

→ The time-series of PLTs needs to be analyzed



Flow-based Web-browsing: Challenges (2)

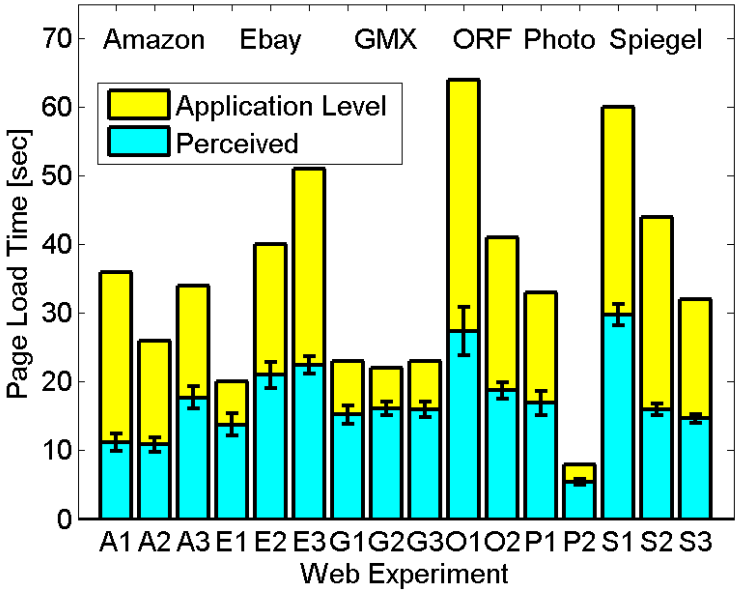
- No simple 1:1 relationship between QoS and PLT
- PLT can vary by factor 10 within one test condition



Flow-based Web-browsing: Challenges (3)

- Result from dedicated lab study:

  Subjectively perceived page-load time (PLT) differs from technical PLT at varying proportions

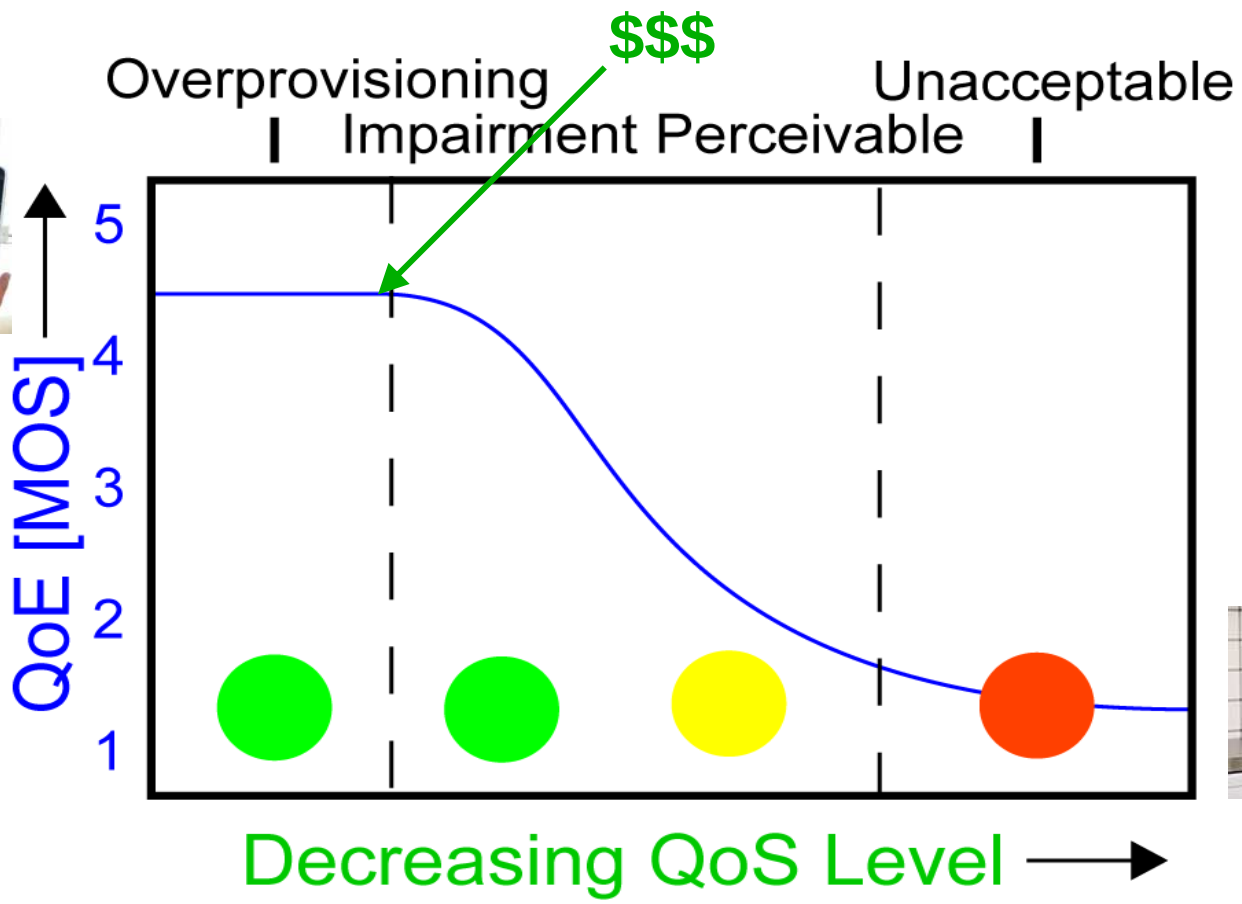


→ User-perceived PLT (the performance metric closer to QOE) differs considerably from technical PLT

- But: Perceived PLT depends a lot on what happens during rendering on screens

→ Estimation based on network traces = still a research challenge!

Another Typical Relationship between QoS and QoE



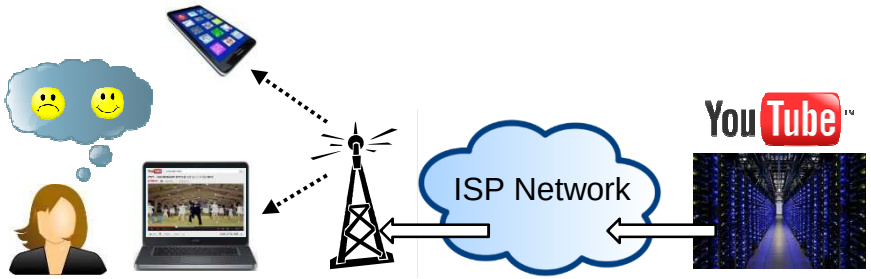
Non-linearities and saturation effects = typical for QoE

Summary of key aspects

- Temporal aspects (e.g. speed) dominate Web QoE
- Common laws of psychophysics (e.g. WFL) do apply (but not always!)
- Realistic QoE assessment setups can lead to interesting results
- Saturation effects and non-linearities = very common quality perception phenomena

→ that‘s why going beyond technical quality and studying QoE is so important!

QoE–based Monitoring in YouTube



Which is the most annoying impairment when watching YouTube videos?

- We propose a **system** to retrieve **stallings from passive monitoring** of network traffic, specifically targeting 3G Networks

Why QoE in YouTube and why should an Operator care about it?

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YouTube traffic volume is overwhelming:

- YouTube represents about 30% of the overall Internet‘s traffic
- 100 hours of video uploaded every minute
- More than 1 billion unique users visit YouTube each month
- Video streaming is expected to account for 57% of the overall Internet‘s traffic in 2015

YouTube in mobile broadband networks poses a big challenge:

- Mobile makes up more than 40% of YouTube's global watch time
- More than one billion views a day
- Bandwidth is still a limited resource in mobile networks

Why QoE in YouTube and why should an Operator care about it?

YouTube traffic volume is overwhelming:

Network Operator

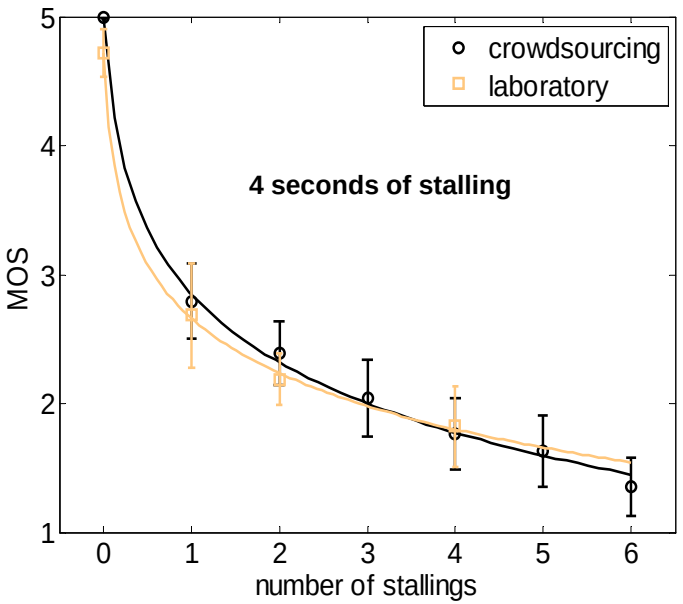
YouTube in mobile broadband networks poses a big challenge:

- Mobile makes up more than 40% of YouTube's global watch time
- More than one billion views a day
- Bandwidth is still a limited resource in mobile networks

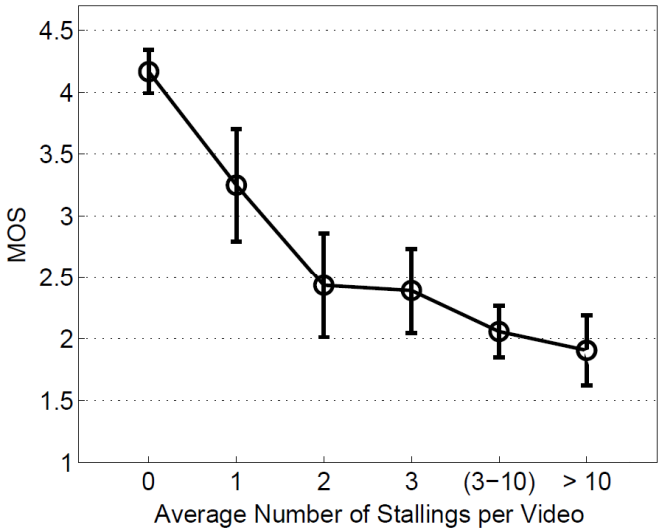
And why stallings?

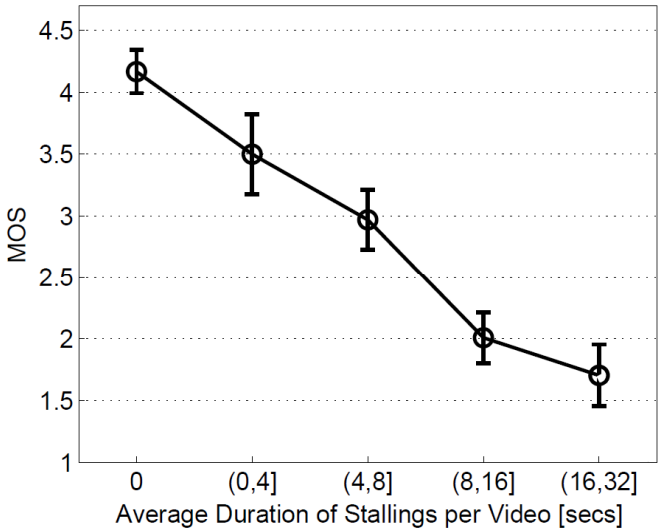
- Stallings are the impairments perceived by the end-user (independently of QoS and video resolution)
- 1 single stalling event heavily deteriorates the experience of the end-user
- 2 or more stallings already means bad quality
- Duration of the stallings is less critical, but also has an important impact on QoE

Lab studies



On the real mobile network





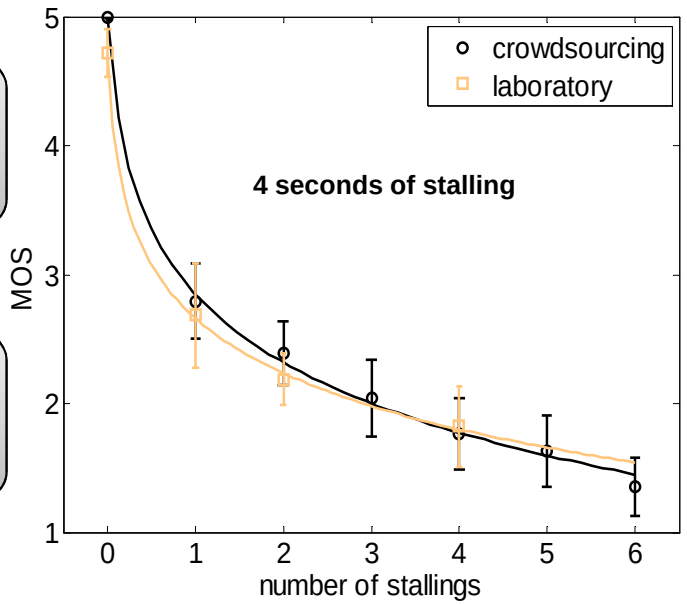
And why stallings?

- Stallings are the impairments perceived by the end-
- experience of the end-user
- an important impact on QoE

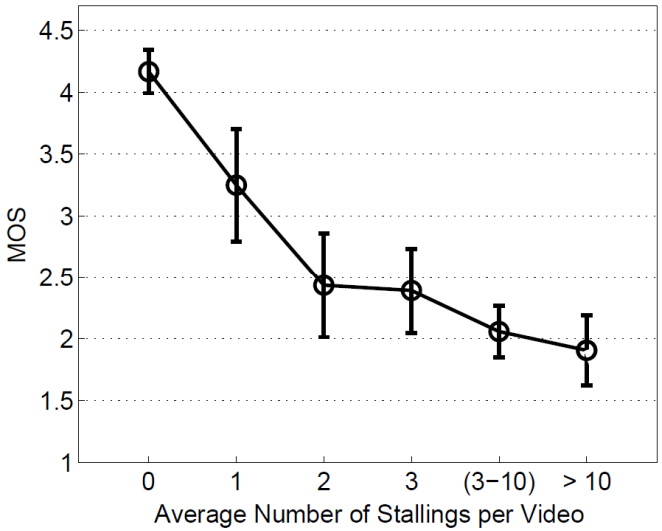
In previous studies, we've developed a model to map stalling patterns → YouTube QoE

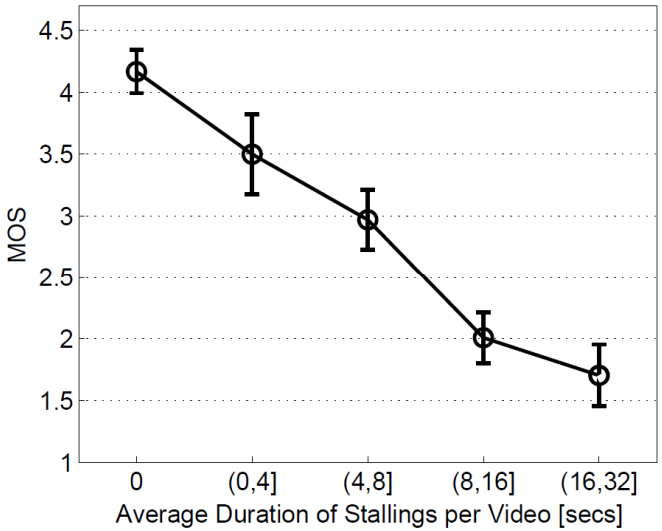
How to retrieve the YouTube stalling patterns from passive network measurements?

Lab studies



On the real mobile network



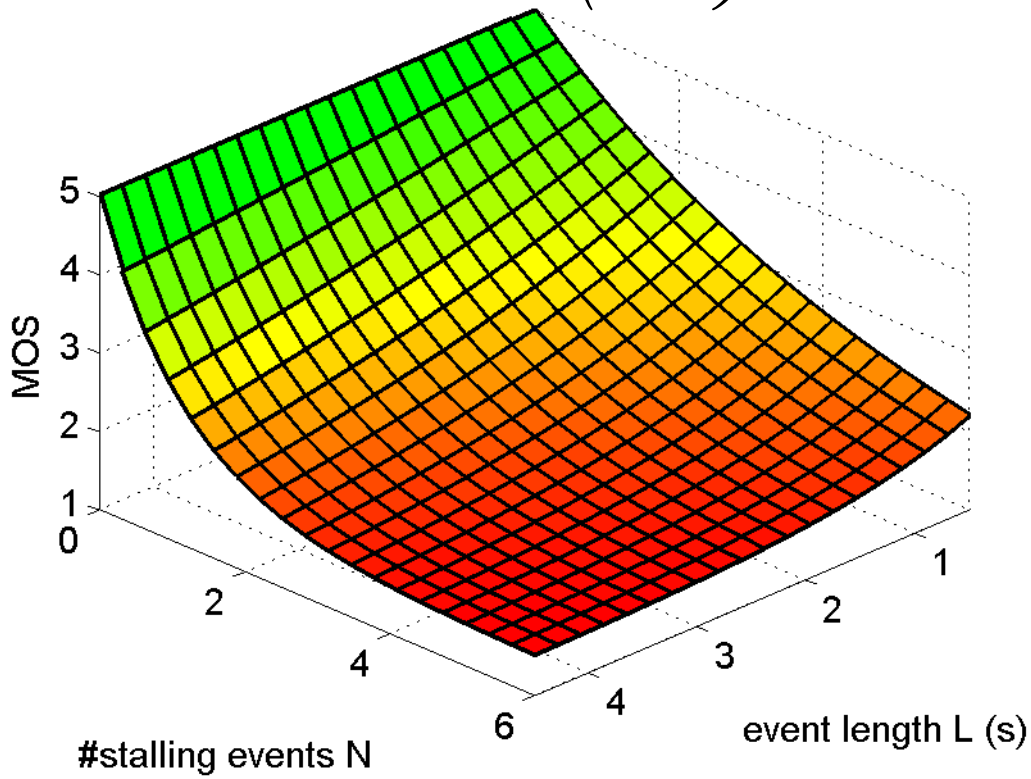


And why stallings?

- Stallings are the impairments perceived by the end-

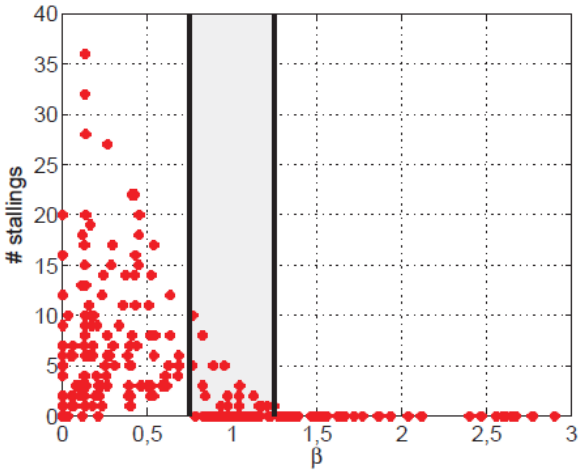
In previous studies, we've developed a model to map stalling patterns → YouTube QoE

$$\text{MOS} = \mathcal{F}(\text{N}, \text{L})$$

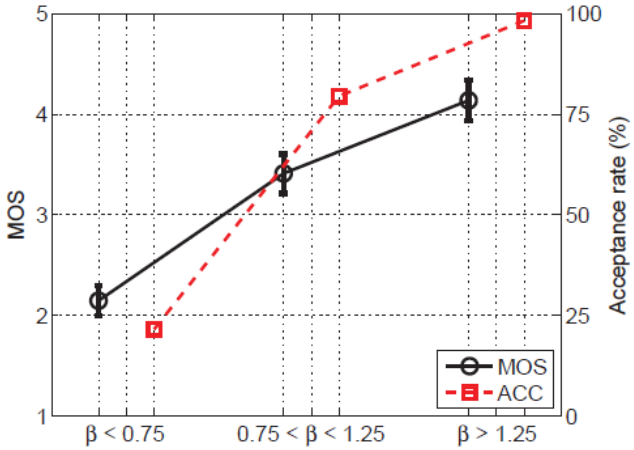


Why do stallings occur? → Playback Buffer Depletion

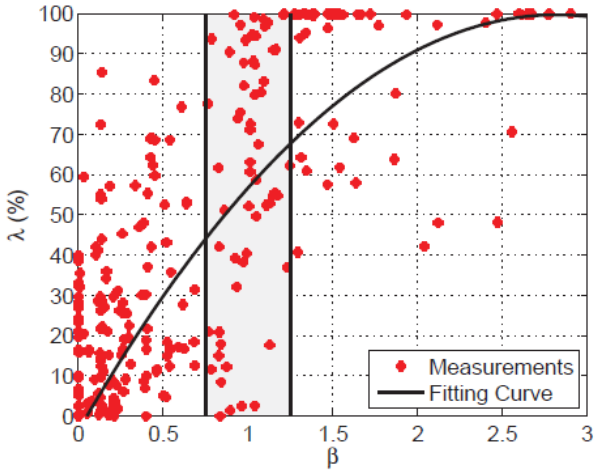
- Buffer depletion generally occurs because the downlink bandwidth (DBW) is lower then the video bitrate (VBR)
- However, it is difficult to assess the number of stallings for each single video relying only on DBW and VBR



(a) # stallings vs. β



(b) MOS and acceptance vs. β

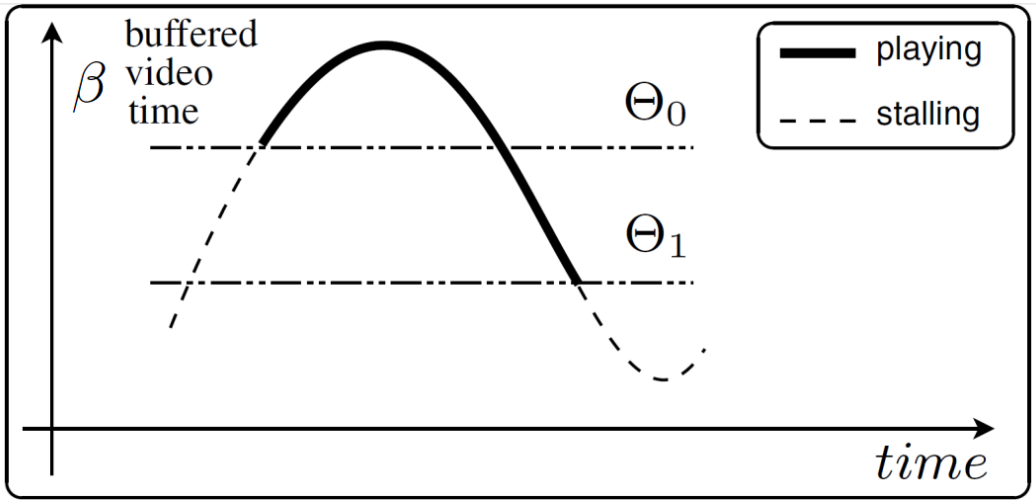


(c) User engagement (λ) vs. β

$$\beta = \frac{avg.down\ throughput}{video\ bit\ rate}$$

Playback Buffer Depletion → YouTube Player Model

- YouTube playback starts after the amount of buffered video time β exceeds a certain playing threshold Θ_0
- When β is below the stalling threshold Θ_1, the playback is stopped and resumed only when β exceeds once again Θ_0

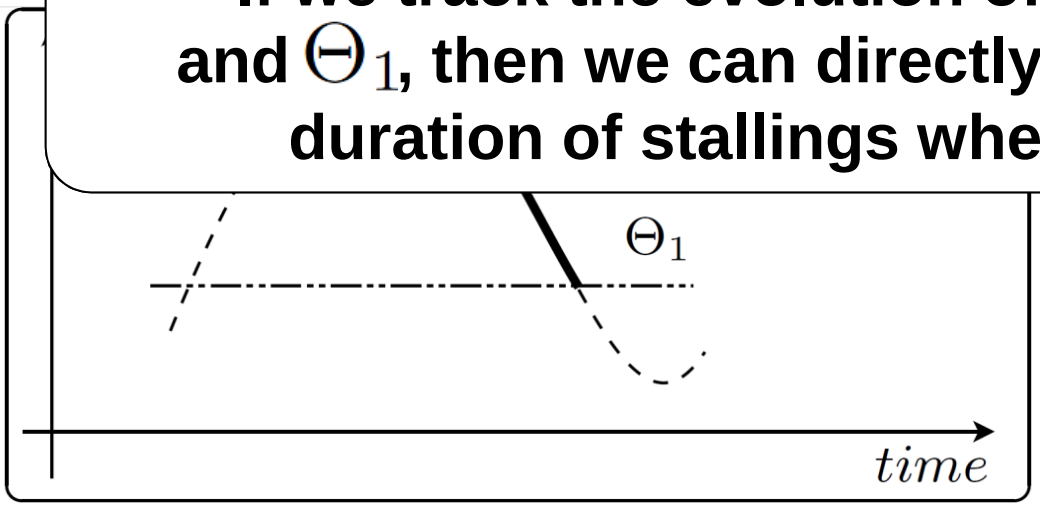


Management of the playback buffer in YouTube

Playback Buffer Depletion → YouTube Player Model

- YouTube playback starts after the amount of buffered video time β exceeds a certain playing threshold Θ_0
- When β is below the stalling threshold Θ_1, the playback is stopped and resumed only when β exceeds once again Θ_0

If we track the evolution of β, and knowing both Θ_0 and Θ_1, then we can directly retrieve the number and duration of stallings when they actually occur



Management of the playback buffer in YouTube

Retrieving YouTube Stallings from Network Measurements

τ_i : total downloaded video duration until i-th TCP ACK of video flow at t_i

YouTube flows are identified by HTTP headers' inspection

τ_i is estimated by analyzing metadata in video container

$$\psi_i = \psi_{i-1} \wedge (\beta_{i-1} < \Theta_0) \vee \bar{\psi}_{i-1} \wedge (\beta_{i-1} < \Theta_1)$$

$$\sigma_i = \sigma_{i-1} + \begin{cases} t_i - t_{i-1}, & \text{if } \psi_i \\ 0, & \text{if } \bar{\psi}_i \end{cases}$$

$$\rho_i = \rho_{i-1} + \begin{cases} 0, & \text{if } \psi_i \\ t_i - t_{i-1}, & \text{if } \bar{\psi}_i \end{cases}$$

$$\beta_i = \tau_i - \rho_i$$

$$\sigma_0 = 0 \qquad \rho_0 = 0 \qquad \psi_0 = 1$$

Evaluation Methodology

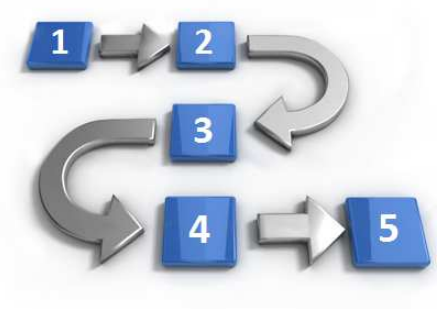
1. **Two YouTube datasets** with **randomly chosen videos** streamed from youtube.com to a local machine: **100 videos (2011), 400 videos (2012)**

2. A **network emulator** was used as proxy to **change network QoS** settings, resulting in **different stalling patterns**

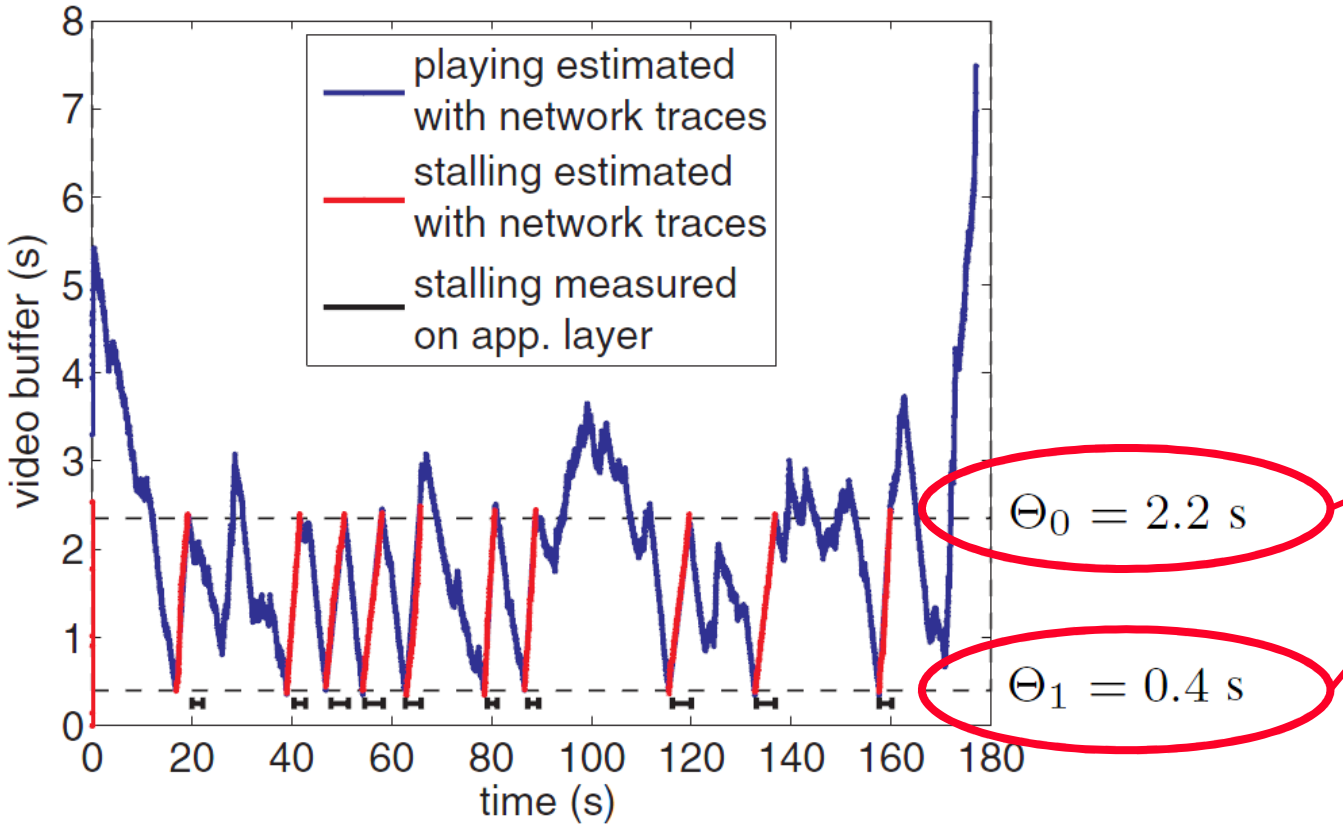
3. **YOUQMON** was used to **estimate the stallings patterns** from the network flows

4. The real **stalling patterns were measured at the application layer** using a javascript-based application **(Ground Truth)**

5. Finally, both the **real and the estimated stalling patterns** were compared



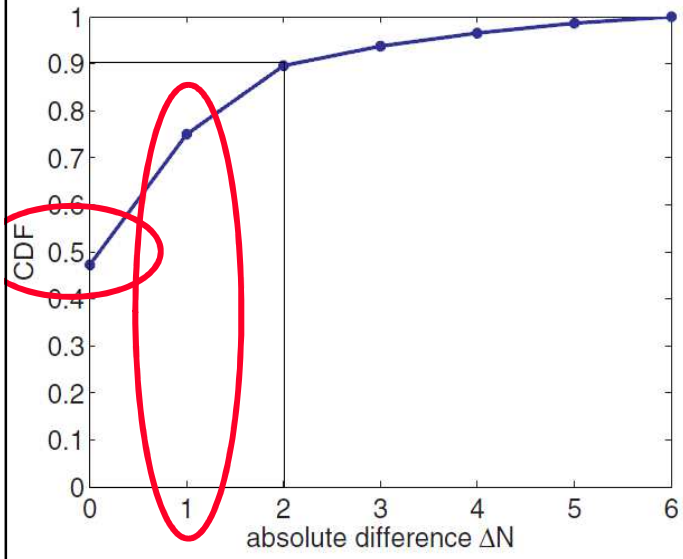
Estimation of the Video Buffer

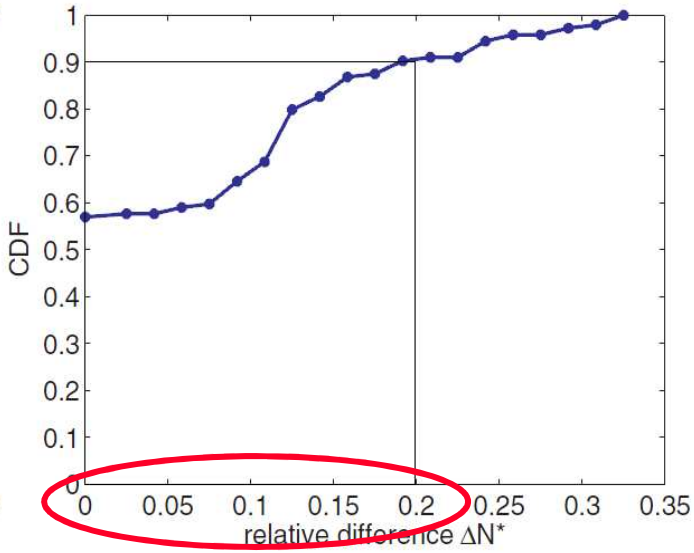


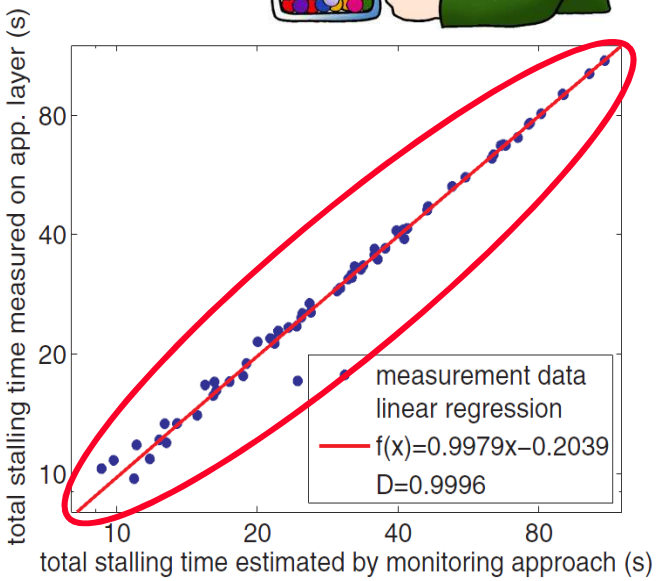
thresholds are critical for the correct estimation

- Example video: estimated stallings match the real stallings
- Playback and stalling **thresholds are average values**, obtained from the analyzed videos at the application layer
- **Small differences** in these thresholds **impact the estimation performance**

Number and Duration of Stallings (2011)





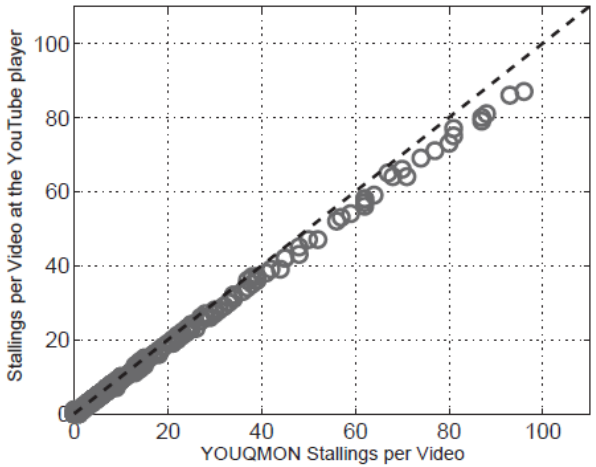


(a) $\Delta N = |N_a - N_e|$

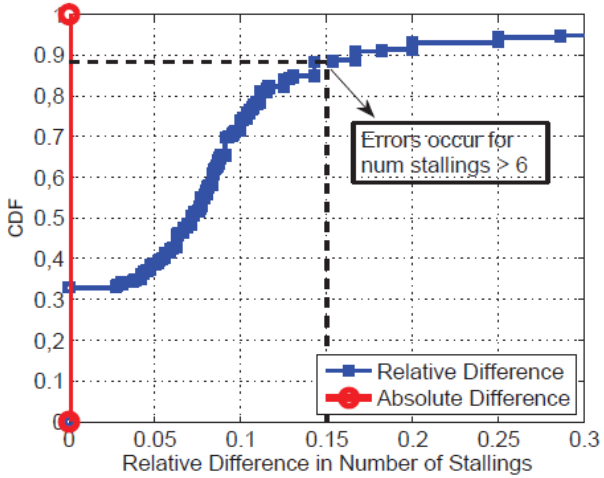
(b) $\Delta N^* = \frac{|N_a - N_e|}{N_a}$

- **# stallings are perfectly estimated for about 50%** of the videos, and the estimation error is below 2 stallings for 90% of the videos
- PROBLEM: recall that 1 or 2 single stallings have a very strong impact on QoE
- BUT **for 90% of the videos, relative errors are below 20%,** showing that this difference of 1 or 2 stallings occur for videos with > 5 stallings → OK!!!
- The estimation of total stalling time is highly accurate

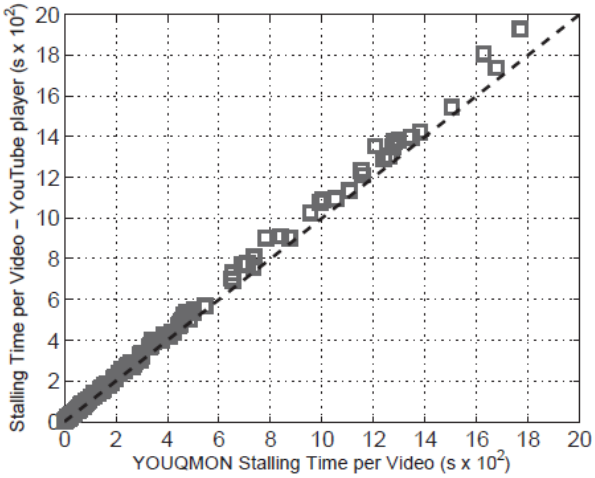
Number and Duration of Stallings (2012)



(a) Estimated number of stallings.



(b) Estimation error distribution.

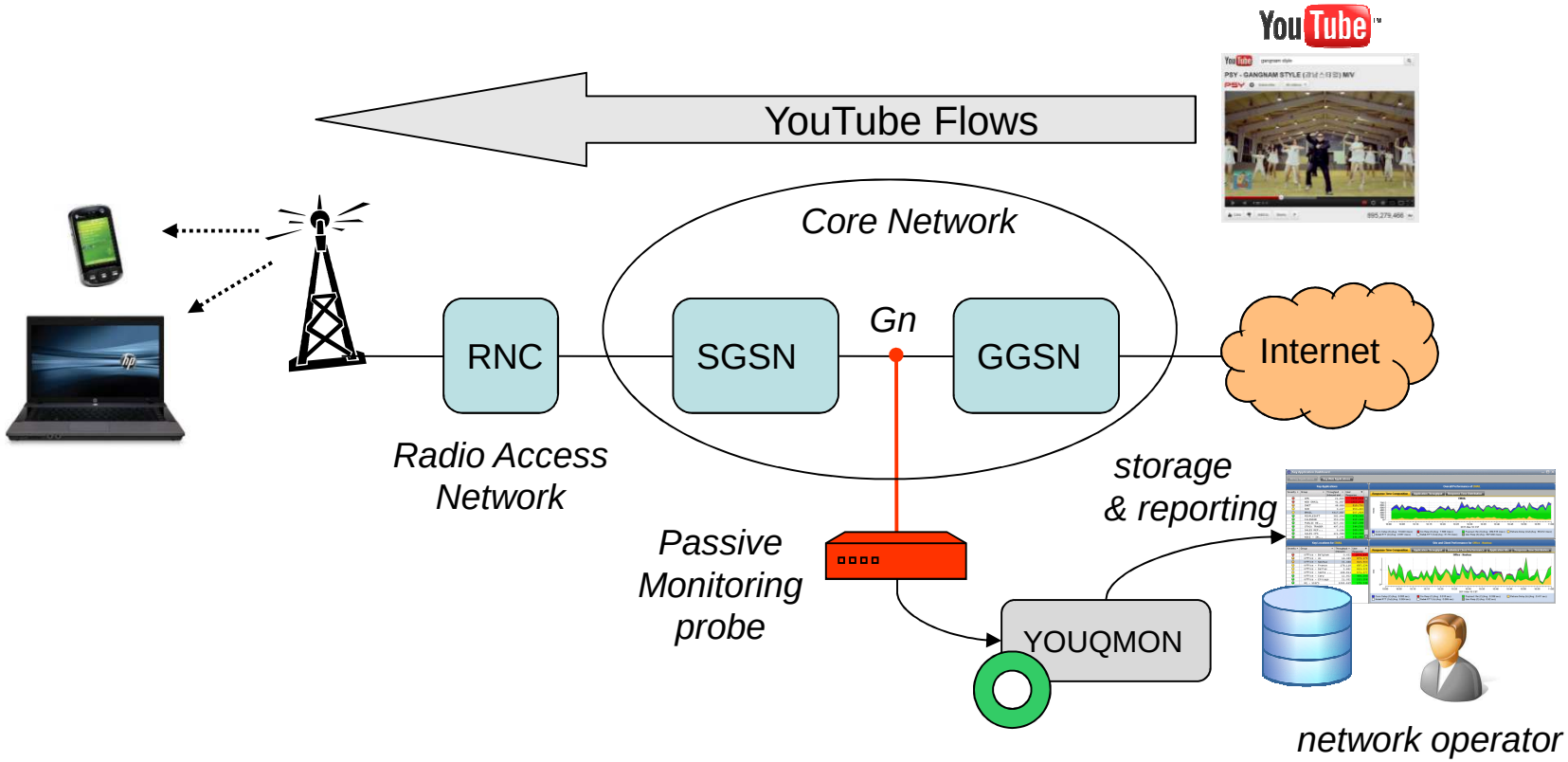


(c) Estimated stalling time.

- **Results still highly accurate after 1 year, even if YouTube is constantly modifying the player and the protocols**
- # stallings are perfectly estimated for about 35% of the videos
- For about 90% of the videos, relative errors are below 15% → **errors for videos with > 6 stallings**
- The estimation of total stalling time is still highly accurate

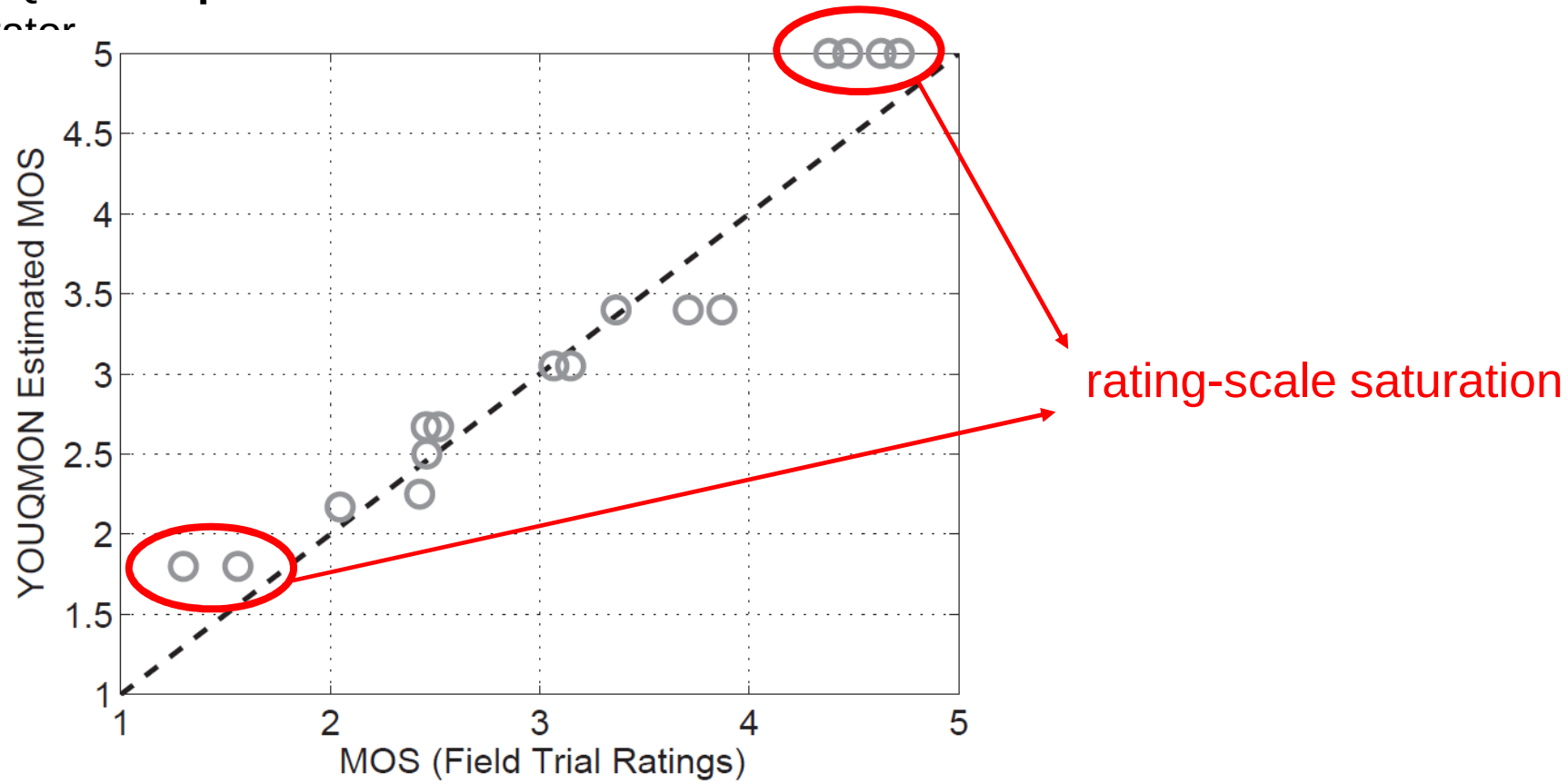
YOUQMON in a Mobile Network

- **YOUQMON** is the implementation of the complete solution on **METAWIN…**
- …a powerful system for **passive, on-line traffic monitoring** in mobile networks
- Includes parsers for **FLV and MP4 videos** (most popular containers in YouTube)
- **QoE tickets reported** for **each single ongoing YouTube video** every 60’



YOUQMON in a Mobile Network

- **Agreement** between **YOUQMON QoE tickets** and **subjective QoE** (field trial)
- Is my Network **providing** the **right experience to my customers**?
- YOUQMON **reported results for 1hr of live traffic** in a National-Wide mobile operator



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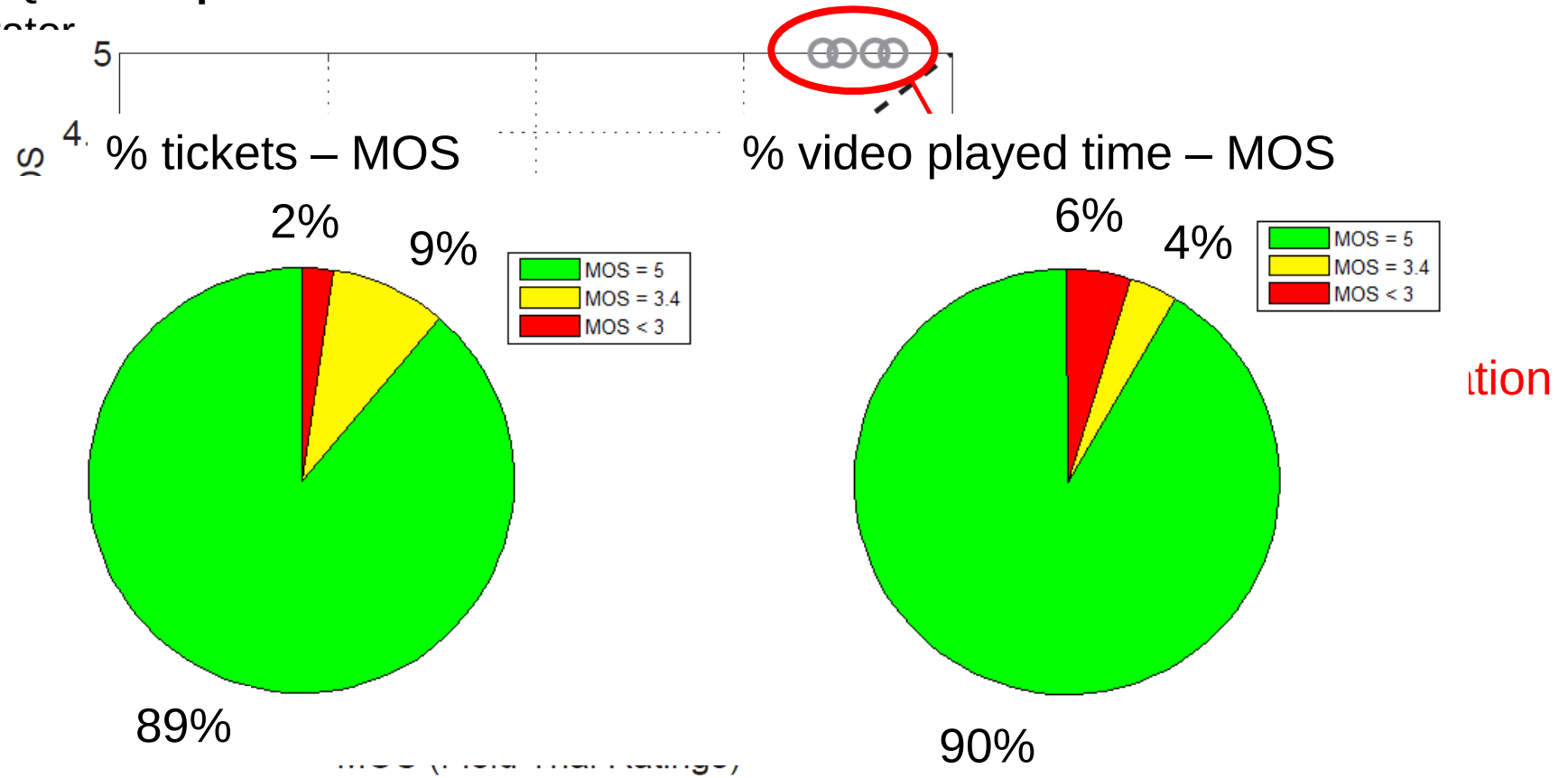
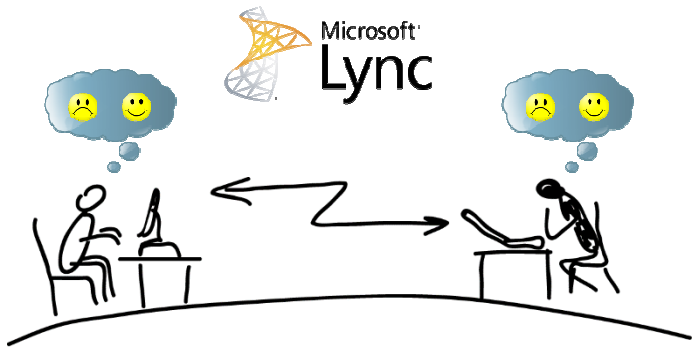


Cloud – QoE
The Case of Microsoft Lync Online



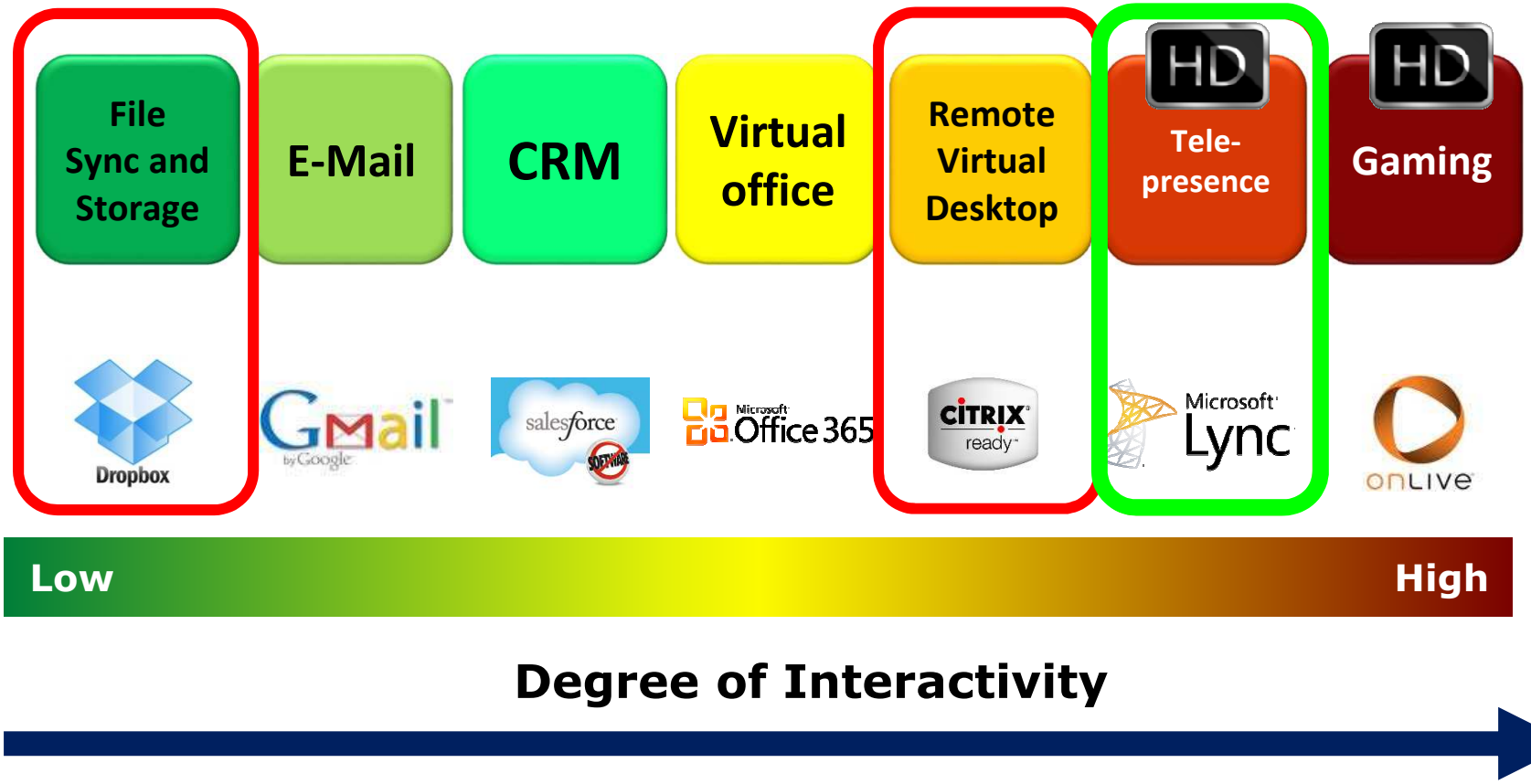
The Context: Cloud QoE

	Good QoE		Excellent QoE		QoE Saturation	
Service	RTT	Access BW	RTT	Access BW	RTT	Access BW
Cloud Storage	< RTT_1 ms	> UBW_{11} Mbps > DBW_{12} Mbps	< RTT_6 ms	> UBW_{61} Mbps > DBW_{62} Mbps	< RTT_{11} ms	> UBW_{111} Mbps > DBW_{112} Mbps
HTTP Video Streaming	< RTT_2 ms	> UBW_{21} Mbps > DBW_{22} Mbps	< RTT_7 ms	> UBW_{71} Mbps > DBW_{72} Mbps	< RTT_{12} ms	> UBW_{121} Mbps > DBW_{122} Mbps
Social Networking	< RTT_3 ms	> UBW_{31} Mbps > DBW_{32} Mbps	< RTT_8 ms	> UBW_{81} Mbps > DBW_{82} Mbps	< RTT_{13} ms	> UBW_{131} Mbps > DBW_{132} Mbps
Telepresence and Remote Collaboration	< RTT_4 ms	> UBW_{41} Mbps > DBW_{42} Mbps	< RTT_9 ms	> UBW_{91} Mbps > DBW_{92} Mbps	< RTT_{14} ms	> UBW_{141} Mbps > DBW_{142} Mbps
Virtual Desktop	< RTT_5 ms	> UBW_{51} Mbps > DBW_{52} Mbps	< RTT_{10} ms	> UBW_{101} Mbps > DBW_{102} Mbps	< RTT_{15} ms	> UBW_{151} Mbps > DBW_{152} Mbps

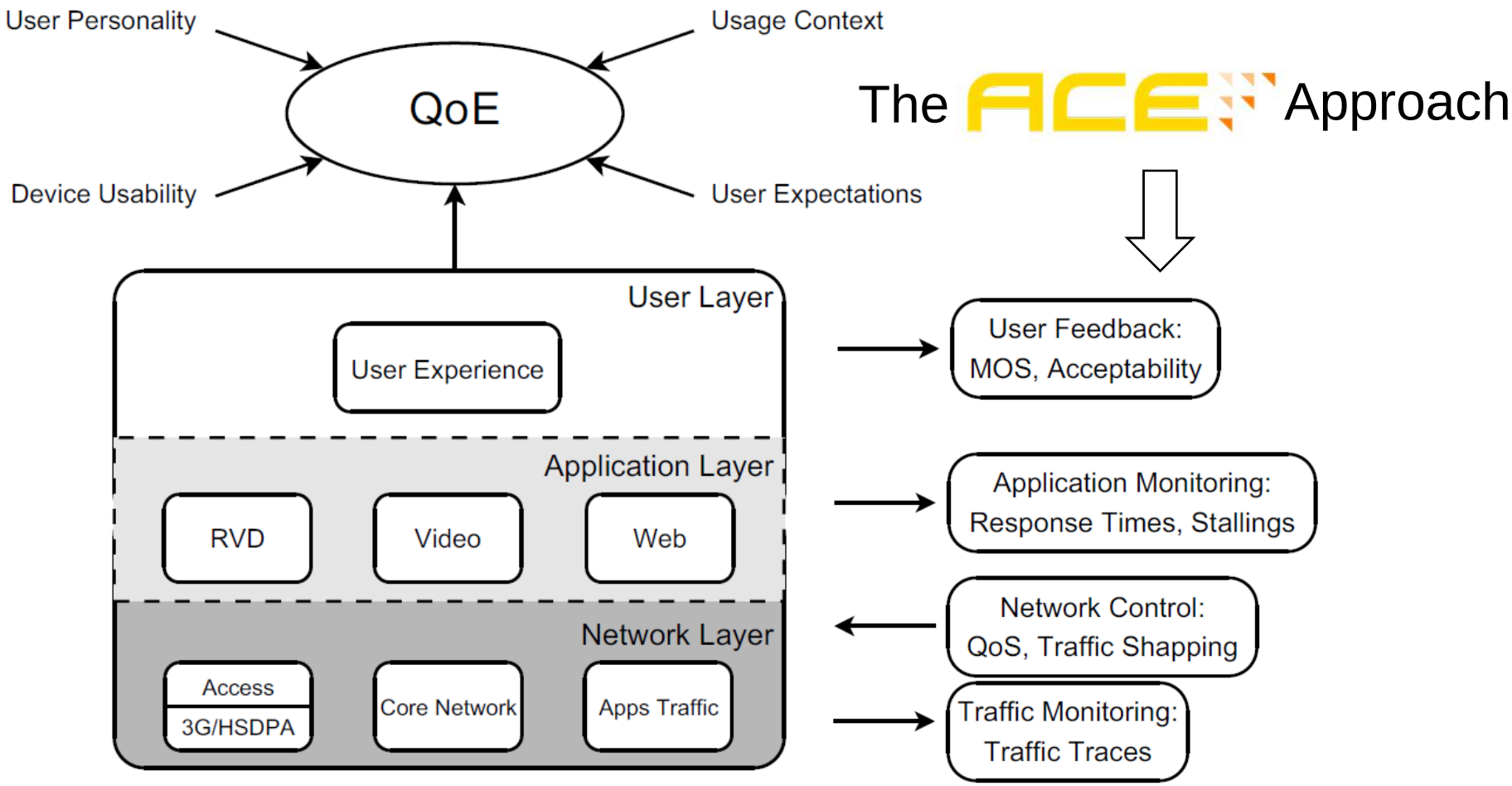
Cloud QoE is about interactivity

- The **impacts of the Network on Cloud QoE** are tied to the **interactivity degree of the application**:

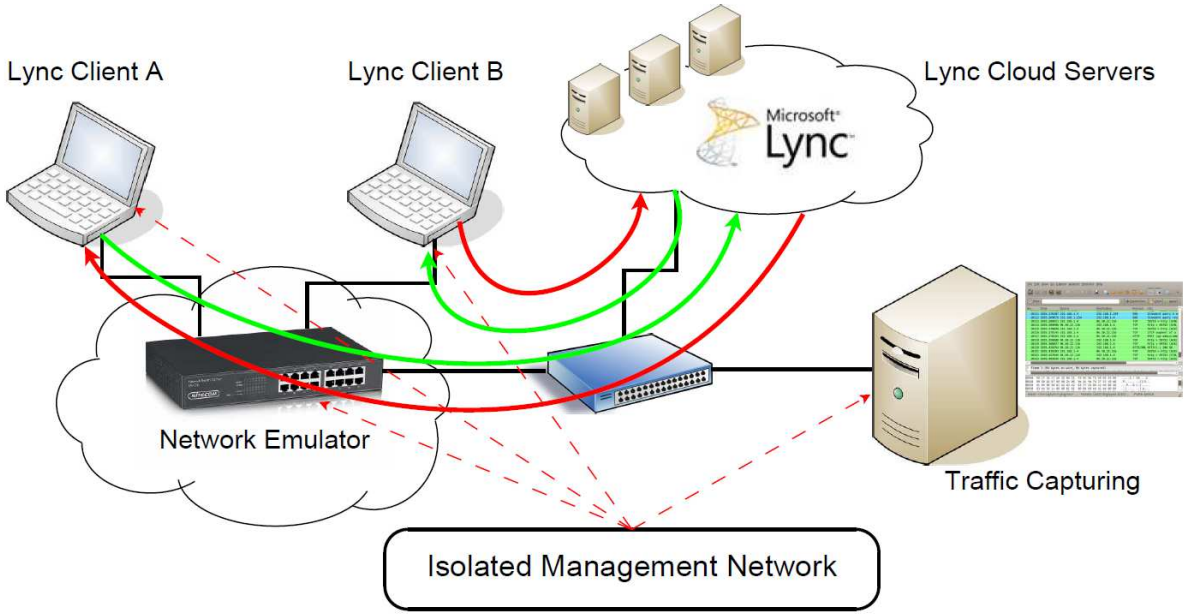
The ACE Project



QoE in Telepresence and Remote Collaboration



Testbed Layout using the iLab



- **Lync Online Cloud Service**, cloud servers located at Dublin and the Netherlands
- **Standard laptops with HD multimedia capabilities** as end devices
- **Traffic shaping at both access networks** (RTT and symmetric Up-link/Down-link)
- **Two independent rooms for remote participants**, independent control room with audio-visual access to testing rooms
- All the **traffic flows are captured** for post-analysis (re-bining of results)

Lync TRC QoE Tests

- **4 tasks covering** the different **interactivity levels** used in the context of **telepresence and remote collaboration**:
  - **Audioconferencing**: SCT tests
  - **Videoconferencing**: gamification (“who am I”), extended SCT tests
  - **PPT joint editing (with audio)**: gamification (thematic tours game)
  - **Full desktop sharing (with audio)**: gamification (puzzle game)
- **Gamification approach:**
  - Implement testing tasks as a game
  - Improve participant engagement
  - Permits to increase testing duration

TRC QoE Tests: QoS Levels

- Testing conditions:
  - we consider mobile networks' scenarios
  - 8 access RTT QoS levels (**RTT = 30, 50, 75, 100, 150, 200, 300, 500 ms**)
  - 7 access BW QoS levels (**BW = 256, 512, 756 kbps, 1, 2, 4, 16 Mbps**)
- User experience **ratings (by automatic prompting)**:
  - continuous ACR scale
  - **overall experience** in this specific task
  - **perception of network speed**
  - **audio quality, video quality, audio-visual synchronization**
  - **acceptablility** to use the application in the experienced conditions
  - **difficulty in achiving a task**
- **Note:** the following results consider both users as mobile users, and report only the Access network conditions for each participant (i.e., end-to-end RTT = 2 x Access RTT + 2 x network RTT to the cloud servers)

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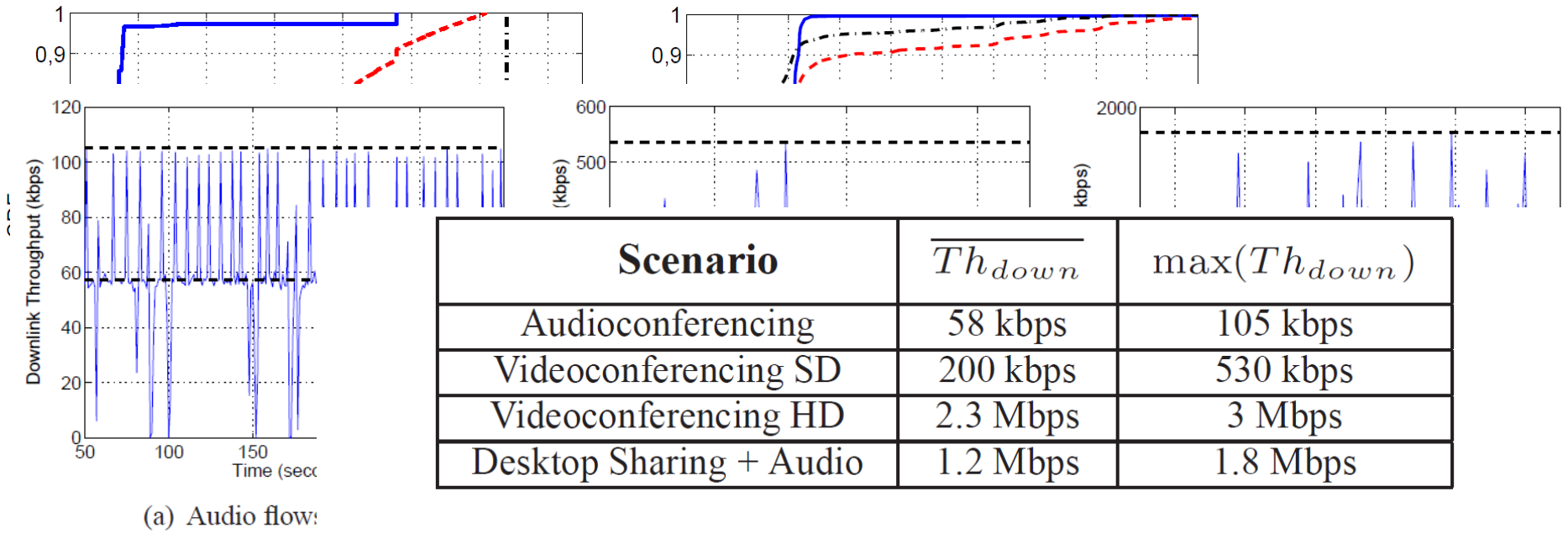
  - **audio quality**
  - **acceptablility**
  - **difficulty in a**

Access Tech	Access RTT (ms)
LTE	< 50
HSPA+	< 50
HSPA	< 150
UMTS	< 200
EDGE	< 350
GPRS	< 650

- **Note:** the following results consider both users as mobile users, and report only the Access network conditions for each participant (i.e., end-to-end RTT = 2 x Access RTT + 2 x network RTT to the cloud servers)

TRC traffic flows and Down-link Throughput



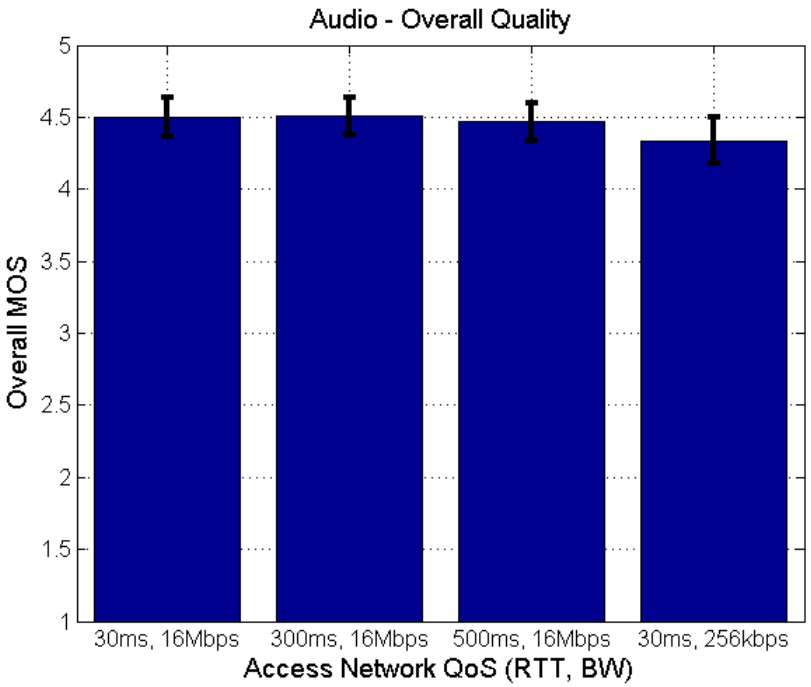
(a) Audio flows

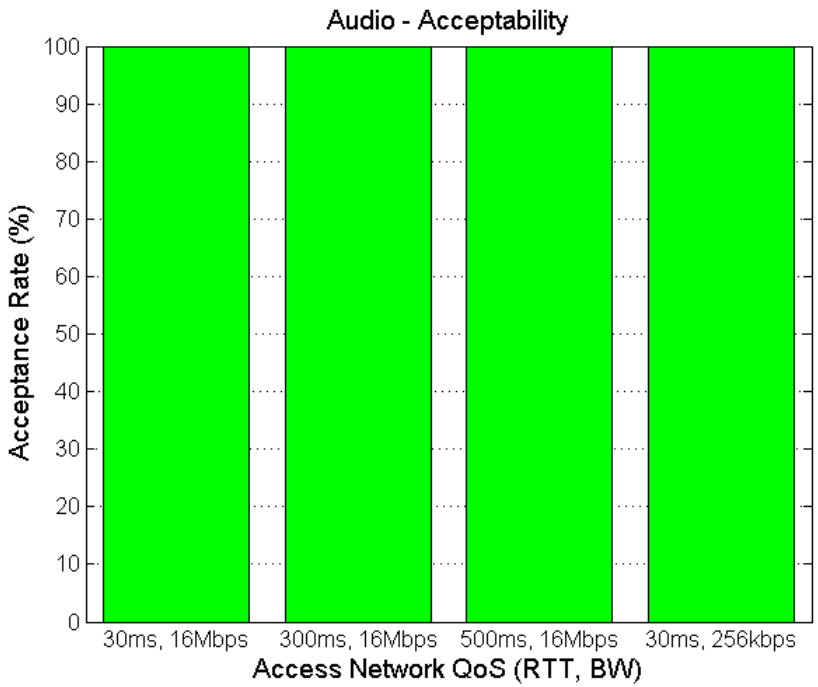
Scenario	$\overline{Th_{down}}$	$\max(Th_{down})$
Audioconferencing	58 kbps	105 kbps
Videoconferencing SD	200 kbps	530 kbps
Videoconferencing HD	2.3 Mbps	3 Mbps
Desktop Sharing + Audio	1.2 Mbps	1.8 Mbps

Average and maximum throughput achieved by Lync flows in the down-link direction.

- The **traffic characterization** step is paramount to understand the QoS requirements of each application → **define QoS testing conditions**
- Default G.722 codec for audioconferencing + signaling traffic
- Very different traffic patterns for videoconferencing SD and HD
- Desktop sharing requirements depend on the specific task being performed

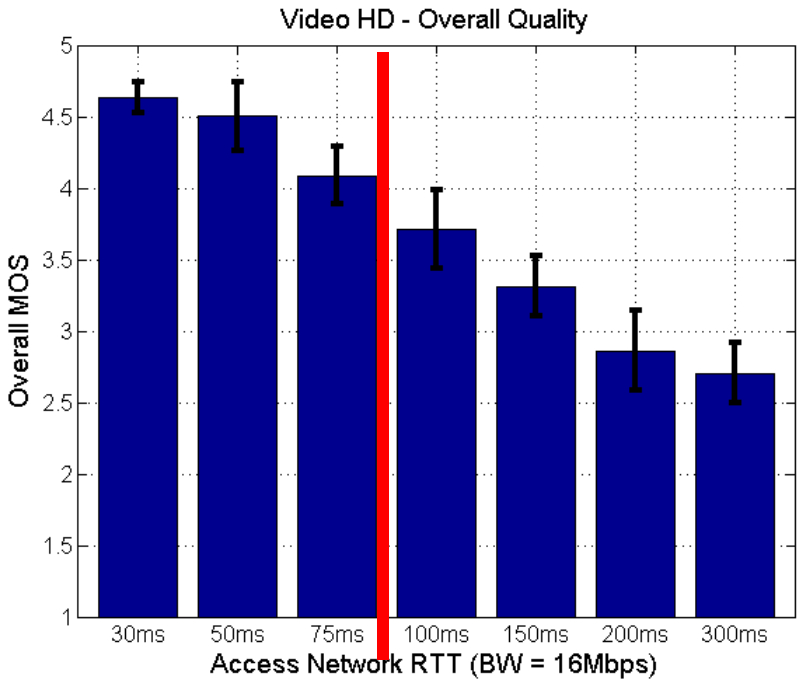
Interactive Audioconferencing

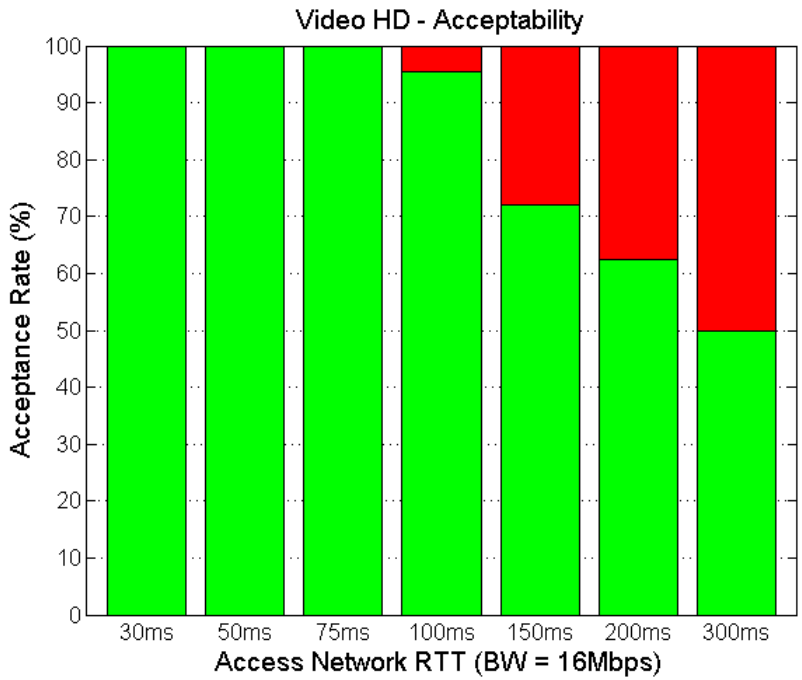




- **Simple "verification" evaluation:** is Lync Online good enough to handle voice calls with low QoS requirements? → YES
- **QoE in audio** calls is **not impacted** for the **tested QoS** cond.
- **Even and Access RTT = 500 ms and an Access BW of 256 kbps is almost imperceptible for the end users**

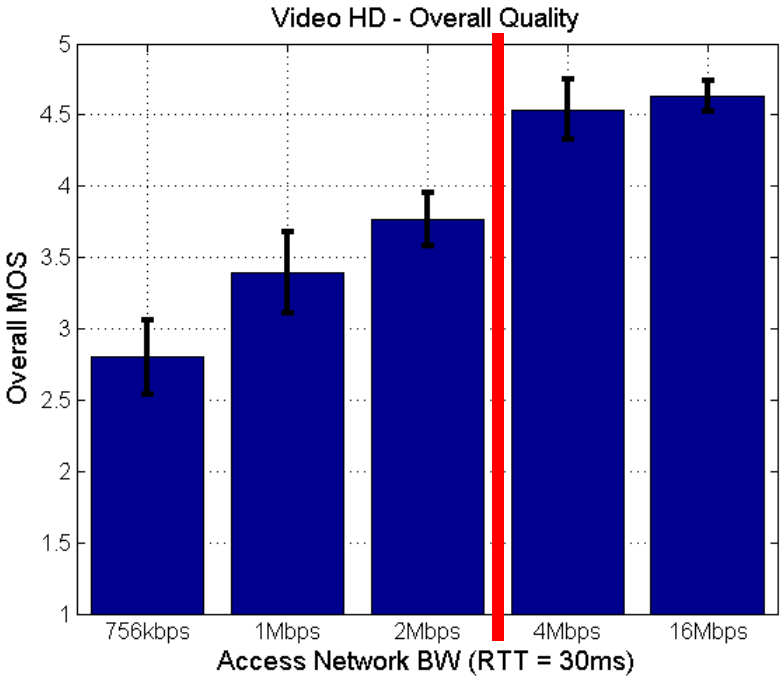
Videoconferencing – RTT analysis

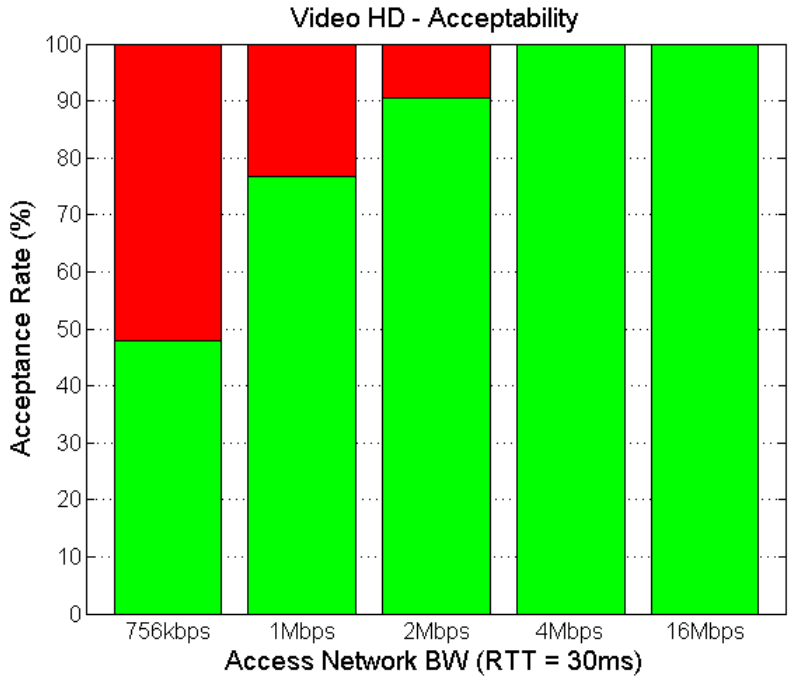




- The **overall experience** with Videoconferencing SD is **near optimal for up to Access RTT = 300ms**
- **Access RTT < 100ms has limited impact on the overall QoE and acceptability of Videoconferencing SD**
- **Results are much more critical for the HD case:**
  - **Access RTT <= 75ms** provides **good to optimal overall QoE** and **full acceptance**
  - **Access RTT = 100ms** drops **overall QoE** to **average experience**

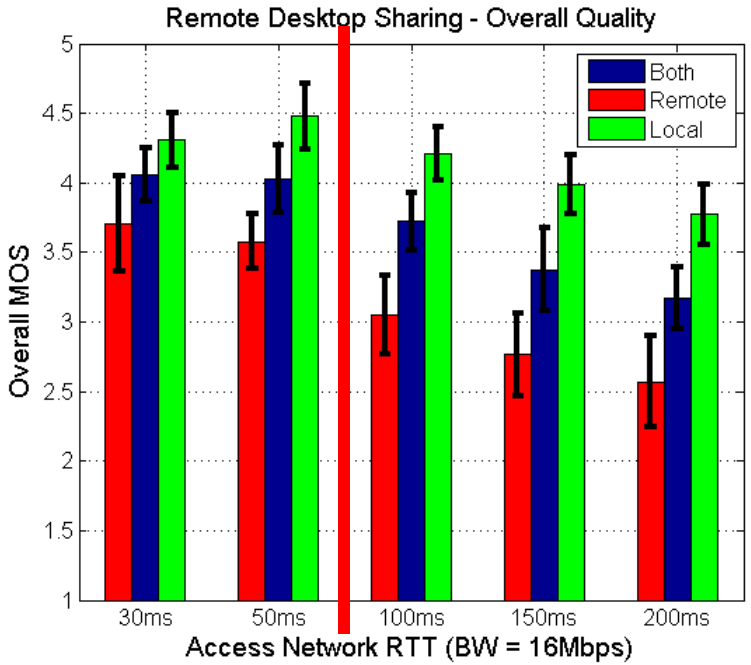
Videoconferencing – BW analysis

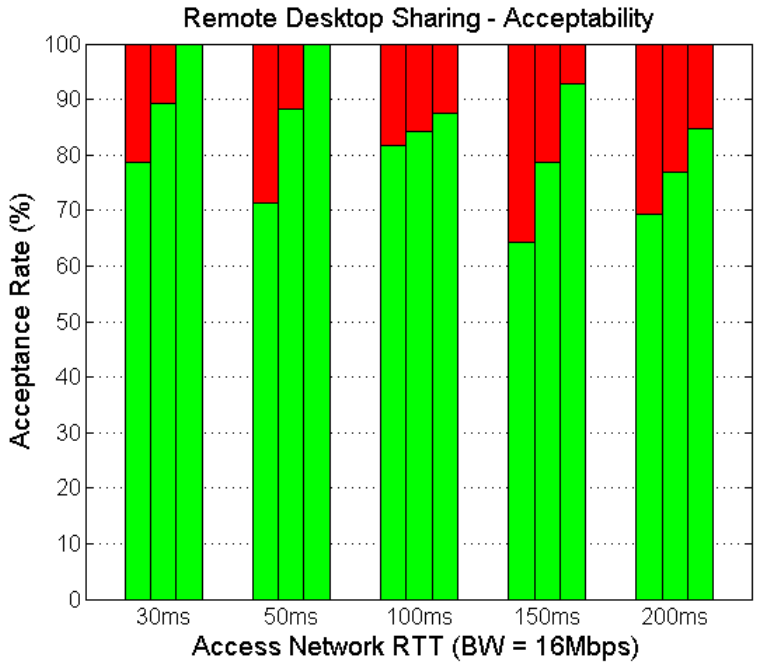




- **BW = 1Mbps** provides **optimal overall experience** with acceptance rate > 95% in **Videoconferencing SD**
- **QoE saturation for BW > 1Mbps**
- **BW = 4Mbps** provides **optimal overall experience** with acceptance rate of 100% in Videoconferencing HD
- **QoE saturation for BW > 4Mbps**
- **BW** should be **high enough to avoid traffic shaping** to limit QoE degradation

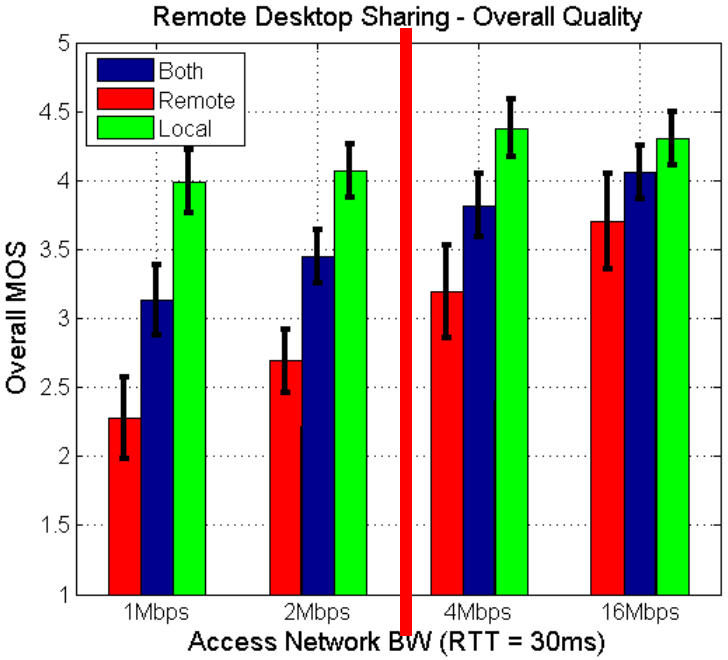
Remote Desktop Sharing – RTT analysis

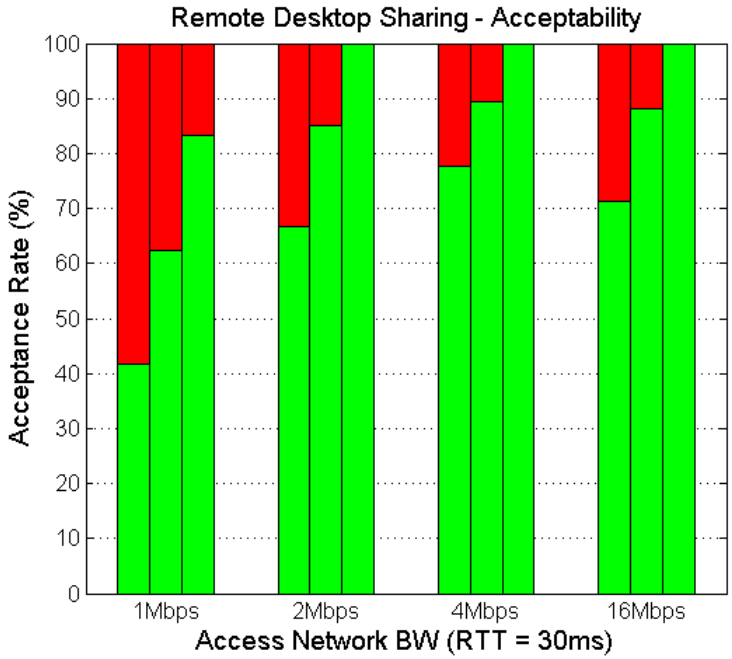




- **NOTE:** the impacts on QoE are different for the **Local** participant who shares the desktop and for the **Remote** one who remotely interacts with the desktop
- As expected, the **QoE of the local** participant is **always lower** than the undergone by the **remote** one
- **Optimal QoE is not achieved for this task in Lync Online for both users**
- The **overall experience** and **acceptability** begin to **degrade** for **Access RTT > 50ms**

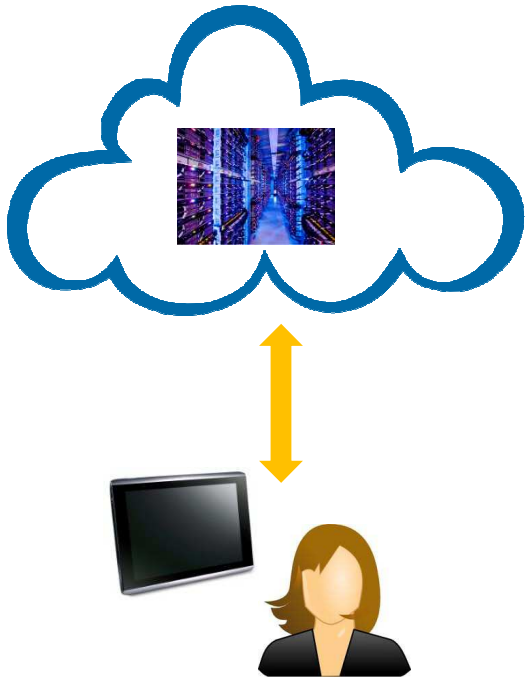
Remote Desktop Sharing – BW analysis



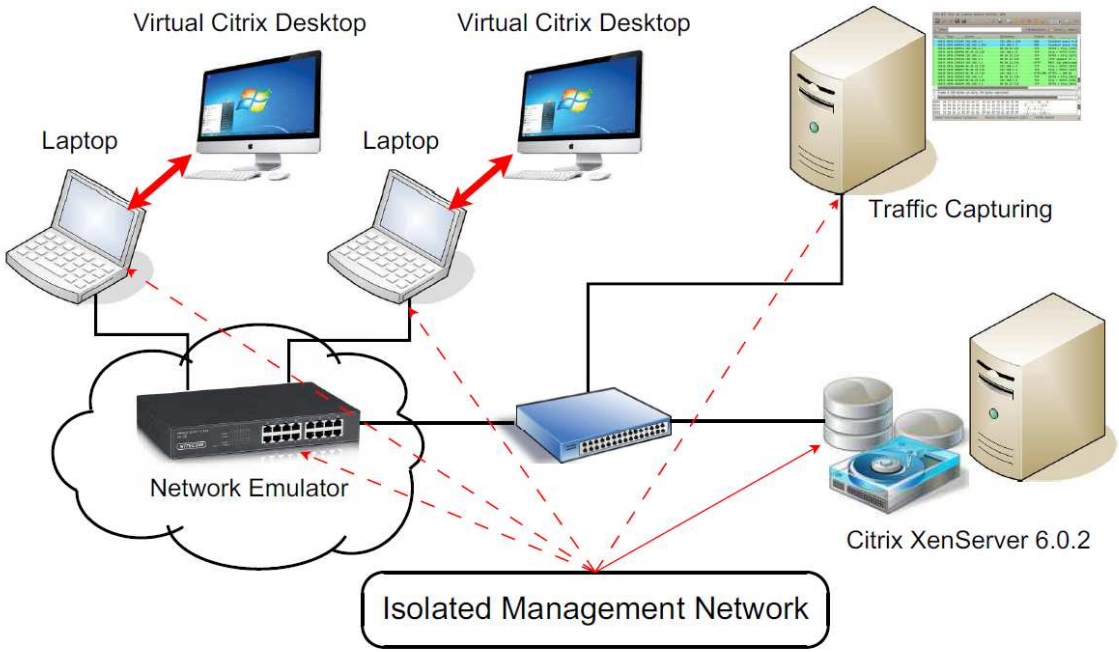


- **Close to good overall experience** and **high acceptability** are achieved for **BW = 4Mbps**
- Bandwidth-eager application: **improved QoE for the Remote user with bandwidth increases above 4 Mbps**
- Still, optimal QoE is not achieved for full remote desktop sharing through Lync Online → **quality context–awareness (don't expect a local edsktop!)**

Quality of Experience in Remote Virtual Desktop Services



Testbed Layout using the iLab



- **Citrix Virtual Remote Desktop System** used in the tests
- Two identical setups: a **laptop** and a **Citrix Remote Virtual Desktop**, provisionned by a **Citrix XenServer** (v 6.0.2)
- **Traffic shaping** b**etween the XenServer** and the Virtual Desktops
- All the **traffic packets between the XenServer and the virtual desktops are captured** for post-analysis

Remote Desktop QoE Tests

- 4 tasks covering the different interaction techniques used in the context of desktop applications:
  - **Typing**: transcribe a printed text
  - **Scrolling**: document reading with scrolling
  - **Drag & Drop**: drag & drop images to specific screen locations
  - **Menu browsing**: multiples menu-browsing

- **Gamification approach:**
  - Implement testing tasks as a game
  - Improve participant engagement
  - Permits to increase testing duration
  - Implementations: Quiz Game, Puzzles, Interactive Menu Browsing

Remote Desktop QoE Tests

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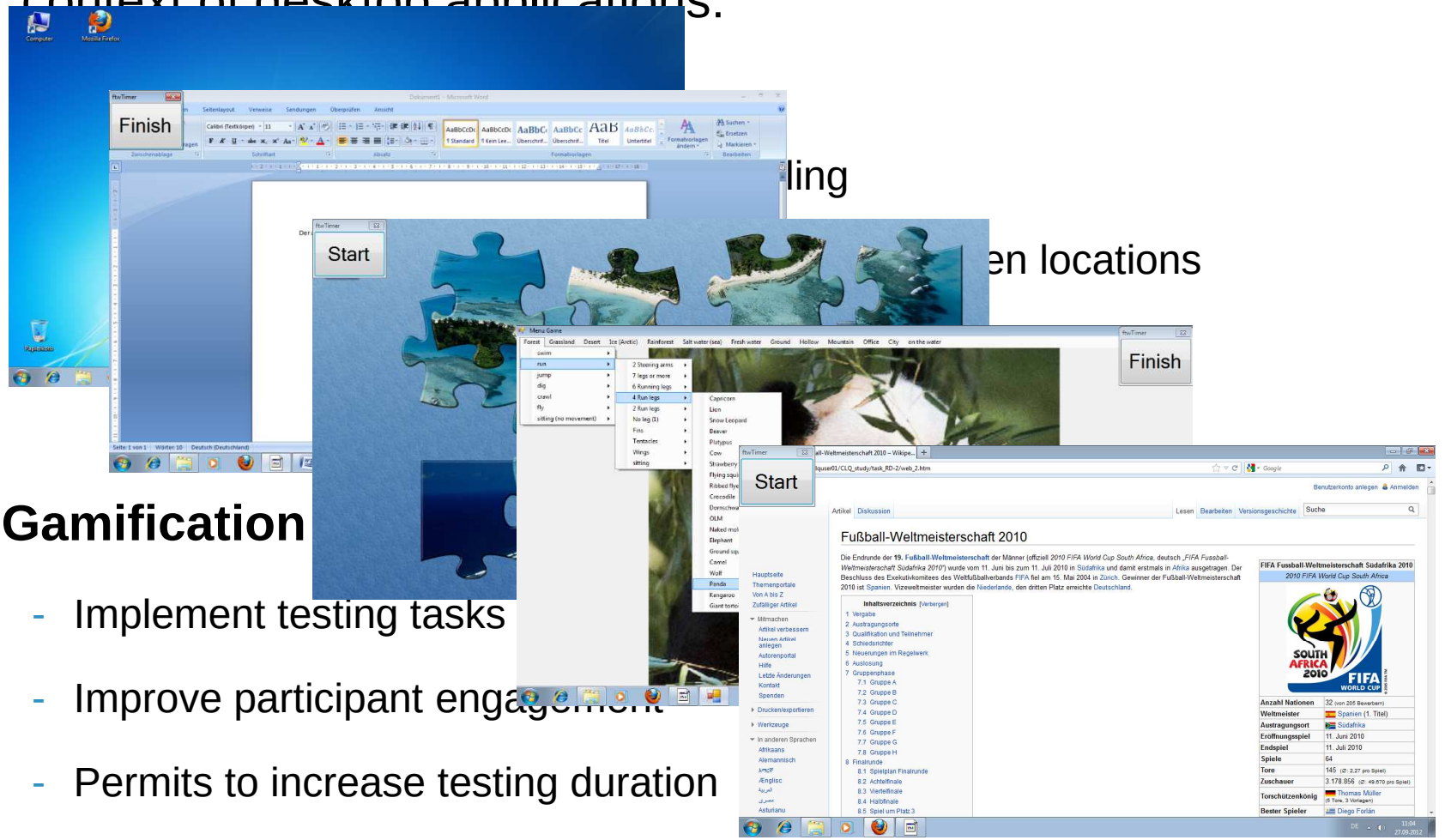

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- **Gamification**
  - Implement testing tasks
  - Improve participant engagement
  - Permits to increase testing duration
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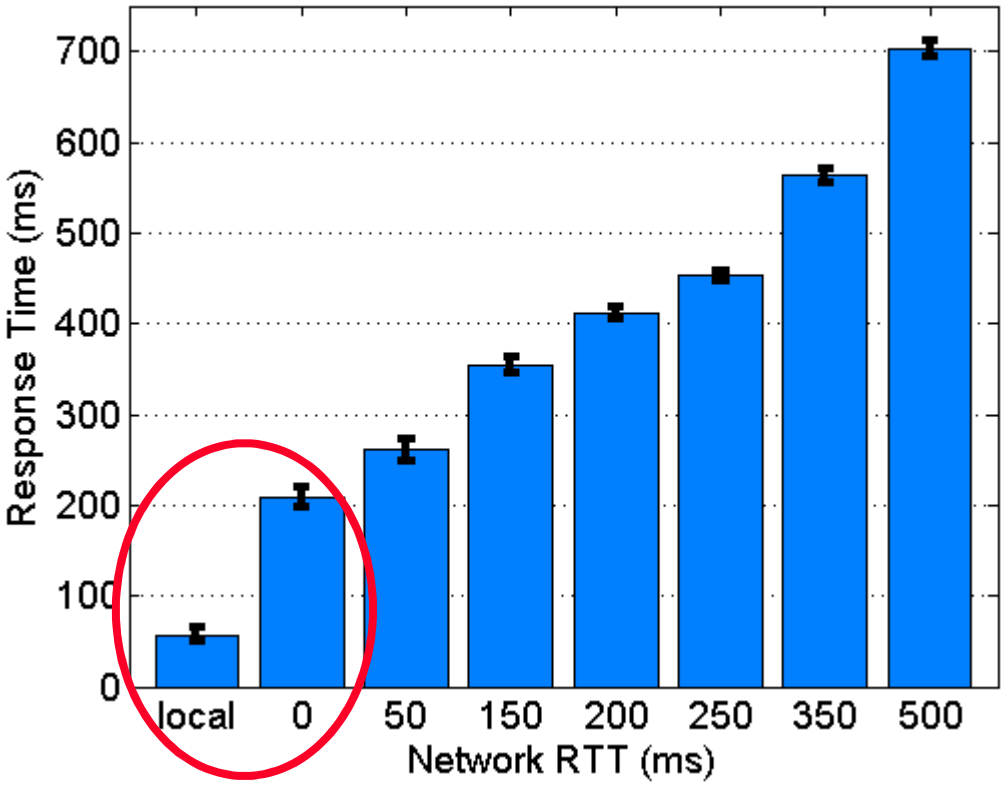
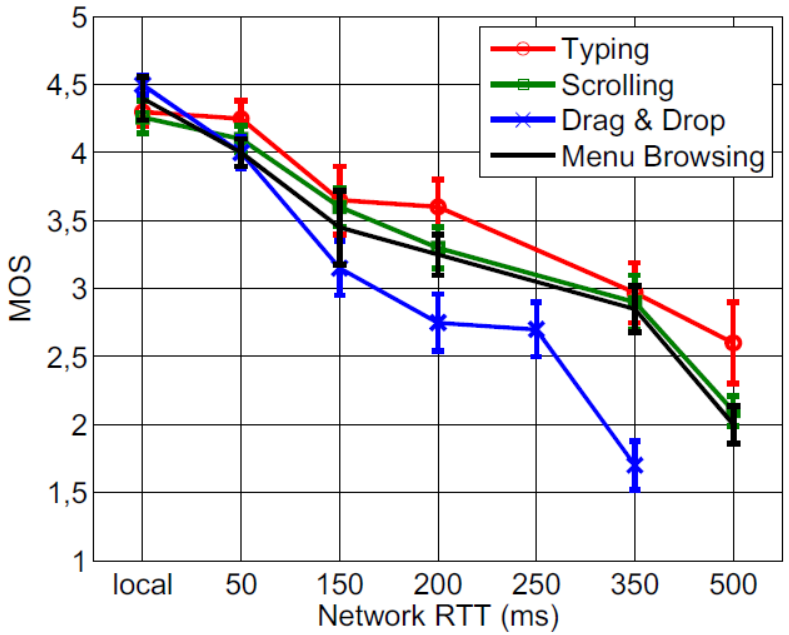
Citrix RVD Response Times



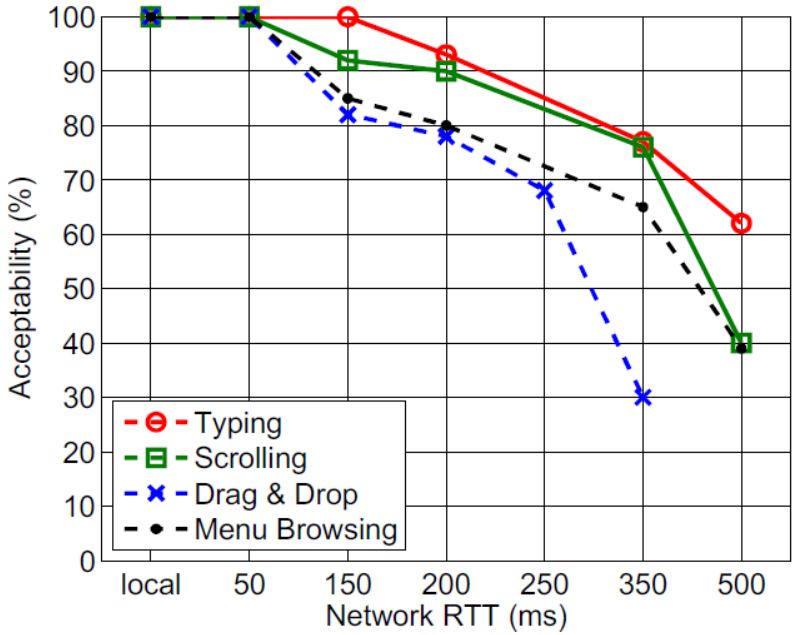
- The **Citrix Response Time** (i.e., time between a user input and the corresponding screen refreshment) **is not negligible**

- Compared to the response times of a local desktop application, **Citrix adds an additional delay of about 150ms**, which **impacts** the **QoE** of the end-user, **even under optimal network QoS** (check the following slides)

RVD QoE vs Network RTT



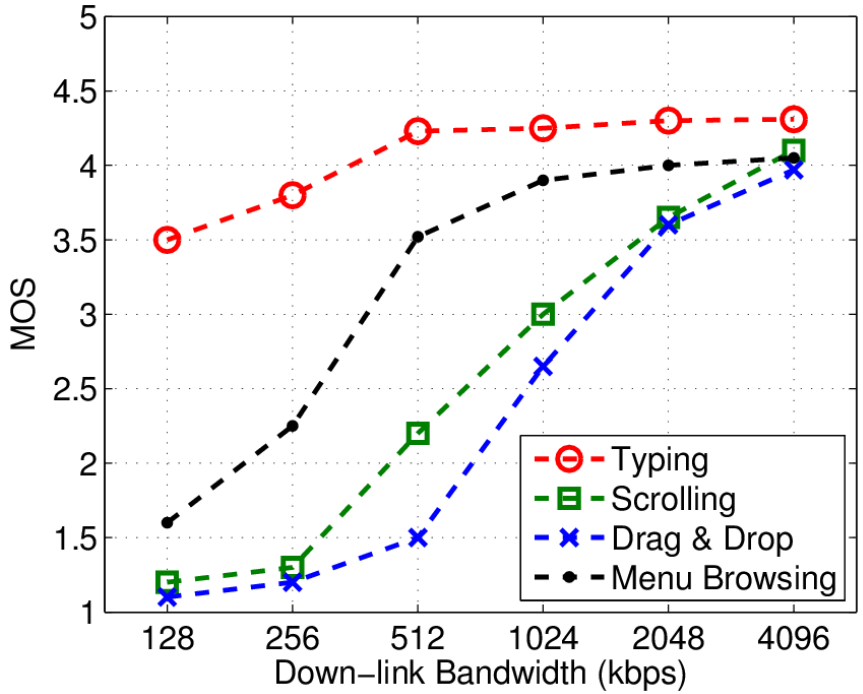
Overall Quality vs. RTT.



Acceptability vs. RTT.

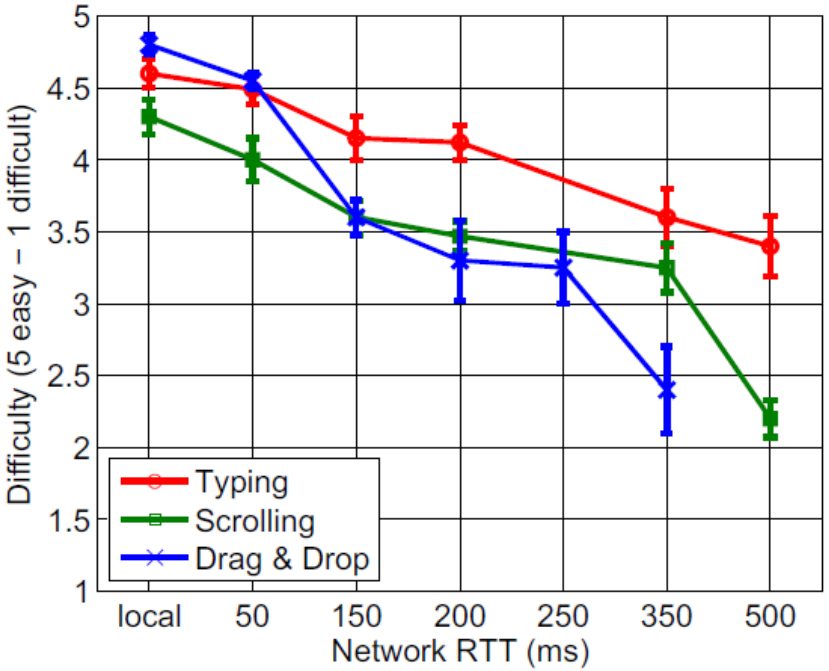
- Depending on their specific characteristics, different tasks have different QoE sensitivity to network impairments.
- More interactive and throughput-intensive applications are more sensitive to RTT
- **RTT should be kept below 150 ms** to achieve good QoE and high acceptance with Citrix RVD systems in generic desktop applications.

RVD QoE vs Down-link Bandwidth

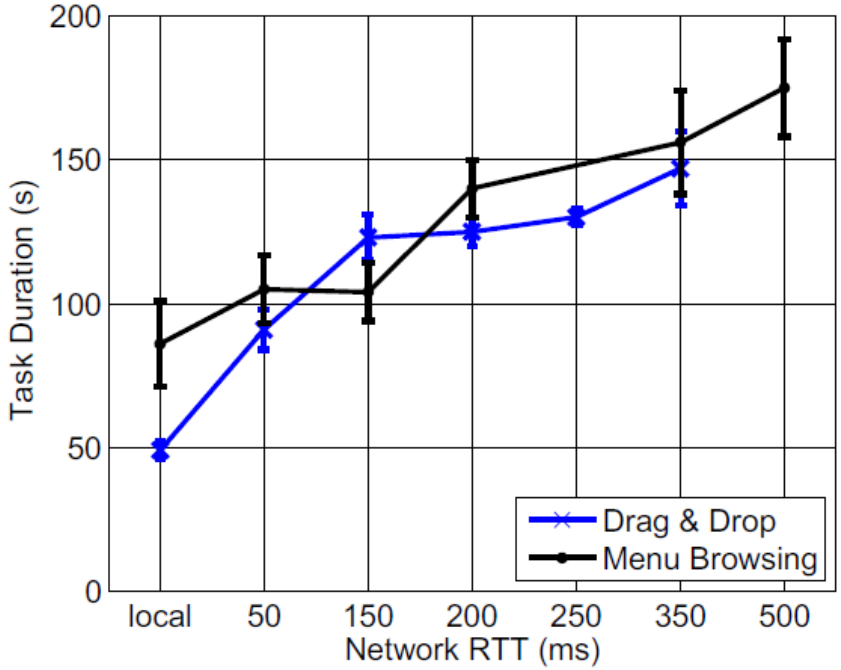


- **Good QoE can be expected if the downlink bandwidth is high enough to avoid shaping the downlink traffic**
- A **minimum downlink bandwidht of 2 Mbps** is necessary to achive **good QoE** in the evaluated tasks
- **4 Mbps of downlink bandwidth avoids QoE degradation** due to downlink traffic shaping

Impact of RTT on User Behavior and Productivity



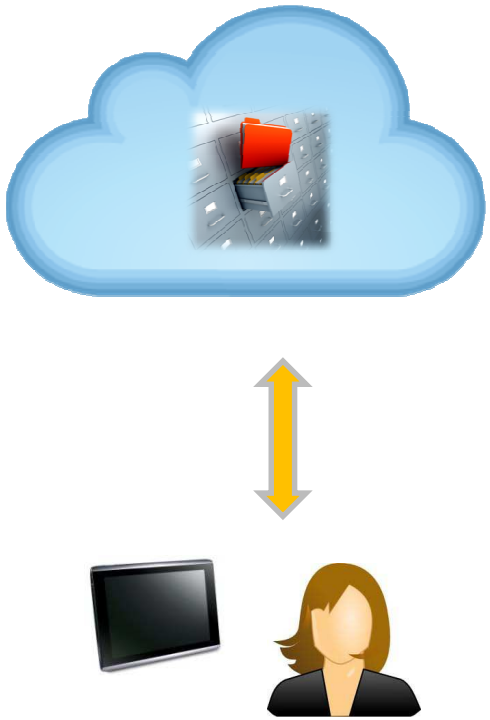
Difficulty to perform the task.



Required time to complete the task.

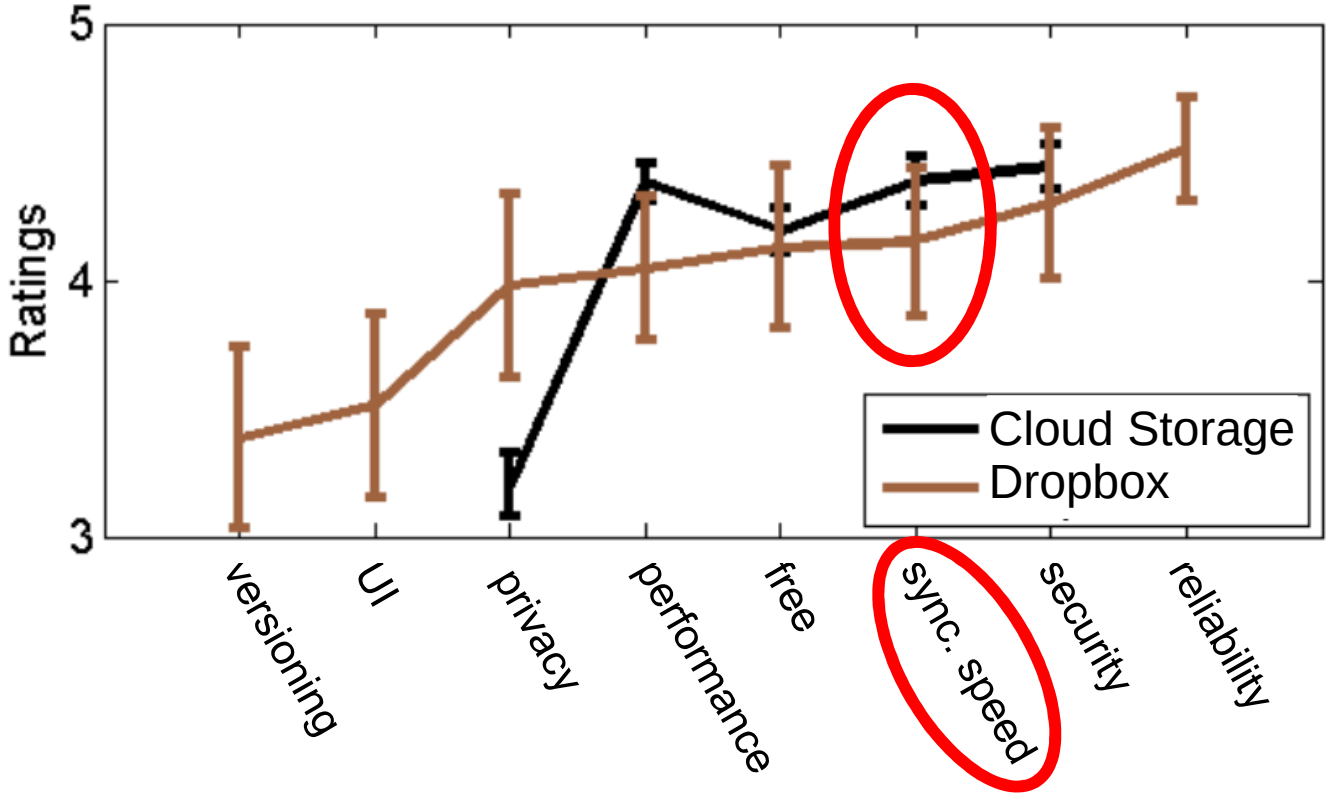
- **Cloud QoE is not only** about **how smooth the application runs on the client**,
- **How difficult** it is for a user to **interact with a remote system** when **response times are high**
- **A RVD user may take up to 3 times more to complete a task in poor network conditions w.r.t. a local Desktop**

A First Look at QoE in Personal Cloud Storage Services



What Matters for Cloud Storage Users?

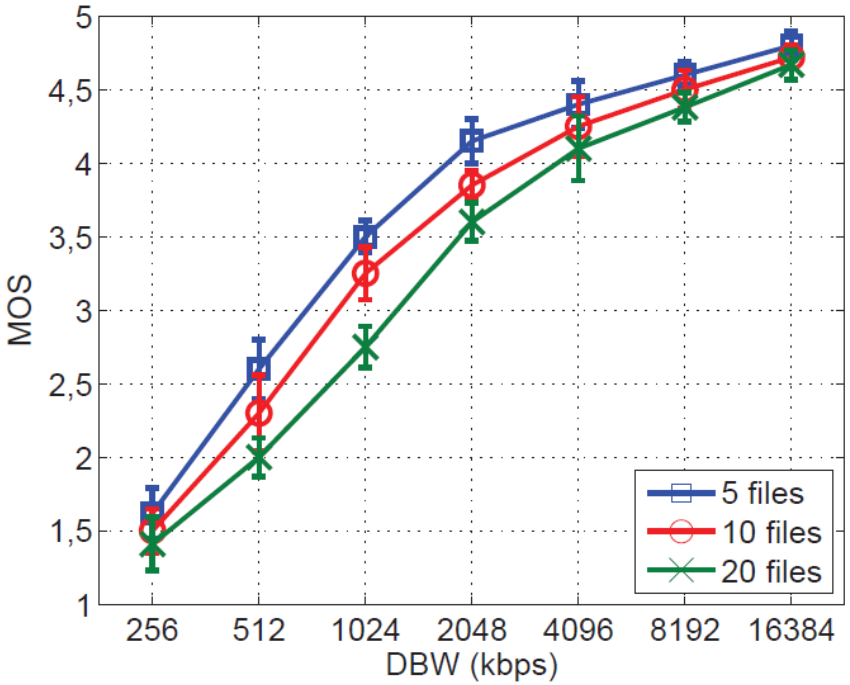
- **Survey** on **Cloud storage services** (about 400 participants) to identify **QoE influencing factors** and relevant features
- **File synchronization time** (or speed) is the most relevant QoE feature from an operational perspective



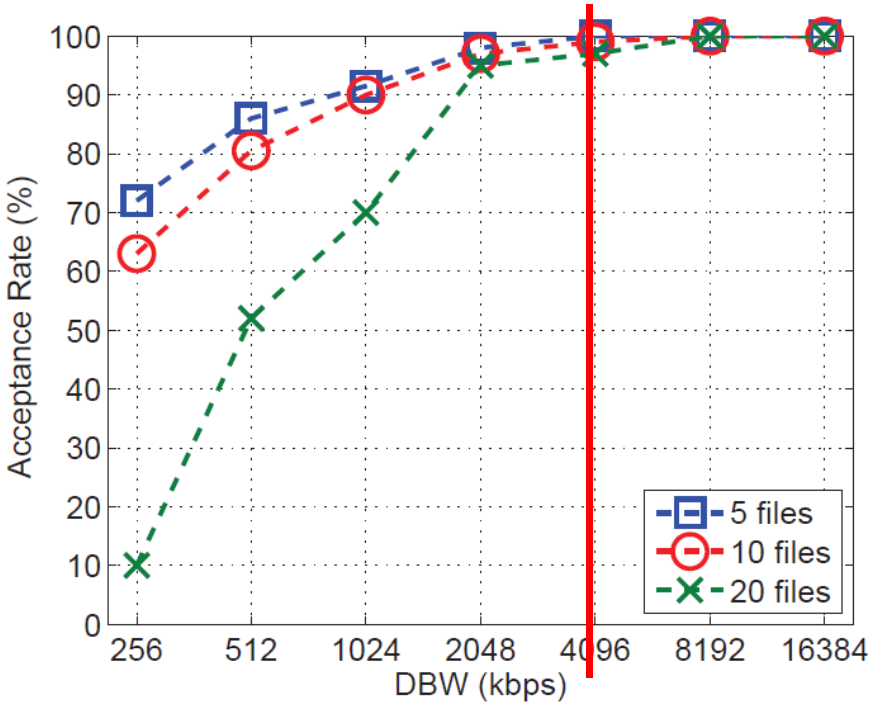
From:
Amrehn et al.
PQS 2013

Average rating on the importance of different features

Down-Synchronization of files



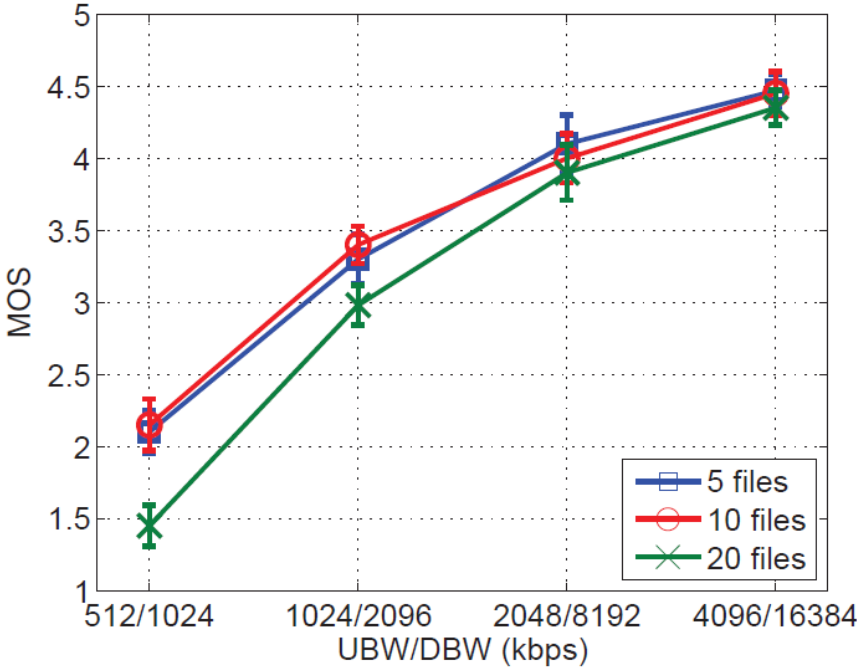
(a) Overall Quality vs DBW.



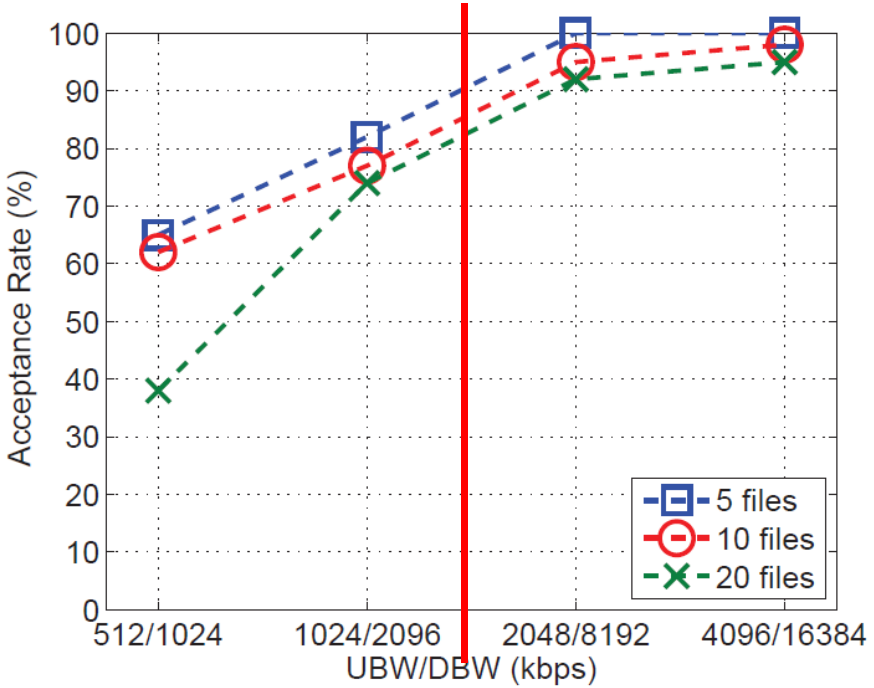
(b) Acceptance rate vs DBW.

- A **downlink bandwidth (DBW)** of **4 Mbps** is enough to reach **100% acceptance** and good QoE
- **Saturation effects** are very **dependent** on the **size and number of files** transmitted, which translates into **different waiting times**:

Multi-Device Synchronization of Files



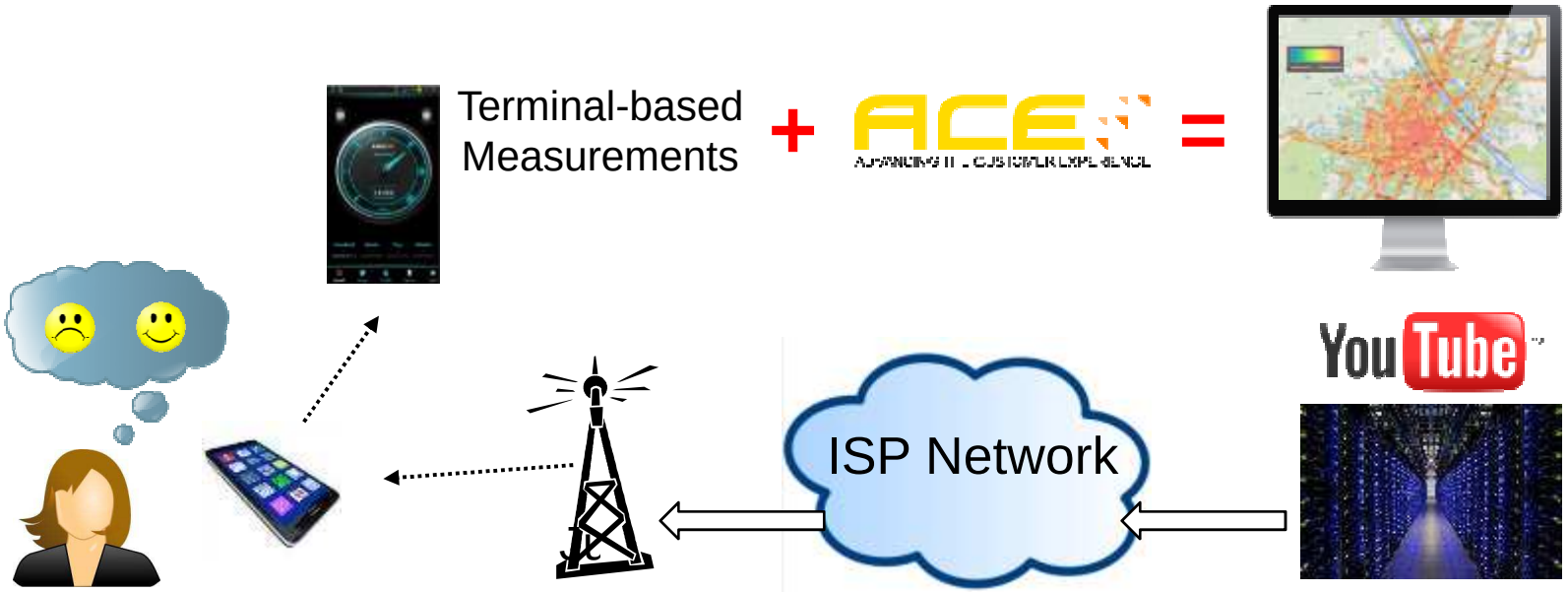
(a) Overall Quality vs UBW/DBW.



(b) Acceptance rate vs UBW/DBW.

- In multi-device sync, the number of files has little influence on the user ratings: participants seem to compensate additional waiting times with synchronizing more files
- An **uplink/downlink bandwidth** of **2048/8192 kbps** to reach **> 80% acceptance** and good QoE
- **Saturation effects** are highly **dependent** on the **size of files** transmitted

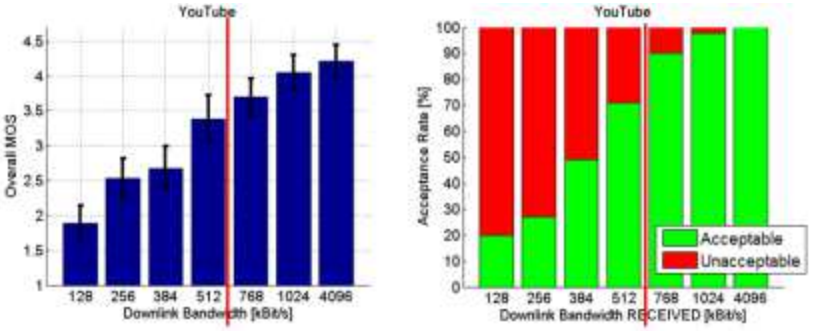
Smart – QoE
QoE Monitoring from Mobile Devices



Terminal-based QoE Measurements – Use Cases

- **Motivations:**
  - **Enable customer-centric** network and service **quality** measurement for **mobile terminals.**
  - **Bridge the gap** between **QoE** knowhow and the **operation/optimization** of **mobile networks**.
- **What for? Use Cases**
  1. QoE-based mobile network assessment and reporting
     - How good is my mobile network to satisfy my customers?
  2. QoE-based mobile network monitoring and fault diagnosis
     - Which KPIs reveal what QoE problems, and why is my mobile network experiencing those problems?
  3. QoE-based mobile network dimensioning and deployment
     - How should I dimension, deploy and operate my network to satisfy my customers?

QoE-based Network Assessment and Reporting (1/3)



(1) FTW QoS → QoE mappings

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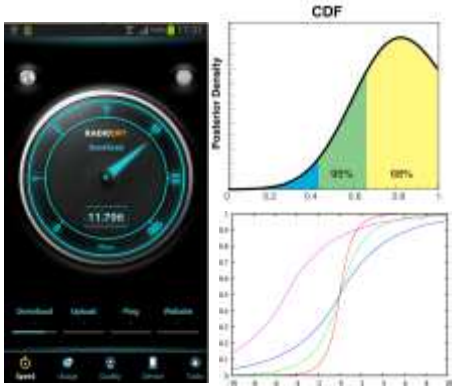

(2) Throughput measurements from end-devices (RadioOpt) → Extended with app-level KPIs

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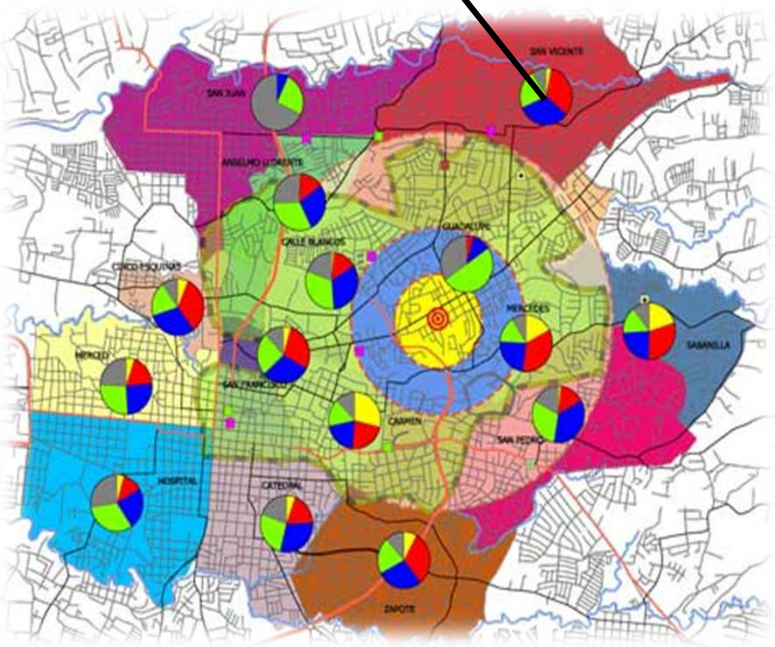
64% YouTube QoE is Excellent
20% YouTube QoE is Good
10% YouTube QoE is Fair
6% YouTube QoE is Bad

(3) Combine both to estimate the QoE experienced by the customer

QoE-based Network Assessment and Reporting (2/3)

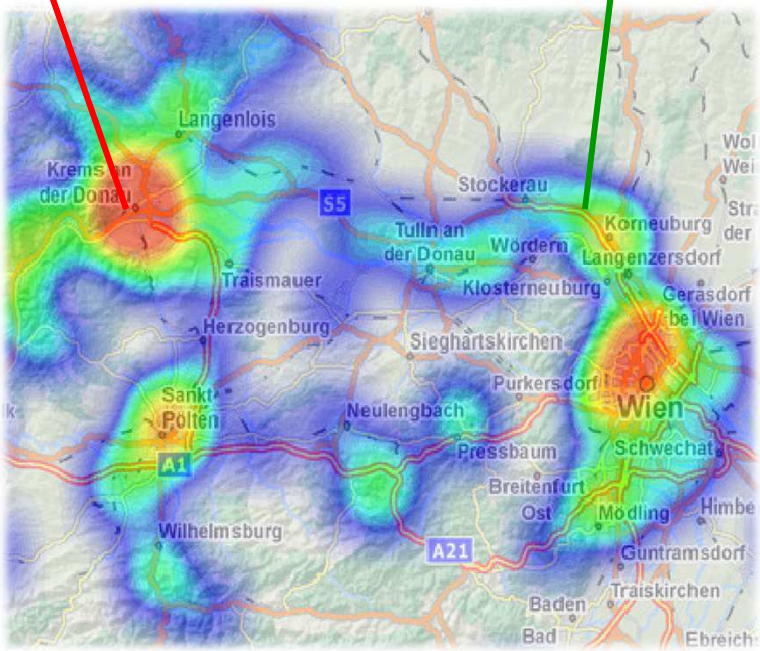
- **QoE–based dashboard that assesses network performance**

QoE distribution
Per service



Bad QoE
Low acceptance rates

No quality issues
High acceptance rates



QoE-based Network Assessment and Reporting (3/3)

- It is **sufficient to measure the QoE of the most critical/popular applications** to assess the QoE-based performance of the network

- For example:
  - My **customers use** mainly **YouTube, Facebook, WhatsApp, and Web Browsing**
  - Evaluate the **QoE of these services**
  - Based on the results of these services, **gauge the performance of the network**
  - Define a **more general and aggregated KPI** reflecting the performance of the network, **according to** the previous, **per-service QoE estimations**

Terminal-based Measurement Tools

- **Multiple tools available** for terminal-based network and traffic measurements **related to network quality**.
- A **brief taxonomy** includes:
  - Active/passive **network speed measurements**
  - **Application-level measurements**
  - Traffic **utilization volumes** per application
  - **Signaling** and **coverage** measurements
  - **RAN measurements**
- The next slides briefly describe some of these tools, selected on the basis of their popularity and/or their capabilities

Terminal-based Measurement Tools

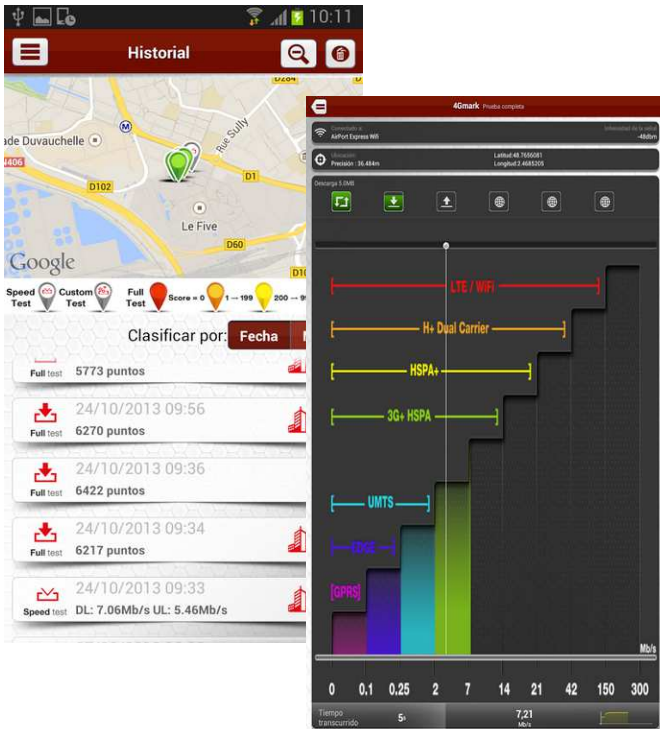
Active/passive network speed measurements (1/2)

- **Speedtest.net:**
  - The **most popular speed test tool** (10M+ downloads)
  - **Only active** measurements (uplink/downlink)
  - Relies on a global set of anchor servers (including voluntary hosting) to perform accurate throughput measurements
- **RadioOpt Traffic Monitor:**
  - The tool used in the study
  - **Active and passive speed measurements**, split by the application generating the traffic, results compared to co-location values
  - Active measurements include **application-level KPIs such as page load times** and **video stallings** (this was not verified by FTW, as measuremnets were not available in the accessed TM logs).
  - Geo-location included

Terminal-based Measurement Tools

Active/passive network speed measurements (2/2)

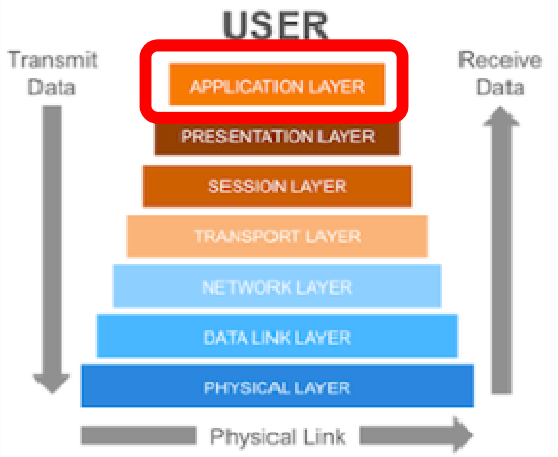
- **4G Mark:**
  - **Only active** measurements
  - **Great GUI**, including **RAT ranges** in speed measurements (better user interpretation)
  - **Explicit location feedback** request for active tests (e.g., train, office, walking, car, metro etc.)
  - **Page load times** and download **throughput** to **popular websites** (google, youtube, facebook, etc.)
  - Geo-location included



- **Open Signal:**
  - Mainly focused on **coverage and signal strength**
  - **Includes active** measurements (uplink/downlink)
  - **ISP benchmarking**

Terminal-based Measurement Tools

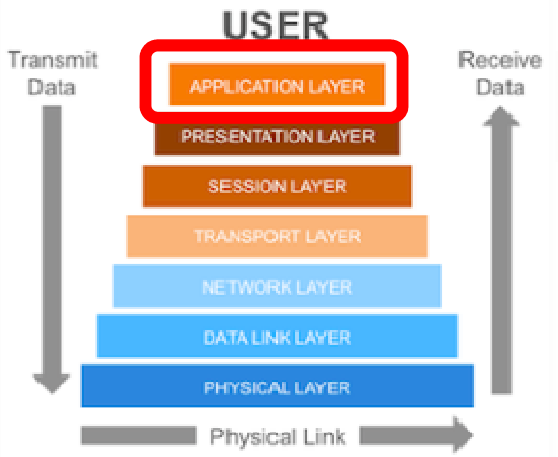
Application-level measurements (1/2)



- **RadioOpt Traffic Monitor:**
  - App-level KPIs are limited to active measurements.
  - **Page-Load Times (PLTs)** to a customized web-site (not linked to popular content) and monitoring of the **video buffering** in HTTP progressive video download (this was not verified by FTW, as measuremnets were not available in the accessed TM logs).
- **4G Mark:**
  - **Active** based, covering only **page load times**
  - Extends the RadioOpt TM approach by considering a **more evolved analysis of the PLTs** → includes the **most popular websites** to perform the active PLTs tests.

Terminal-based Measurement Tools

Application-level measurements (2/2)

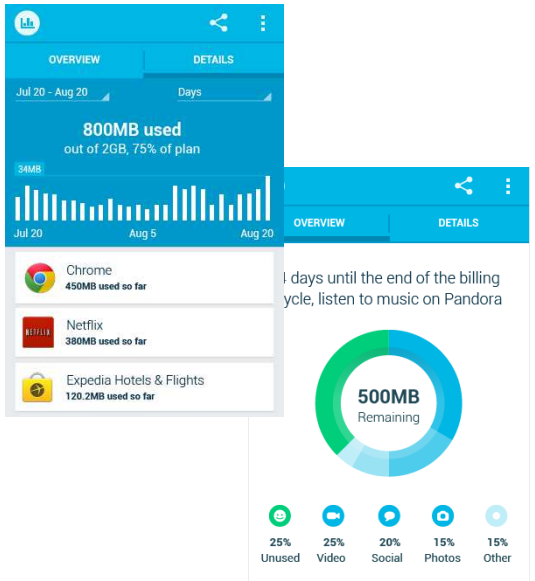


- **HttpWatch**
  - **Passive** tracking of **page load times**
  - **Only** available **in iOS** in the case of **mobile devices**
- **Chrome PLT debugging-mode**
  - **Passive** tracking of **page load times in Chrome** web-browsing
  - Based on Remote Debugging Chrome on Android
  - FTW is currently developing a complete system to passively track and export all the data generated by the Chrome debugging mode
- **Video buffer monitoring → YoMo tool**
  - **Browser plugin**, monitors **buffer level** and quality settings of YouTube
  - Available for PC, currently **being extended for Android**

Terminal-based Measurement Tools

Traffic utilization volumes per application

- **Onavo Count**
  - High populairy, **great GUI** (5M+ downloads)
  - Tracks and monitors per-app traffic utilization
  - Data is used for **trend analysis (e.g., app popularity)** and **user profiling**

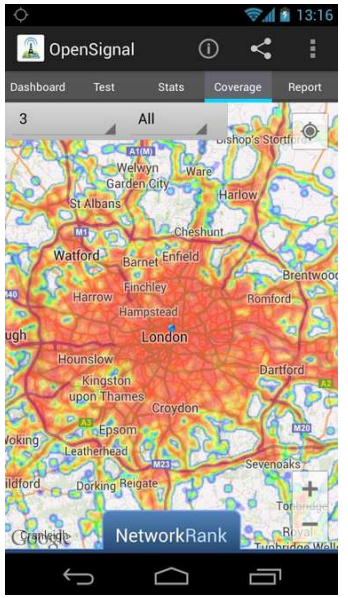


- **RadioOpt Traffic Monitor:**
  - Tracks and monitors per-app traffic utilization
  - **Separated counters** for passive speed **measurements per-app**

Terminal-based Measurement Tools

Signaling and coverage measurements

- **Open Signal**
  - High populairy (5M+ downloads), **great GUI, including performance maps and ISP ranking**
  - **Coverage maps** and cell locations
  - **Signal quality**
  - **Active speed measurements**, including **quality reporting** for web, video, and VoIP (basic thresholding, values not specified)
  - **ISPs benchmarking and network ranking**



Terminal-based Measurement Tools

RAN measurements

- **RILAnalyzer**
  - Research-based application, developed by Telefonica (http://rilanalyzer.smart-e.org/)
  - **Targets RAN troubleshooting**
  - Tracks **low-level radio information**
  - Monitors cellular network **control-plane data**,
  - as well as **user-plane data**

Application – level KPIs – SmartQoE

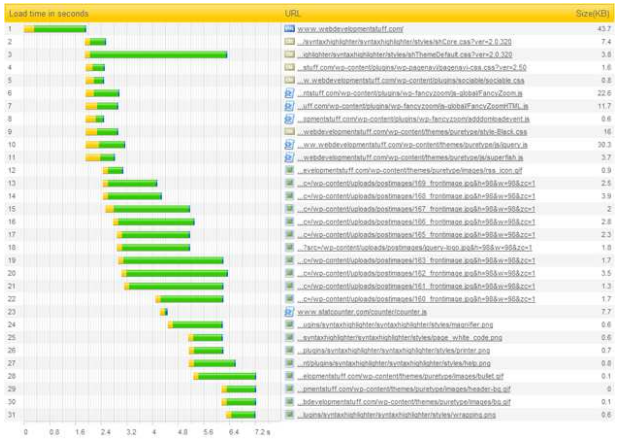
- **Two apps developed by FTW for app-level KPI monitoring**

1. SmartQoE – YouTube tracking

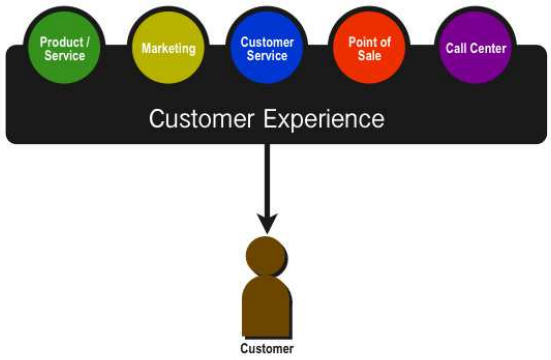
- Stallings detector
- DASH quality changes tracking
- Based on Chrome YouTube player

2. Page Load Time tracking

- Full page (objects) load time
- Tracking done through Chrome browser)



QoE and Customer Experience



Connecting the dots between Network QoS, end-user QoE and Customer Experience

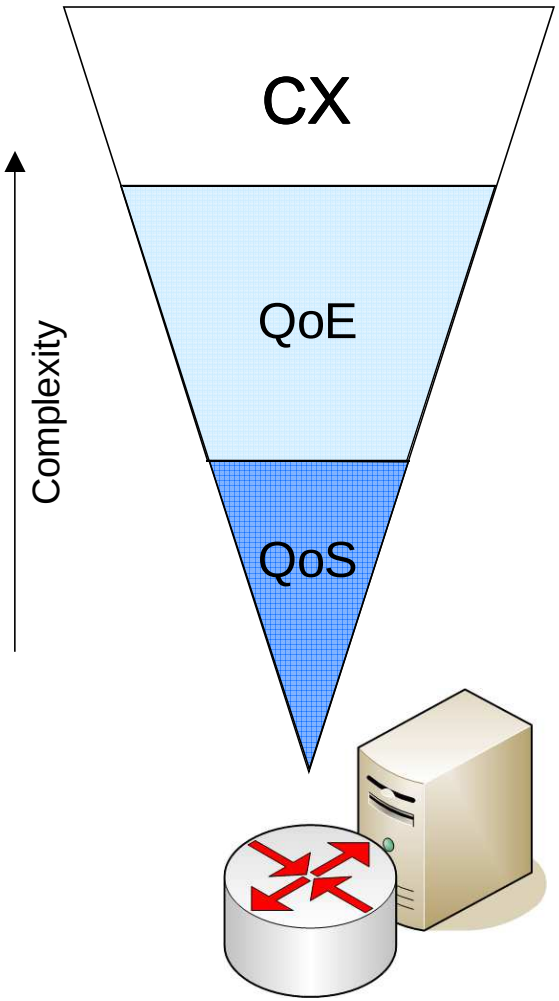
ftw Creating Communication Technologies

Customer eXperience (CX)

QoS

QoE

Connecting QoS, QoE and CX



Whole Customer Lifecycle
Preferences, Complaints, Churn,...

Perceived Quality
Page load time, Download time, ...

Produced Technical Quality
Throughput, RTT, ...

Network Traffic Monitoring

Knowledge for Business

Connecting QoS, QoE and CX…
…but WHAT FOR?

- **Paramount role of Customer eXperience (CX) in business-related activities** (marketing, decision making, CRM, churn analysis, etc.)

- **Real-time feedback from QoE monitoring can directly enhance CX management**

- Such **knowledge** is **already available in the network** and can be directly obtained by passive monitoring

Benefits from QoS, QoE and CX analysis: QoE and Customer Churn Analysis

- Most common reasons for customer churn include high cost and **inadequate service quality**
- Idea: **Improve Churn Prediction** by adding real-time **QoE** monitoring information into the process
- Does **QoE** have an **impact** on **customer‘s** probability of **churning?**
- How do we **measure** and **model** this impact?
- Can we use **QoE management** as **proactive anti-churn** action?

Benefits from QoS, QoE and CX analysis: QoE and Business Models

- Are customers **willing to pay for a higher QoE** service?
- **Up-selling** and **willigness-to-pay**: customers experiencing good QoE are more prone to accept new high-QoE services?
- Can we forecast the utilization and success of a new service based on the offered QoE?
- Does good QoE translate into more utilization of a service?

Benefits from QoS, QoE and CX analysis: QoE and Customer Profiling

- Customer profiling and segmentation from network monitoring data
- **Identify groups** of similar customers based on **QoE preferences**
- **Customer value** based on a trade-off between revenue and utilization (e.g., which users provide more revenue using less the network)
- Identify groups of similar customers based on other criteria (behavior, service utilization rates, consumed services, accepted offers)
- **Map user behavior to QoE**: evaluate predictive quality of engagement time, cancellation rates, etc.

Benefits from QoS, QoE and CX analysis: QoE and Marketing Strategies

- Can we measure the link between QoE and acceptance of a new service or marketing offer? (e.g., HD video service on mobile devices)

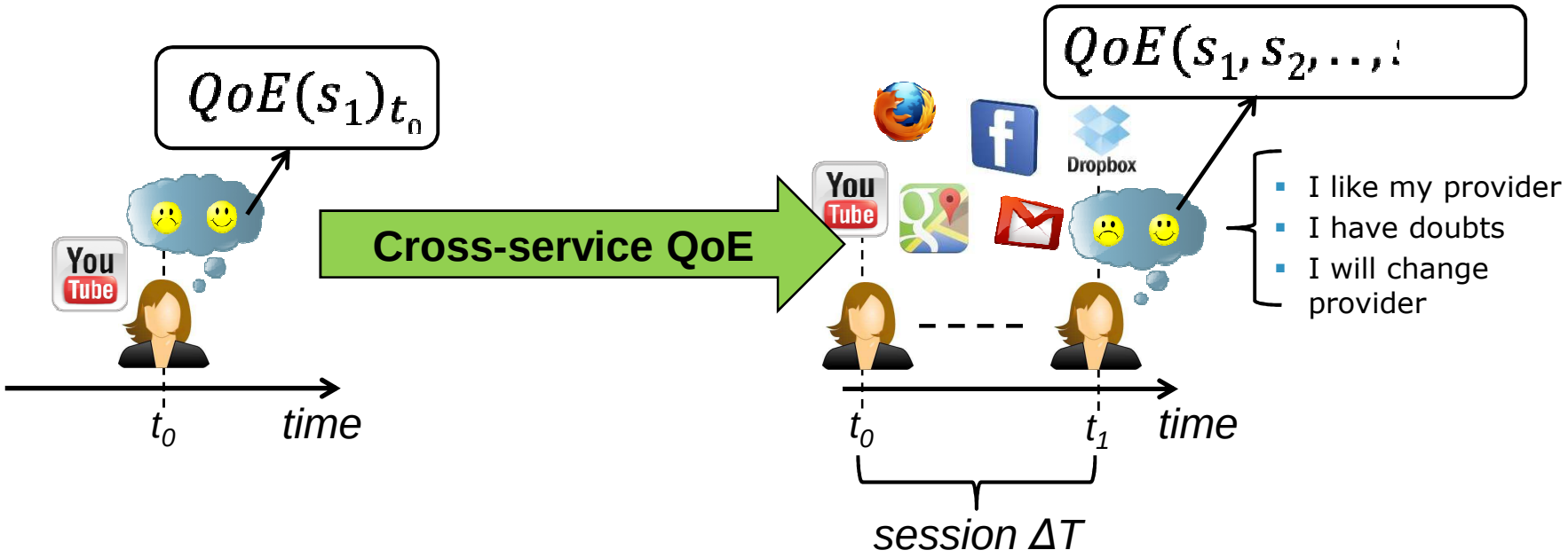
- Can we use QoE user preferences to **create better-targeted marketing packages?** (e.g., customers who prefer paying more for better quality vs. customers who prefer paying less for average QoE)

- Detect patterns and trends in customers traffic, detect trend changes to offer new services in the right moment.

Other QoE Topics

Cross-service QoE

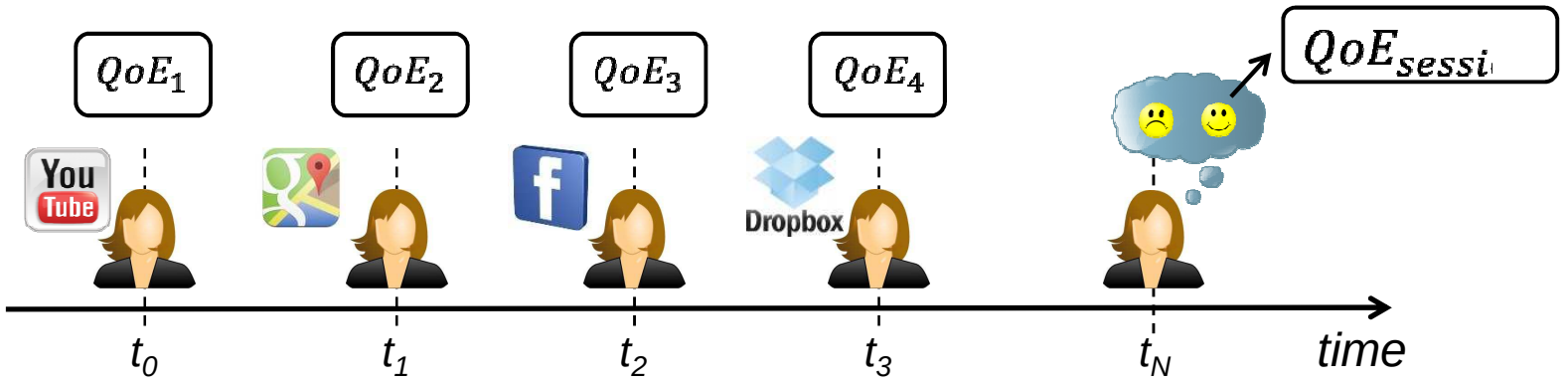
- **Current QoE**-research focuses on **momentary QoE** when using a **single service**.
- But **OpCos** are **interested** in the **overall opinion** about their **performance as provider**, as influenced by **QoE on multiple services**.



- Given a **user-profile on the mix of services** used in the network, which is the **expected overall QoE** of the users? → **Modular-Multi-Service QoE Integration**

- Derive not only **integration models** but **reference cases and standards** to **assess Cross-service QoE**

Modular-Multi-Service (MMS) QoE Integration



- $QoE_1 = F_1(QoS)$
- $QoE_2 = F_2(QoS)$
- $QoE_3 = F_3(QoS)$
- $QoE_4 = F_4(QoS)$

$$QoE_{session} = F(QoE_1, QoE_2, QoE_3, QoE_4)$$

$$\text{e.g.,}\ QoE_{session} = \alpha.QoE_1 + \beta.QoE_2 + \gamma.QoE_3 + \lambda.QoE_4$$

- We can **derive QoE levels** from Network **QoS** for different services (YouTube, Facebook, Dropbox, Web Browsing, etc.)
- We can derive **user-profiles on the mix of HTTP services** used in the network (network monitoring)
- Lab study approach:
  - ***N* services** (services-mix user-profiles), single device, and **single task per service**.
  - For a given **session of length *ΔT*,** users rate the QoE of the session (their **overall experience**).
  - Derive **MMS QoE integration models**

Impacts of Throughput Fluctuations in QoE

- **Current QoE**-research focuses on **average KPI values, particularly in terms of Throughput.**

- But **throughput is not constant** → mobility, fading, interference leading to changes in coding and modulation scheme, scheduler algorithm, contention with other users, variation in rate provided by the server…

- **Fluctuations have an impact on QoE for certain services**