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Teletraffic Models for Quality of Experience Assessment

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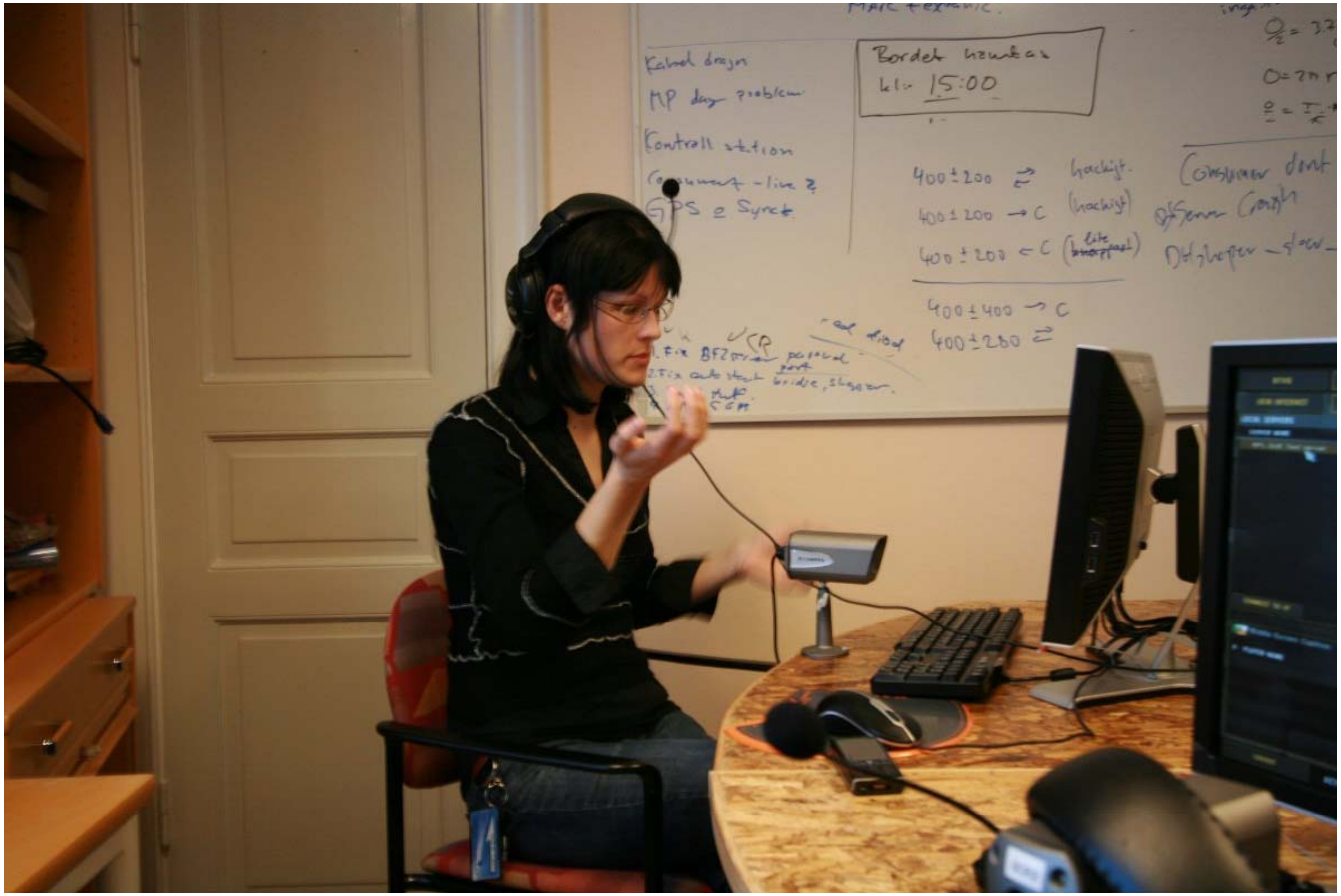
Disclaimers

- Conceptual set of slides
  - To be extended
  - To be modified
  - Storyline to remain
- Please download the final version from http://www.bth.se/com/ccs
  - Password: itc23sfca

Quality of Experience (QoE)

[http://frombogotawithlove.com/wp-content/uploads/2009/10/Bored-Computer-User.jpg]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Customer Satisfaction Survey from an ISP

- Your satisfaction using our High Speed Internet Service
  - Overall satisfaction {1…10}
- **Will you use again our service? {Yes/No}**
- Your satisfaction regarding specific aspects of our High Speed Internet Service
  - Ease of use {1…10}
  - Range of products offered {1…10}
  - Quality of connection {1…10}
  - Price for value {1…10}
  - Quality of customer care (where applicable) {1…10}

At a hotel in Vienna, Austria, March 2010 (WLAN access)

QoE

- Promoted by industry (since ~2001)
  - Economical aspect: user churn
  - E2E-QoS + user-centric parameters
- Both qualitative and quantitative views
  - But so far mostly from a subjective perspective
  - Recent trends to objective QoE measurements
    - User performance
    - Psychophysical measurements
    - Use of quantitative relationships between QoE and QoS

QoE according to a vendor

- White Paper [Nokia, 2005]:
  …*how a user perceives the usability of a service when in use – how satisfied he or she is with a service*
  - End-to-end network QoS
  - Factors such as network coverage, service offers, level of support, etc.
  - Subjective factors such as user expectations, requirements, particular experience
- Key Performance Indicators (KPI) related to
  - Reliability
  - Comfort

QoE in ITU-T Rec. P.10/G.100 Am. 2

- *The overall <u>acceptability</u> of an application or service, as perceived <u>subjectively</u> by the end user.*
  - *NOTE 1 – Quality of experience includes the complete end-to-end system effects (client, terminal, network, services infrastructure, etc.).*
  - *NOTE 2 – Overall acceptability may be influenced by user expectations and context.*

QoE in ITU-T Rec. G.1080

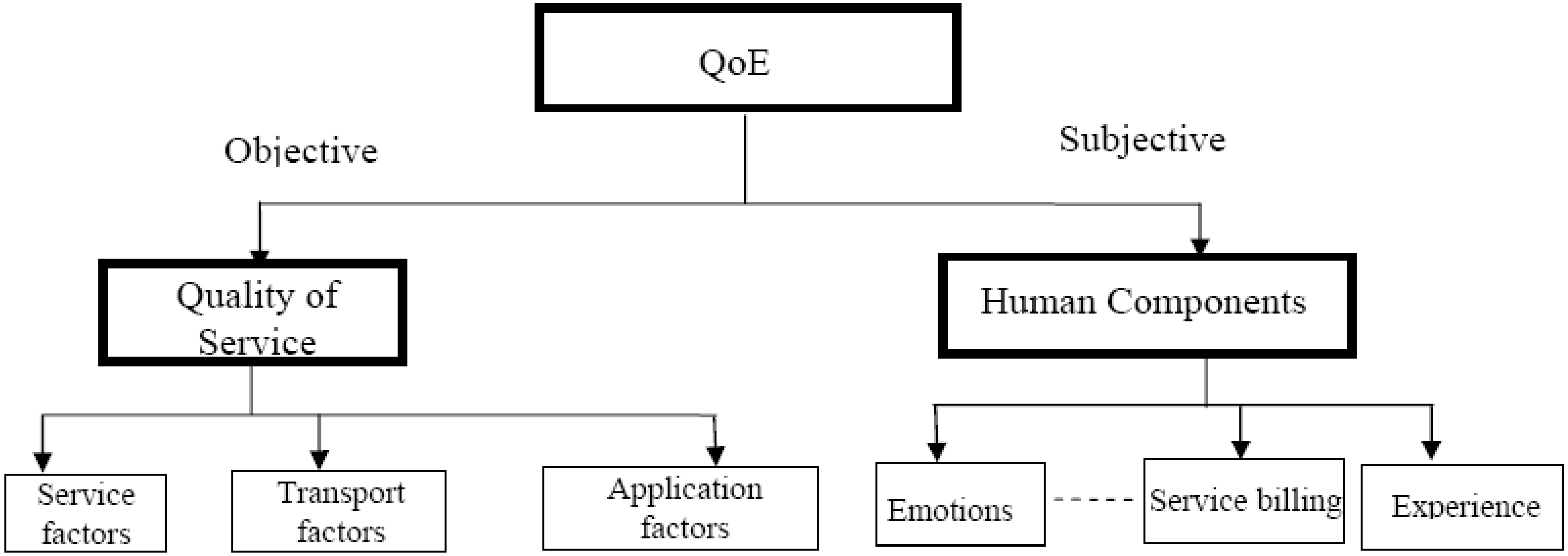


Figure 5-1/G.1080 - QoE Dimension

Source: ITU-T Rec. G.1080

QoE in ETSI STF 354

- [Brooks & Hestnes, 2010], [ETSI STF 354]:
  QoE is a measure of user performance based on objective and subjective psychological measures of using a service or product.
  - *NOTE 1: It takes into account technical parameters (e.g., QoS) and usage context variables (e.g., communication task), and measures the process and outcomes of usage (e.g., user effectiveness, efficiency, satisfaction, and enjoyment)*
  - *NOTE 2: The appropriate psychological measures will be dependent on the communication context. Objective psychological measures do not rely on the opinion of the user (e.g., task completion time… task accuracy…) Subjective psychological measures are based on the opinion of the user.*

QoE according to Dagstuhl Seminar

- [Dagstuhl Seminar 09192] ”From QoS to QoE”, May 2009:
  The degree of delight of the user of a service, influenced by content, network, device, application, user expectations and goals, and context of use.

Quality of Service (QoS)

- TelCo/standardisation point of view
  - ITU-T Rec. E.800 (1994): QoS = *the collective effect of service performance which determine the degree of satisfaction of a user of the service*
- Internet/network point of view
  - Property of the network and its components: “Better-than-best-effort” packet forwarding
  - Parameters: cf. ITU-T Rec. Y.1541
- Performance researcher point of view
  - Results from queuing analysis
- Matching needed: **QoE ⇔ (network-)QoS**

Why teletraffic models for QoE?

- Growing interest in QoE
  - Topic around 10 years old
  - User reactions to delivery problems
  - Economic value of QoE
  - Ecologic value of QoE
- Successful QoE control
  - Depends on models
  - Importance of parameters

Aims

- Building bridges:
  Re-discover teletraffic models and results, and **make them useful for contemporary QoE research**

- Not too many models at this point ...
  ... but hopefully some **starting points and ideas for future research**

Building bridges …

Why should we?

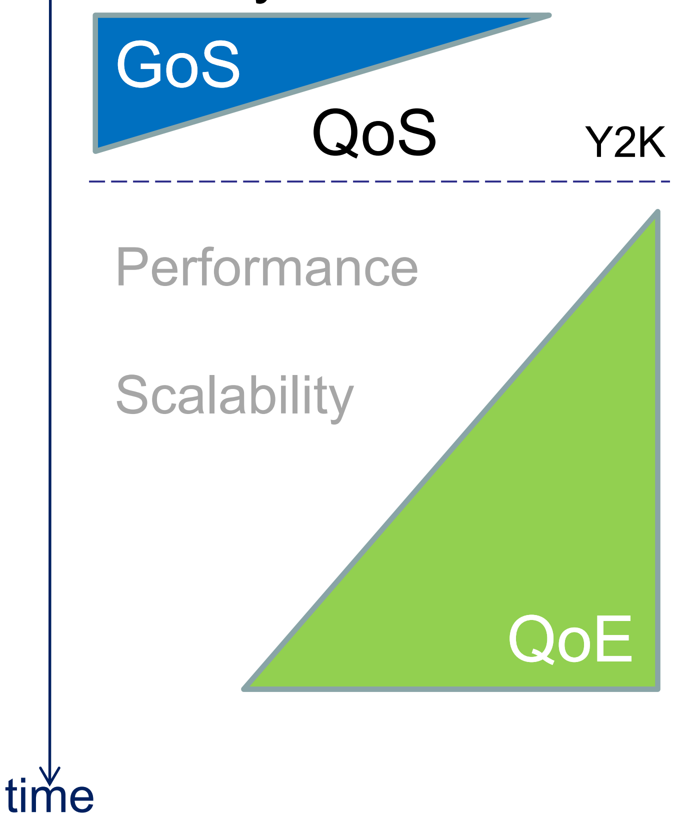
- A technician's perspective
  - "*Come on, we design, build and manage the networks as good as feasible, keep the user out of that game.*"
- A user's perspective [HP, 2000]
  - "*If it's slow, I won't give my credit card number.*"
- Researchers' perspectives?
  - *Depends on their "schools"*

A personal retrospective ...

Teletraffic analysis for

- POTS
- ATM
- IP (IntServ, DiffServ), MPLS
- Wireless
- P2P
- Future Internet
  - {Information|Content}-Centric Networking
  - Virtualisation
- Etc.

Quality notions



… on changes in teletraffic analysis

- Telephony
  - Well-established and valid “classical” models
  - Still used in analysis of mobile systems
- B-ISDN
  - Extension of classical models, e.g. Markov-modulation
- Measurements
  - Scaling: self-similar behaviour, (multi-)fractals, etc.
  - Long-range dependence
- Schism: valid models versus analytical tractability
- Experimentation

Challenges for teletraffic analysis

- Realistic models
- Tractable analysis
- Taking care of correlations
- Parameter matchings
- Interpretation of parameters
- Scaling phenomena
- Etc.

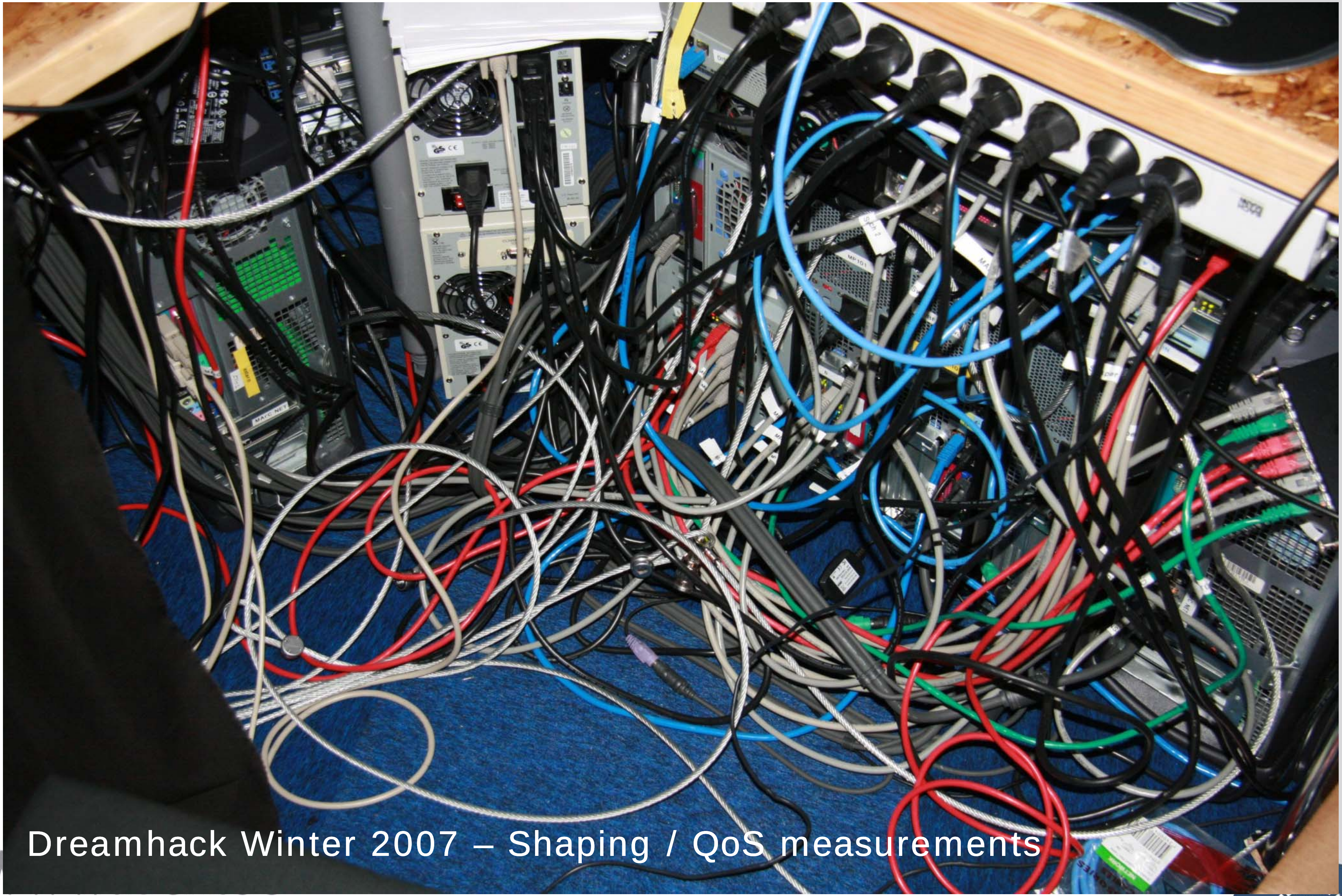
On models

- Model
  - Representation of an object or a system
- Teletraffic model
  - Representation of (parts of) a telecommunication systems

- Key: Behaviour of a system captured in interpretable parameters

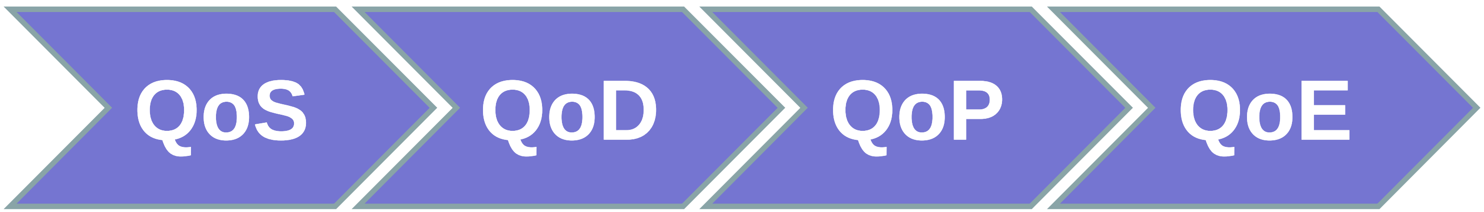
- Goal: Predict and control QoE


Dreamhack Winter 2007 – Gaming QoE



Dreamhack Winter 2007 – Shaping / QoS measurements

Qo* value chain

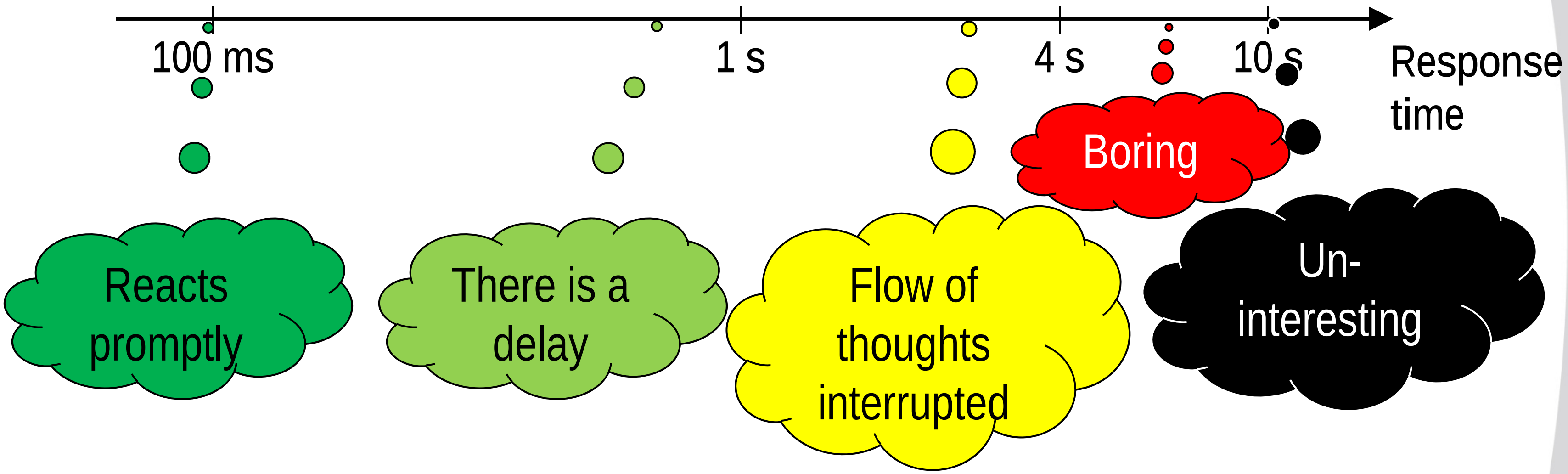


1. QoS = Quality of Service
2. QoD = Quality of Delivery
3. QoP = Quality of Presentation
4. QoE = Quality of Experience

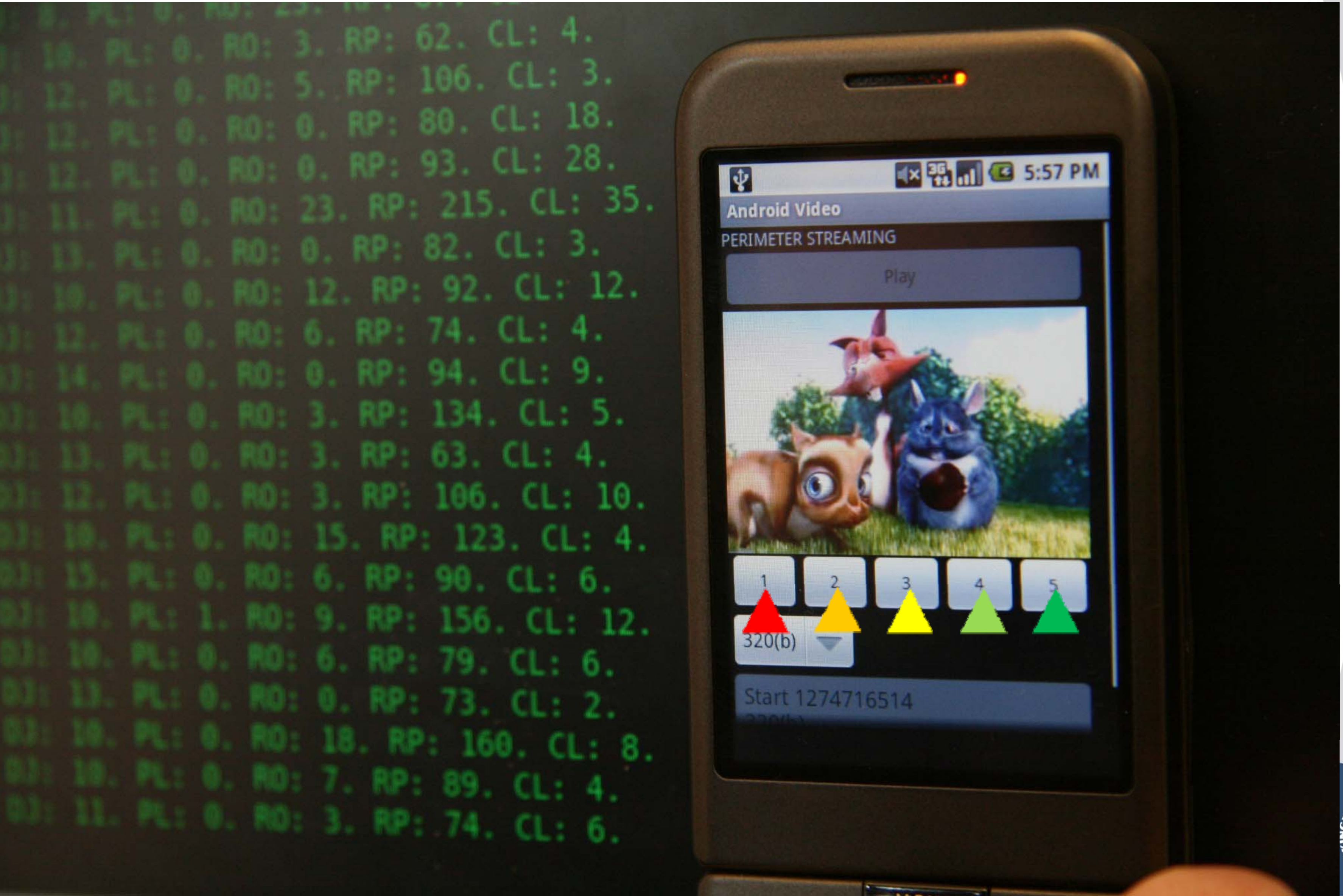
Examples

1. Web download via TCP
2. Streaming
   a. YouTube via TCP
   b. Live via UDP

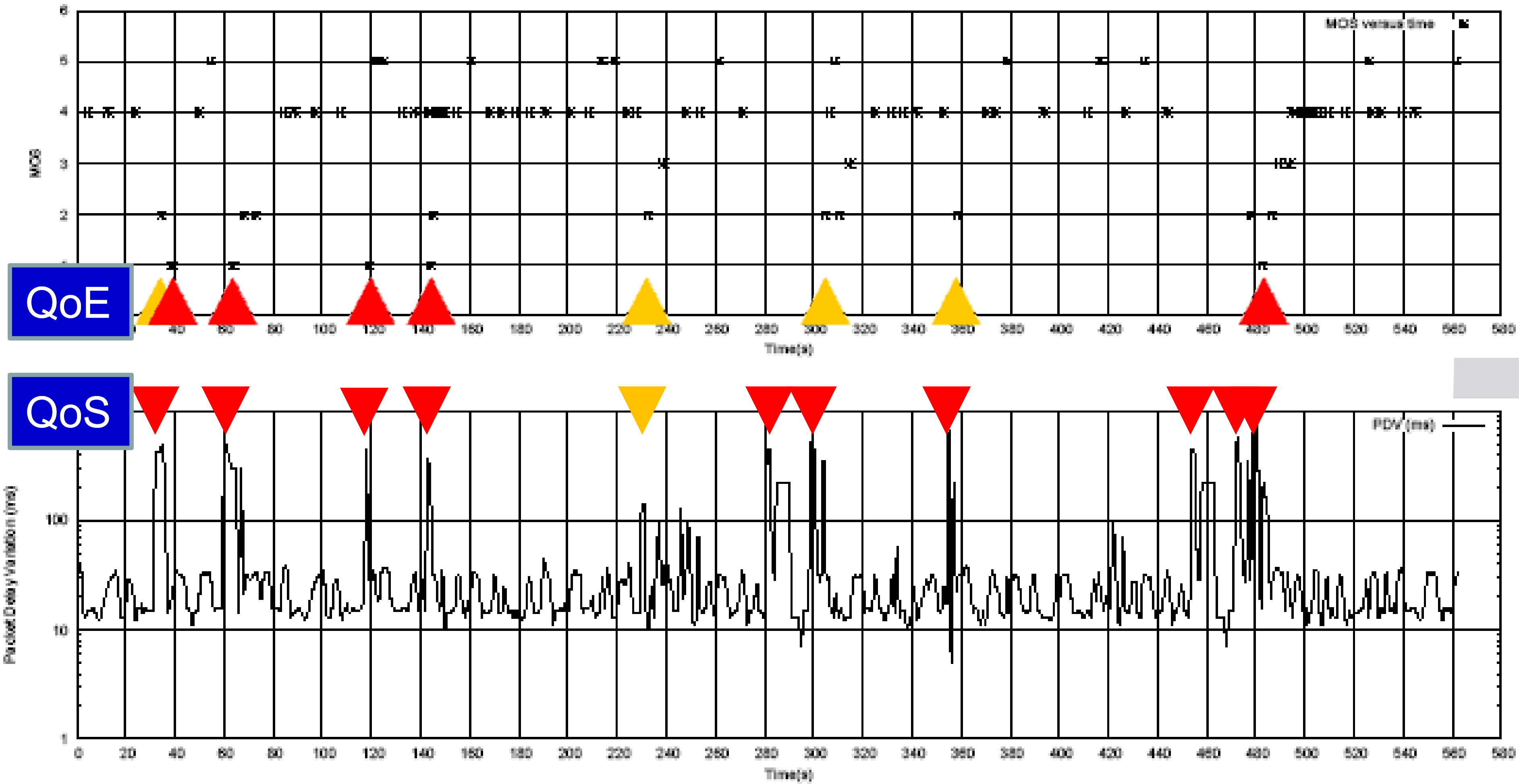
User perception of response times



Video streaming with user feedback



OS and PDV (via HSDPA)



QoE is …

- … more than rating video and audio quality
  - Most attention from scientists, standardisation, etc.
  - Quality of Presentation ⇦ Quality of Delivery
- … more than translated QoS
  - Identification of key parameters necessary
    - Re-consideration of typical parameter sets such as {loss, delay, jitter, bandwidth}
  - Macroscopic disturbances matter
    - Loss bursts
    - Delay peaks, zero throughput times

QoE has always been around…

- Call blocking probability in POTS
  - *The* performance measure (Go
- TCP reactions and fairness
  - Decrease in throughput = longer waiting times
- Flow-based networking
  - More transparency = less freezes / waiting
- Any kind of shared network resource
  - Fewer disturbances = less freezes / waiting

QoE-related models

- Typically QoE = f(p_1, p_2, …)
  - **Fundamental relationships**
  - Typically steady-state
  - Provide thresholds and discrimination of states for teletraffic models
- **Teletraffic models** provide **added value**
  - Stochastic processes (states, transitions)
  - **Dynamic** behaviour expressed in **QoE-relevant parameters** and **related statistics**
  - Allows for **transient and steady-state** analysis

Fundamental QoE-QoS relationships

- Dependencies on network conditions typically addressed by parameter vectors [QoS_i, …, QoE]
  - Results from questionnaires, observations, measurements
  - Several impact factors: $QoE = f(QoS_1, QoS_2, \ldots)$
- We focus on **one impact factor at a time**
- Description by **partial** differential equations
- Consider fundamental relationships of the type

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

- Maximise/minimise QoE to **interval [1, 5]** afterwards

Fundamental QoE-QoS relationships

- Investigated set:
  - Linear $QoE \propto QoS_i$
  - Logarithmic $QoE \propto \log(QoS_i)$
  - Exponential $\log(QoE) \propto QoS_i$
  - Power $\log(QoE) \propto \log(QoS_i)$
- Properties
  - Seen from regressions on linear vs. logarithmic scales
  - Reasoning behind each relationship
- Most examples from [Shaikh et al., 2010]

Linear relationship

$$\partial QoE \propto \partial QoS_i$$

QoE axis		QoS axis
• Linear scale	←	Linear scale
• Additive change	←	Additive change

- QoE gradient independent of QoE and QoS
- Linear regression often the first choice
- Local approximation
- Example:
  - Download time perception as function of loss

$$QoE \approx 4.3 - 31PLR \ \ (\Re^2 > 0.99)$$

Logarithmic relationship $\partial QoE \propto \frac{\partial QoS_i}{QoS_i}$

QoE axis		QoS axis
• Linear scale	←	Logarithmic scale
• Additive change	←	Multiplicative change

- QoE gradient proportional to reciprocal QoS
- Weber-Fechner Law (1834):
  - Just noticeable differences, multiplication on stimuli side
- Utility functions (implicit proportional fairness)
- Example:
  - Download time perception as function of bandwidth

$$QoE \approx 1.2 + 3.3 \lg(R/\mathrm{Mbps}) \quad (\Re^2 > 0.99)$$

Exponential relationship $\frac{\partial QoE}{QoE} \propto \partial QoS_i$

	QoE axis		QoS axis
•	Logarithmic scale	←	Linear scale
•	Multiplicative change	←	Additive change

- QoE gradient proportional to actual QoE
  - Nuclear decay
  - Human memory
  - IQX hypothesis [Hossfeld et al., 2007; Fiedler et al., 2010a]
- Examples
  - Image quality perception as function of blur, blockiness, … (QoP)
  - Download time perception as function of response time (QoD)

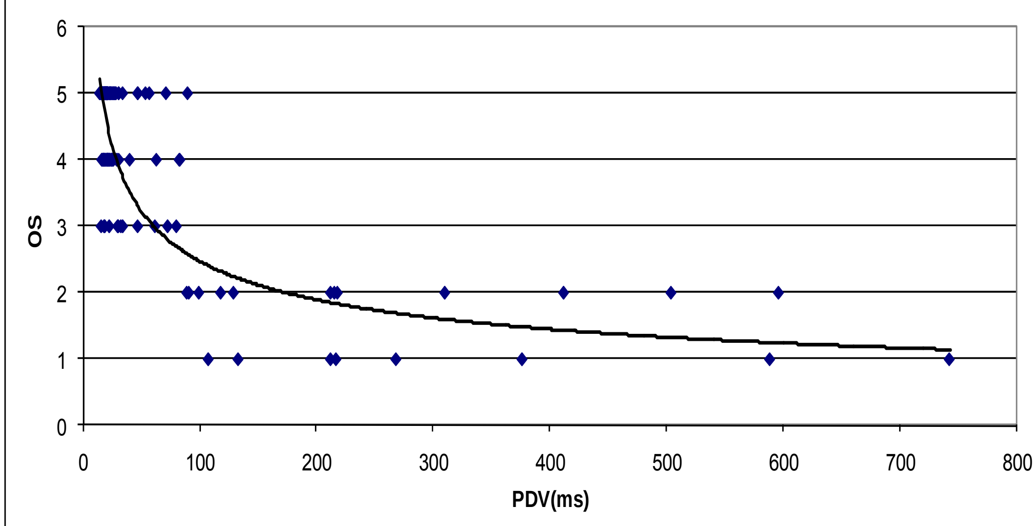
$$QoE \approx 4.8 \exp(-0.15 RT/\mathrm{s}) \quad (\Re^2 > 0.99)$$

Power-type relationship $\frac{\partial QoE}{QoE} \propto \frac{\partial QoS_i}{QoS_i}$

QoE axis		QoS axis
• Logarithmic scale	←	Logarithmic scale
• Multiplicative change	←	Multiplicative change

- Long tails on both axes
- Examples
  - Session volume as function of bandwidth
  - Video perception as function of jitter ➔

$$QoE \approx 14.6(PDV/\text{ms})^{-0.39} \quad (\Re^2 \approx 0.68)$$



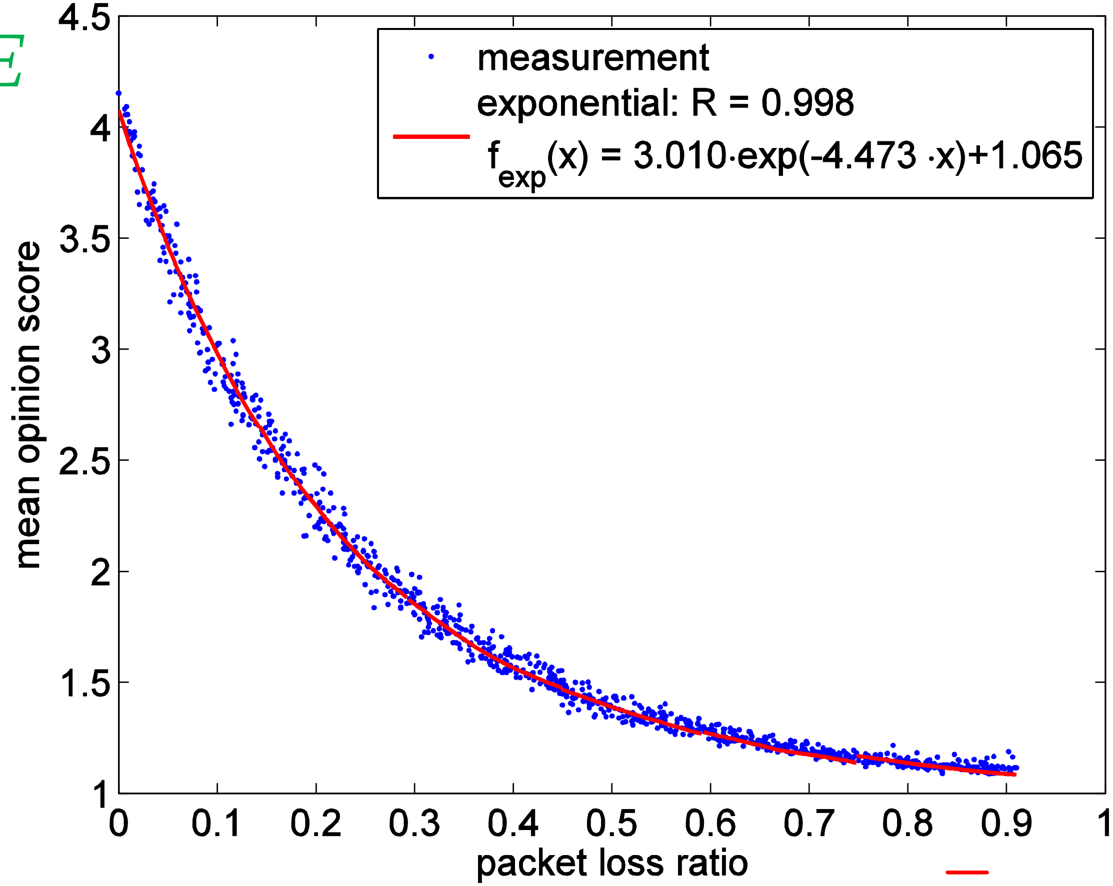
Different types of QoE and QoS parameters

- Success rating QoE
  - The higher, the better
  - Mean Opinion Score (1..5)
- Failure rating $\overline{Q}oE$
  - The higher, the worse
  - Cancellation rate
  - Churn rate
- Watch the signs!

- Resource measure QoS_r
  - The higher, the better
  - Throughput
- Success measure QoS_s
  - Availability (e.g. 99.99 %)
  - Packet success ratio
- Failure measure $\overline{Q}oS_f$
  - The higher, the worse
  - Packet loss ratio
  - Delay jitter
  - Reordering

Skype: MOS = *f*(packet loss ratio)

QoE



$\overline{QoS}_f$

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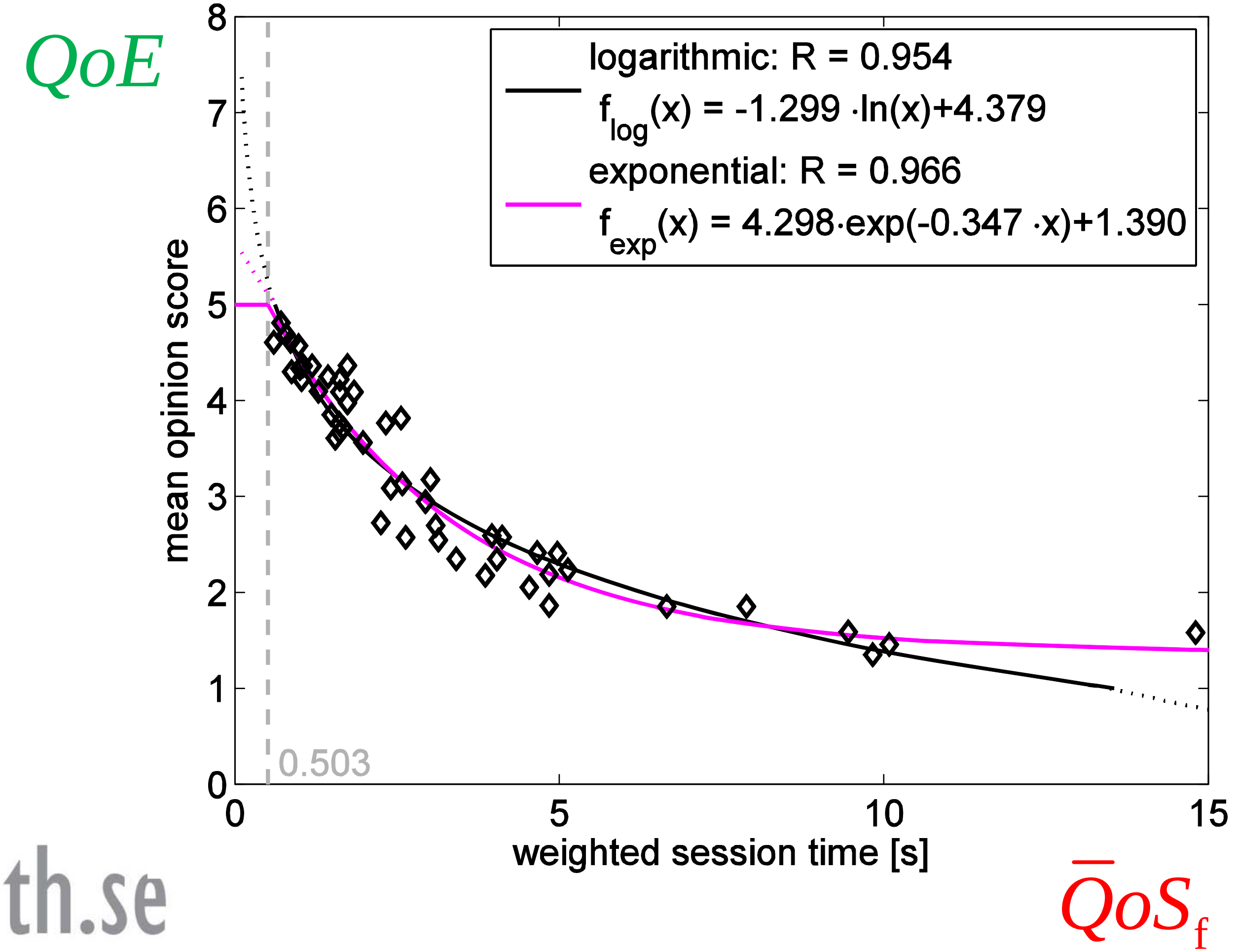
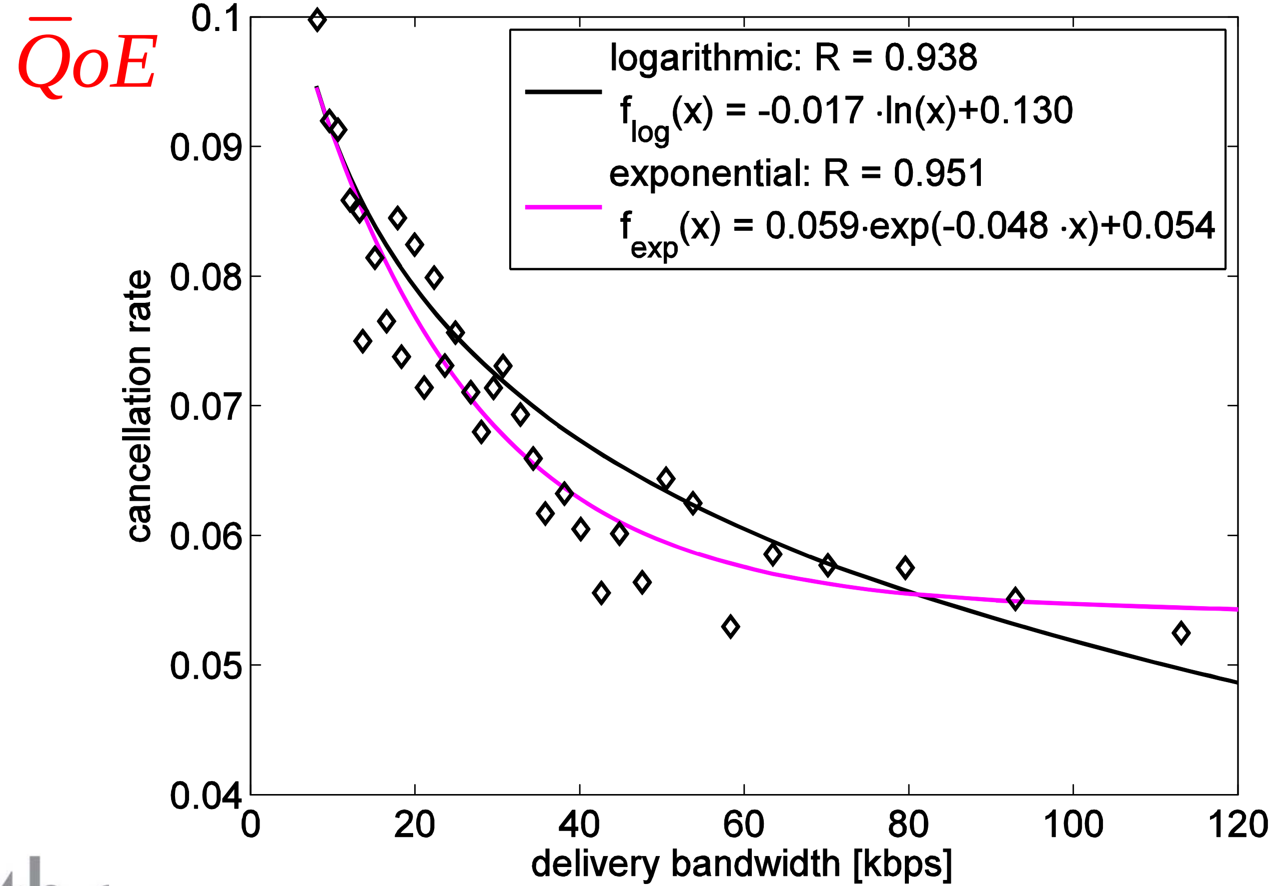
[Fiedler & Hossfeld, 2010]

G.1030/download: MOS = *f*(session time)



[Fiedler et al., 2010a]

Web: Cancel-rate = *f*(delivery bandwidth)



QoS_r

[Khirman & Henriksen, 2002]
[Fiedler et al., 2010a]

Bones of contention

- Unavailability
- Initial delay
- Artifacts
- **Freezes**
- Preemption
- Repetitions
- Etc.

- Video
- Audio
- Web
- Gaming
- SAAS
- Authentication
- Etc.

Explicit user ratings

- Dynamic process
  - Memory effect
  - Forget factor
- Context-dependent
- Content-dependent
- Gossip

- Modelling of the users equally important

Implicit user ratings

- (Objective parameters)
- Degree of task completion
- Time of task completion
- Sojourn times
  - “Happy users surf more”
- Churn

Performance parameters of interest

- Availability
- Loss
- Throughput
- Throughput variability
- Delay
- Delay variation
- Reordering
- Video
- Audio
- Web
- Gaming
- SAAS
- Authentication
- Etc.

Links between QoP, QoD and QoS

- Unavailability
- Initial delay
- Artifacts
- **Freezes**
- Preemption
- Repetitions
- Etc.

- Availability
- Loss
- Throughput
- Throughput variability
- Delay
- Delay variation
- Reordering

Statistics of particular interest

- Averages
- **Standard deviations**
  - CoV
  - Scaling behaviours
- Correlations
- **Tails**
  - How frequent?
  - How long?

QoD ⇨ QoP issues (1)

- Bit rate
  - Lack of support of the service (streaming)
  - Capacity sharing
  - Unacceptable download times
- Loss
  - Artifacts
  - Freezes
  - May turn into delay

QoD ⇨ QoP issues (2)

- Delay/Jitter
  - Latency
  - Freezes
  - May turn into loss (“too late”)
- Reordering
  - Due to multipath transmission
  - Reverberation effects
  - May lead to loss

QoD ⇨ QoP issues (3)

- The role of the transport protocol
  - TCP turns loss (and virtually any other kind of QoS problem) into additional delay
  - TCP reacts to virtually any kind of QoS problem
- Outreach of problems
  - Download duration ⇔ <u>average</u> throughput
  - Shorter time scales may require more sensitive figures
    - Average throughput can be OK even over a jerky channel

QoD ⇨ QoP issues (4)

- Typical sources of QoE problems:
  Capacity mismatch between request and service
  - Matter of time scale
  - “Short” capacity deficits may go unnoticed
- Looking for alternative channels
  - Seamless – caught between a rock and a hard place?
  - Multipath – more capacity at the price of reordering and/or additional delay at the receiver side

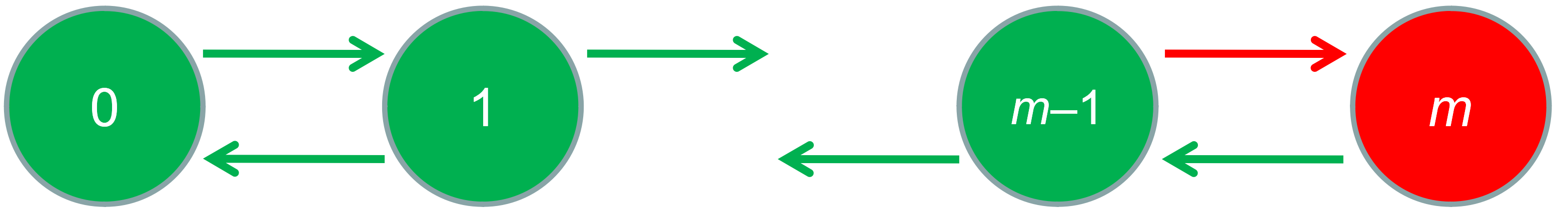
Teletraffic models

Attributes of teletraffic models

- States
  - Good (-for-user-perception) states
  - Bad (-for-user-perception) states
- Transitions
  - Time scales
  - Dynamic behaviour
  - (Quasi-stationarity within a state)
- Stationarity

Classical cases (1)

- M/G/m/0 system ⇨ Erlang-B formula

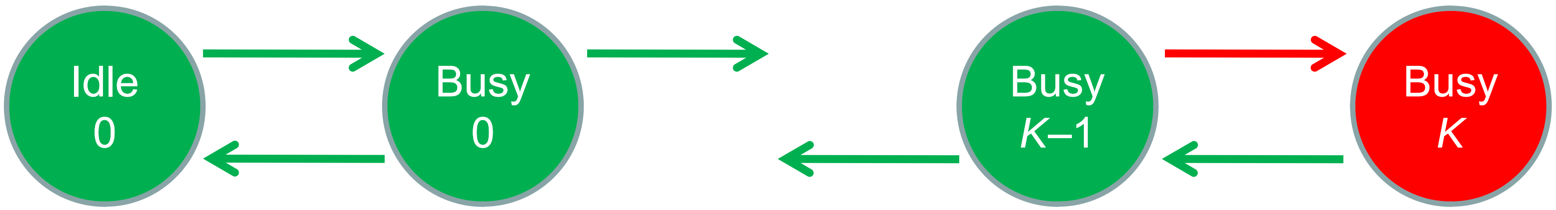


  - Blocking probability
  - **User view given** through PASTA (Poisson Arrivals See Time Averages)

Classical cases (2)

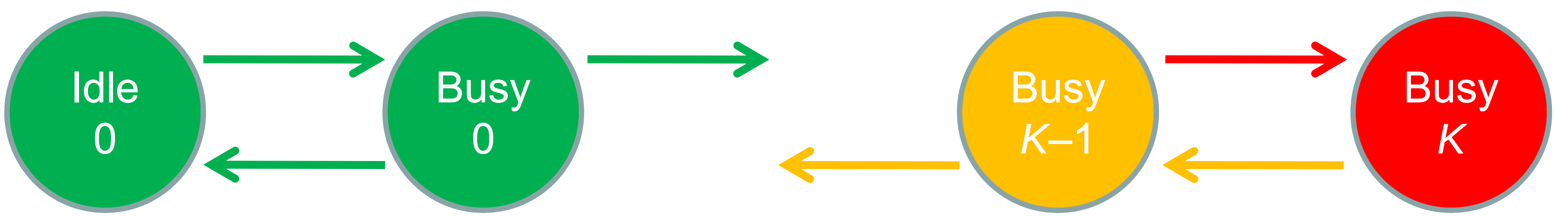
- M/M/1/K system

loss



QoE-critical, ”bad” state

  - Loss probability
  - If buffer levels are an issue: Pr{$X > x^*$}



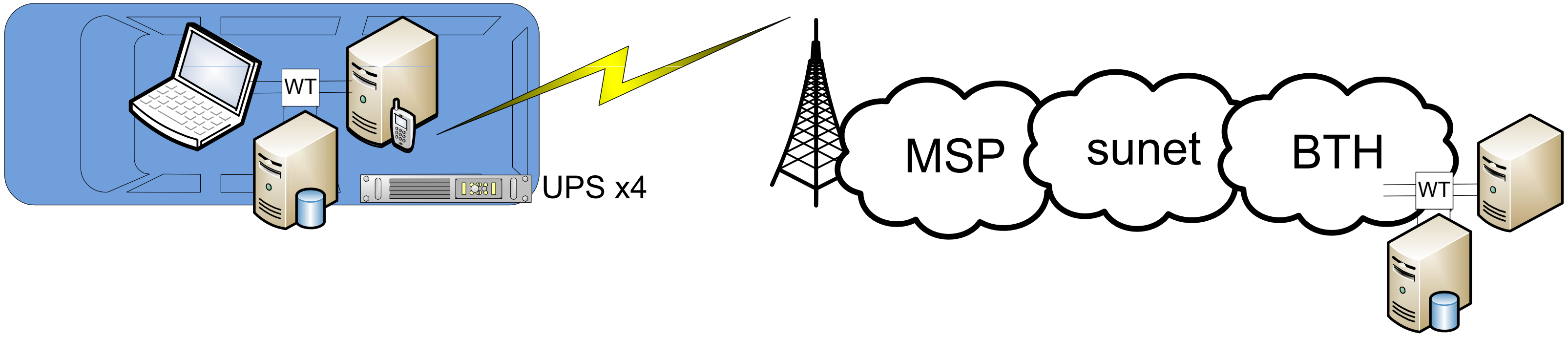
Example 1:
Mobile video live streaming

Mobile video live streaming

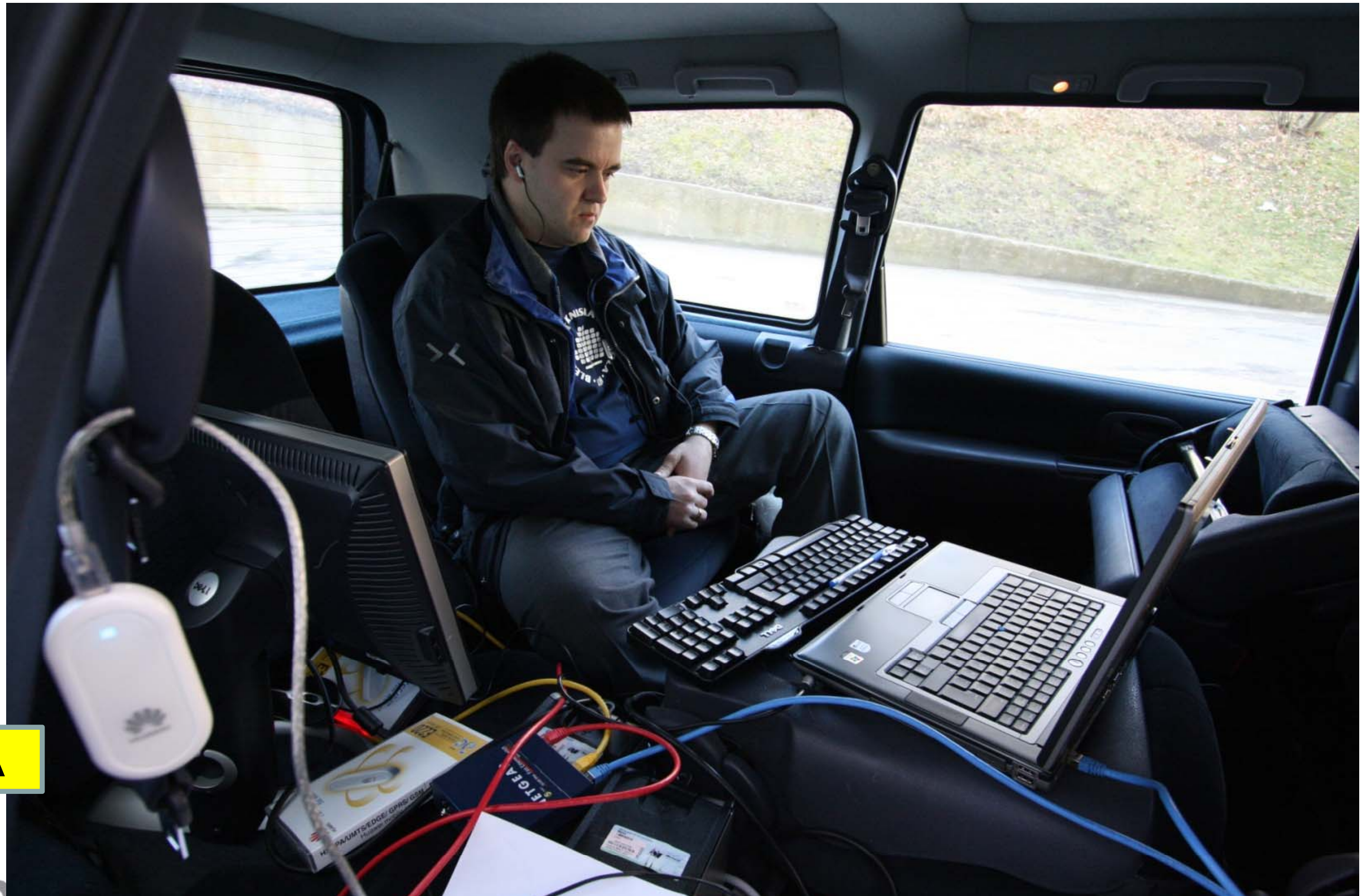
- If pre-loading à la YouTube is not possible…
- Freezes (and jumps) occur when the one-way E2E delay exceeds the playout buffer capacity
  - Typical delay budget: 0.5…4 s
- Modeling of buffer over-/underflow probablility
  - Tail behaviour becomes of interest

Drive tests – setup

- Swedish countryside outside Karlskrona
- UPS-driven DPMI = Distributed Passive Measurement Infrastructure time on wheels



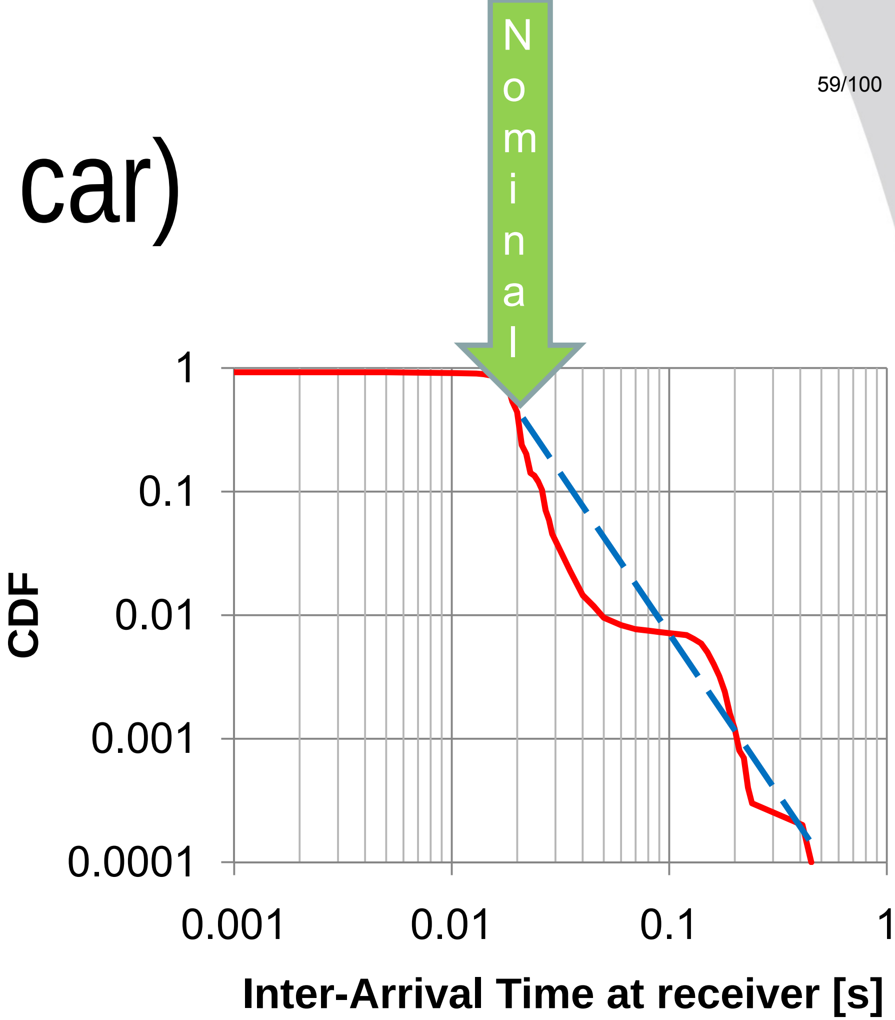
Drive tests – a look inside the car



HSPA

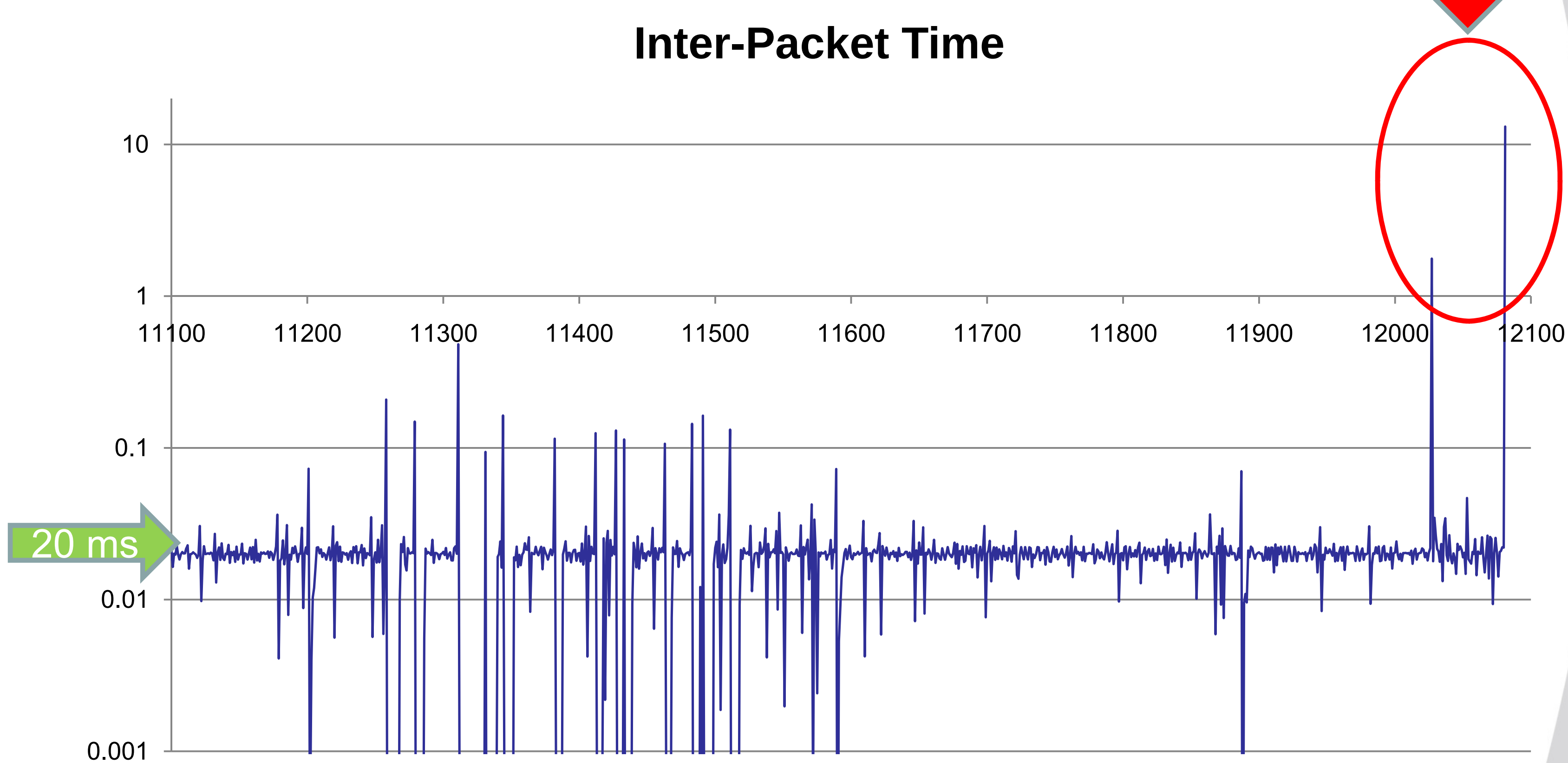
Delay (stationary car)

- IAT Quantiles:
  - 90 %: 26 ms
  - 99 %: 50 ms
  - 99.9 %: 205 ms

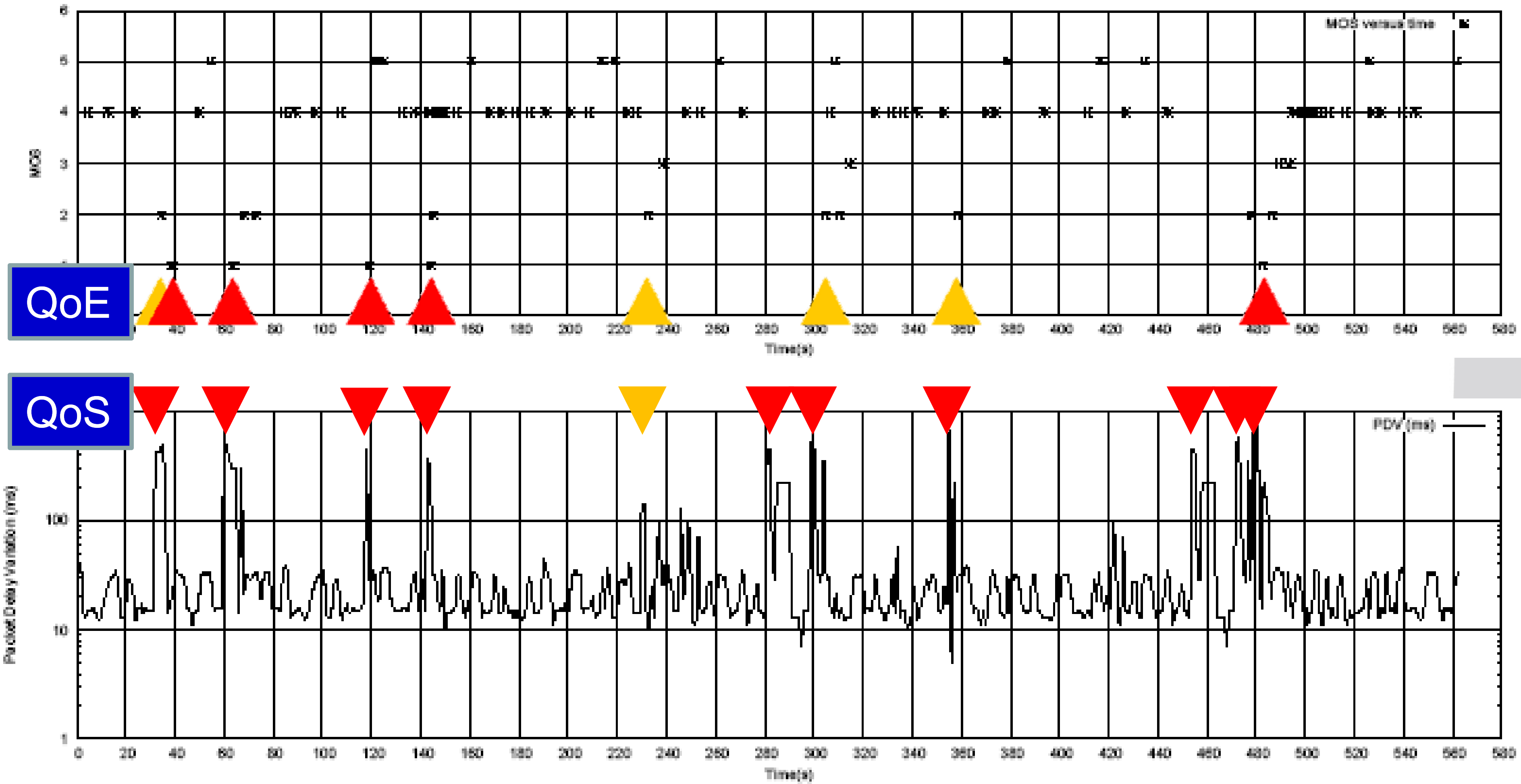


- Indications of a potentially long tail

Delay (moving car)

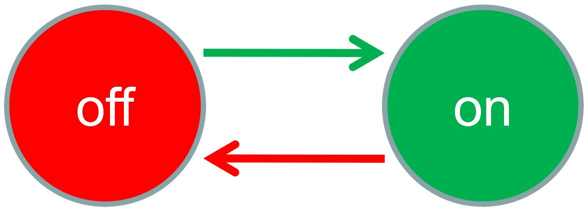


Recap: QoE and QoS (via HSDPA)

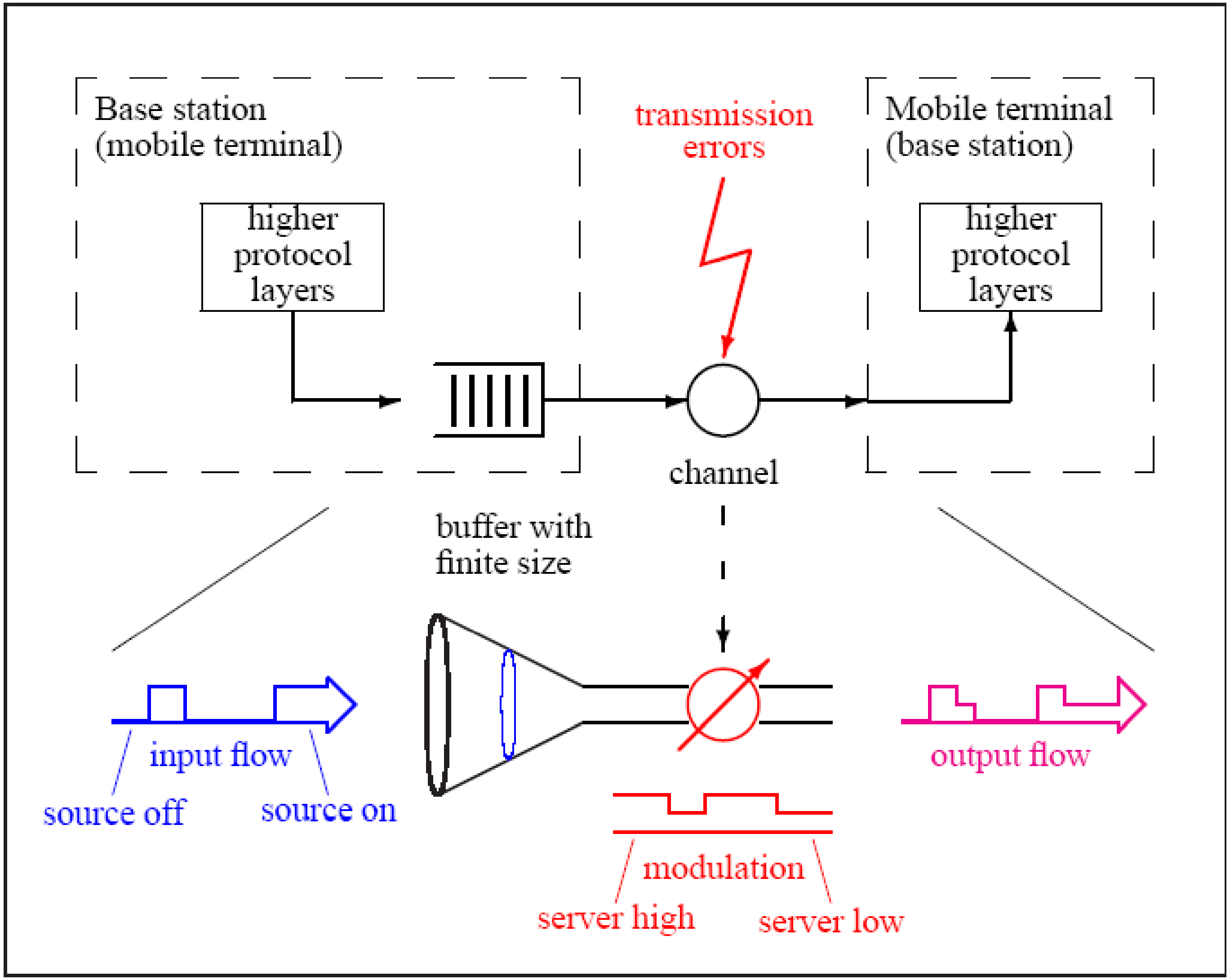


Simplest model for mobile streaming

- RP/IRP/$K(\to \infty)$ system:
  - Simplest Gilbert-Elliott model: channel modulates (interrupts, IRP) constant flow (RP)



  - Marginal distribution: $\Pr\{S = \text{off}\}$
  - (Cond.) Buffer content cdf $\Pr\{X > x\ (\wedge\ S = \text{off})\}$
  - Dynamic behaviour: $\lambda_{\text{off}\to\text{on}}$, $\lambda_{\text{on}\to\text{off}}$



[Fiedler & Krieger 2000]

More advanced models

- D/IDP/1/*K*: includes packet process
- RP/GMRP/*K* (fluid),
- D/GMDP/*K* (packet): general modulation
  - More states
  - Not necessarily exponential /geometric modulation

Example 2:
Network virtualisation

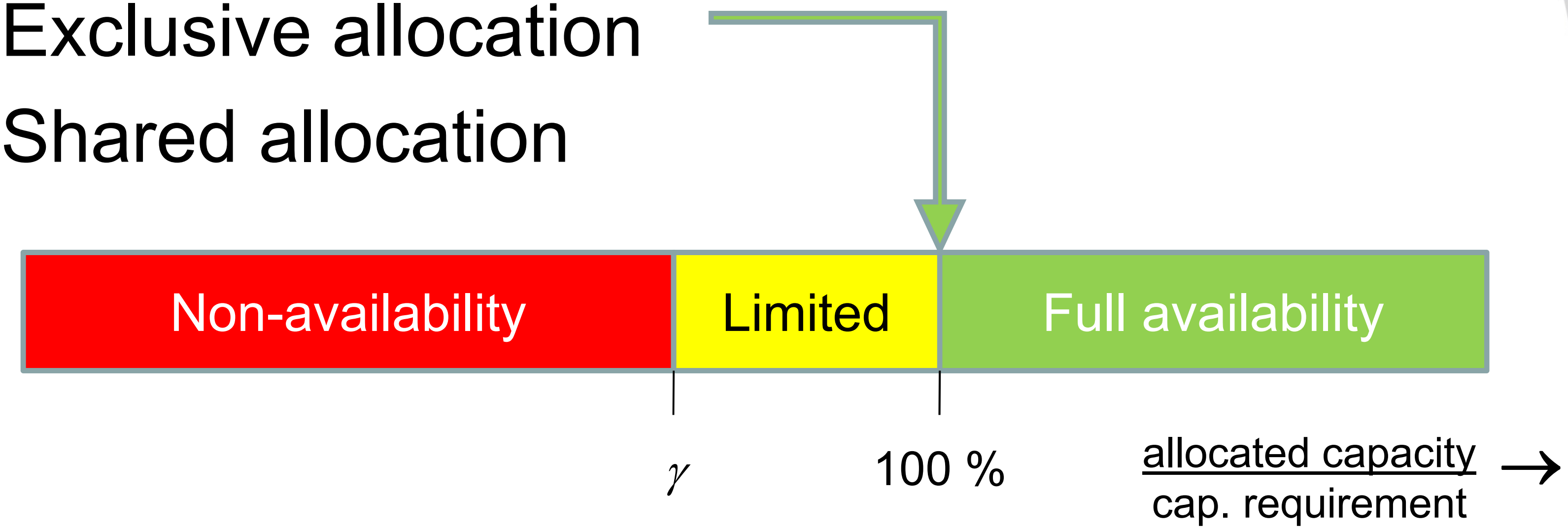
[Fiedler, 2011a]

Network virtualisation

- Transparency
  - Which time scales are affected by resource sharing?
  - Euro-NF SJRP FedNet
- Overbooking
  - A problem comparable to ATM
  - Squeeze additional customers into the system(s)
  - Two-side SLA: **Full versus limited availability**
    - 80 % capacity still provides (very) good user perception, given that we can avoid heavy disturbances

Resource Allocation Per User

- Exclusive allocation
- Shared allocation



- We are not talking of systems with unlimited capacity ☺

Full vs. Limited Availability

- Assume capacity for 10 exclusive users, $\gamma = 80\ \%$
- **Full availability** (100 %) – desired degree: **1 –** δ

1	2	3	4	5	6	7	8	9	10

- **Limited availability** (≥ 80 %) – desired degree: **1 –** ε

1	2	3	4	5	6	7	8	9	10	11

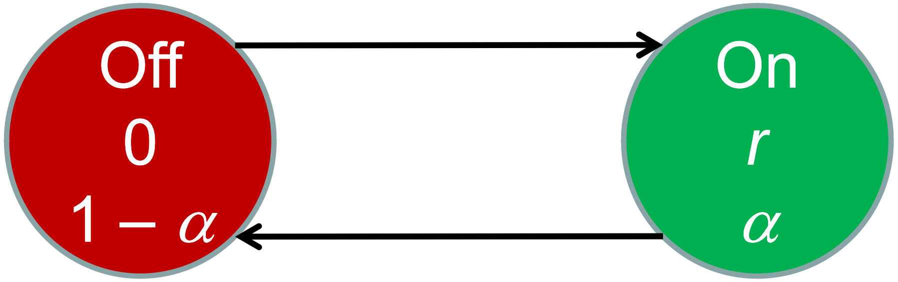
1	2	3	4	5	6	7	8	9	10	11	12

- **Non-availability** (< 80 %)

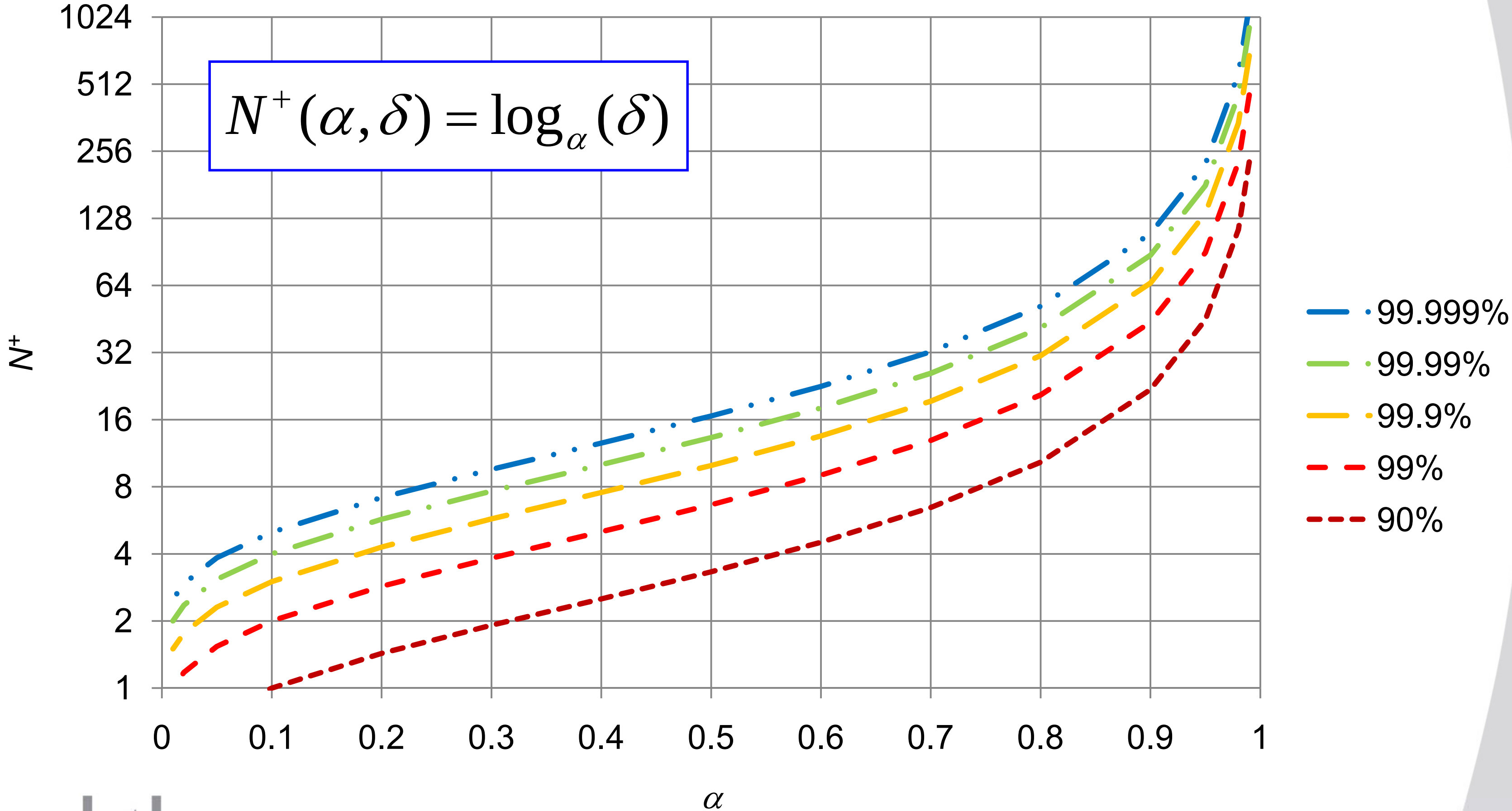
1	2	3	4	5	6	7	8	9	10	11	12	13

User Model

- On-off
  - peak resource request r
  - activity level α
  - not necessarily exp./geom. distributed phases
  - independent of each other



Gain borderline (one extra user)



QoE= $f(\gamma)$?

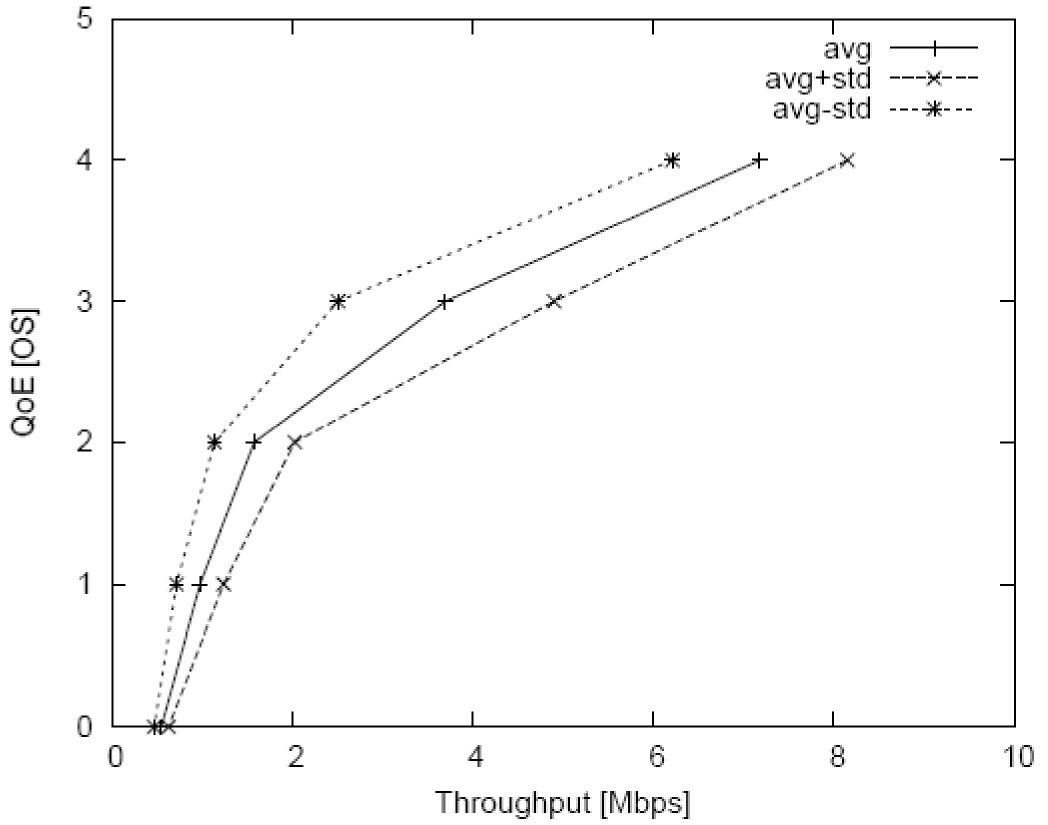
$$QoE = 1.15 + 3.34\,\lg(R/\text{Mbps})$$

$$\rho = \frac{QoE(R) - QoE^\star}{1 - QoE^\star}$$

R/Mbps	γ	QoE	$\Delta QoE(\gamma)$	ρ
10	1.0	4.49		
9	0.9	4.34	0.15	4 %
8	0.8	4.17	0.32	9 %
7	0.7	3.97	0.52	15 %
5	0.5	3.48	1.01	29 %
3.6	0.36	3.01	1.48	42 %
3	0.3	2.74	1.74	50 %

Web: MOS = *f*(throughput)

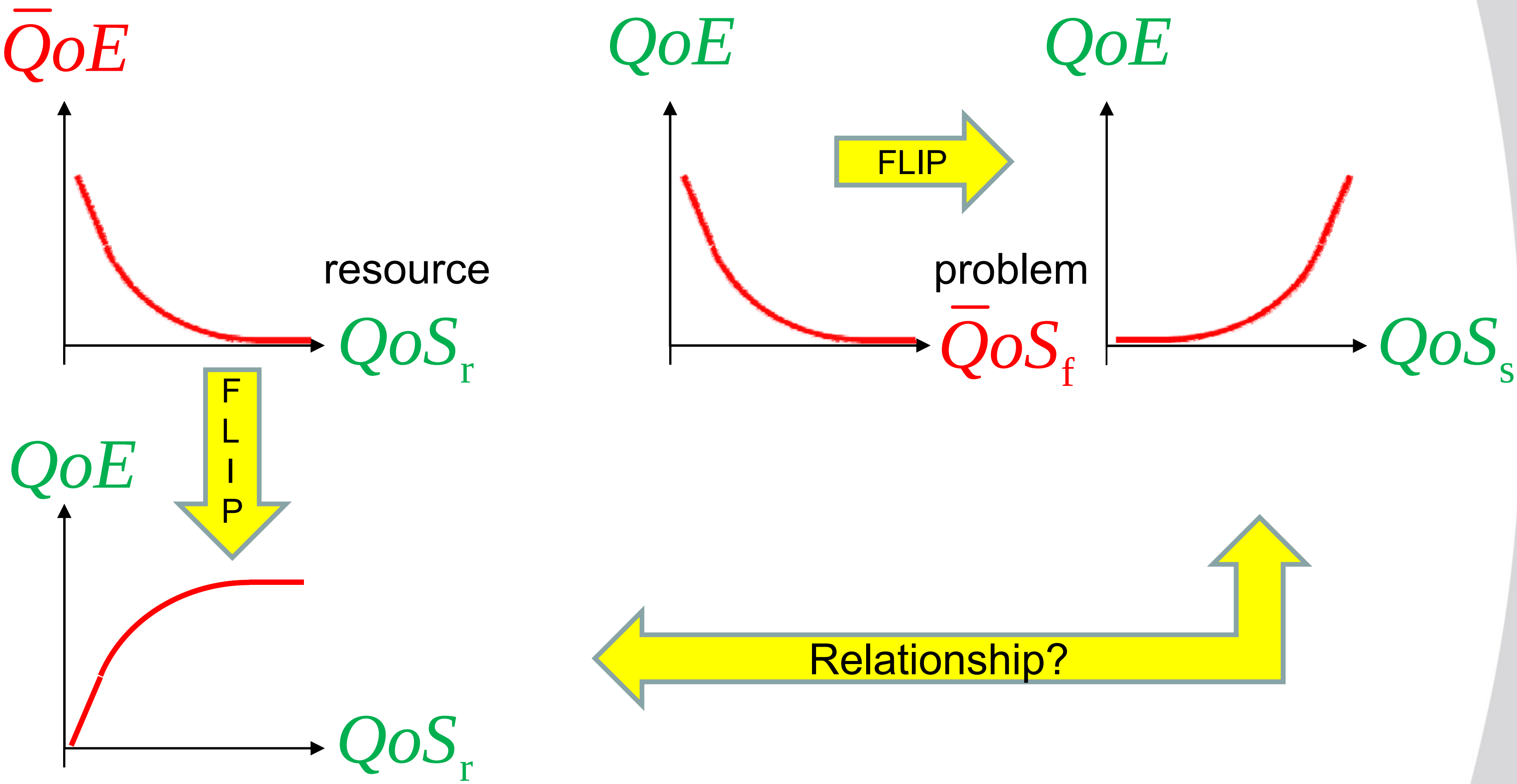
QoE



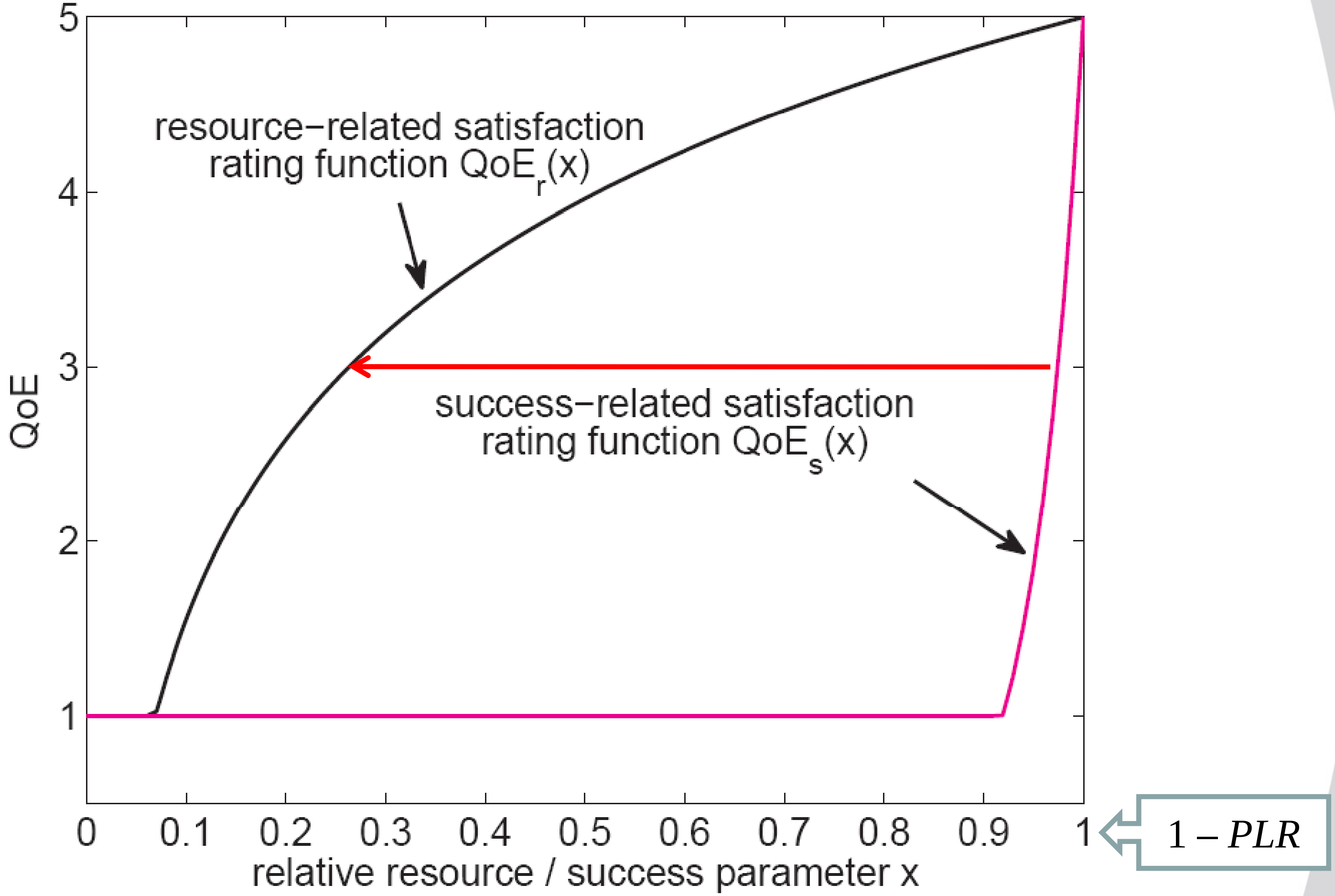
QoS_r

[Shaikh et al., 2010]

Basic shapes



Provisioning-delivery hysteresis for web



[Fiedler & Hossfeld, 2010]

Simple model for network virtualisation

- NMMRP/RP/0 system:
  - E.g. A-M-S-type of system

  - Full availability, full capacity share r: $\Pr\{S \leq N^*\}$
  - Limited availability, share $C/S < r$: $\Pr\{N^* < S \leq N'\}$
  - No availability (share too small): $\Pr\{S > N'\}$

Other candidate models

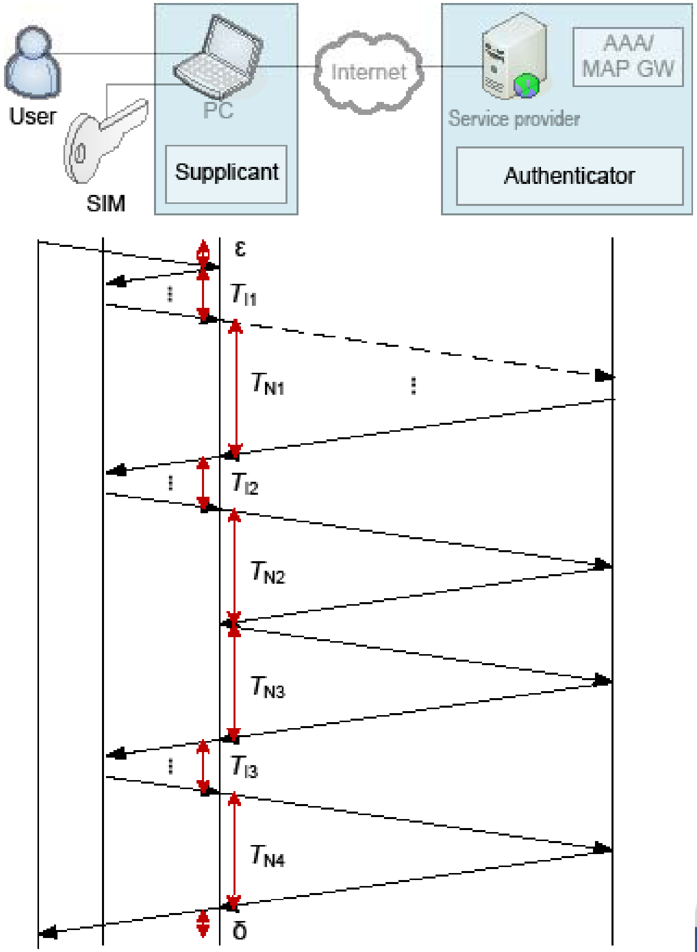
- ND/D/*n* models for non-overbooked systems
- Processor Sharing models
  - M/G/1-PS etc.
  - Generalised Processor Sharing
  - Important to consider tail behavior

Example 3: Service chains

[Lorentzen et al., 2010]

Authentication service chain

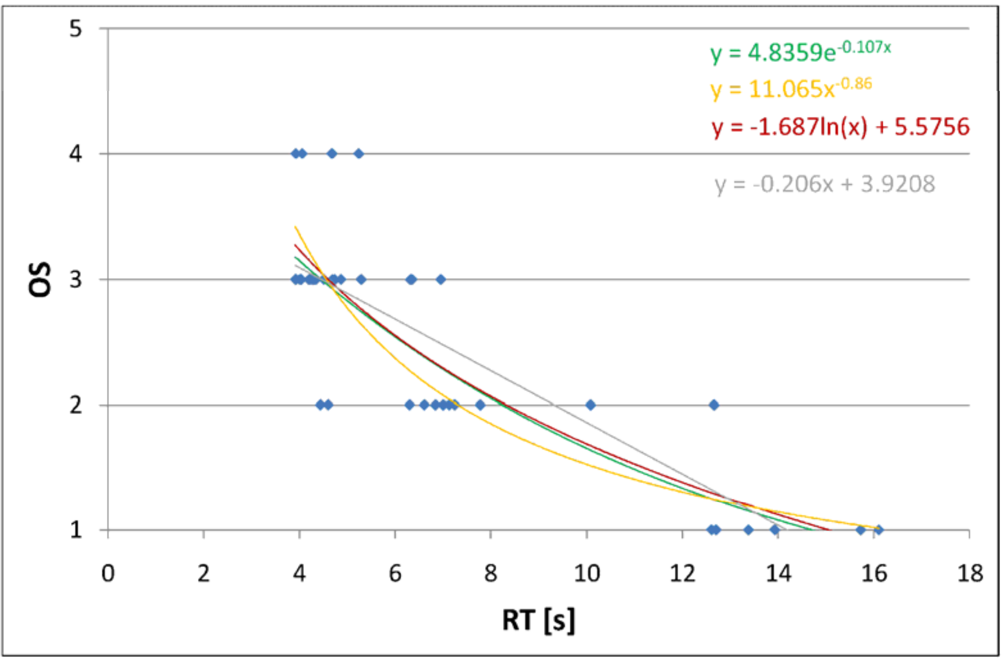
- User at the end of a service chain
  - Delays sum up and become QoE factors
  - Which is the "weakest" link?



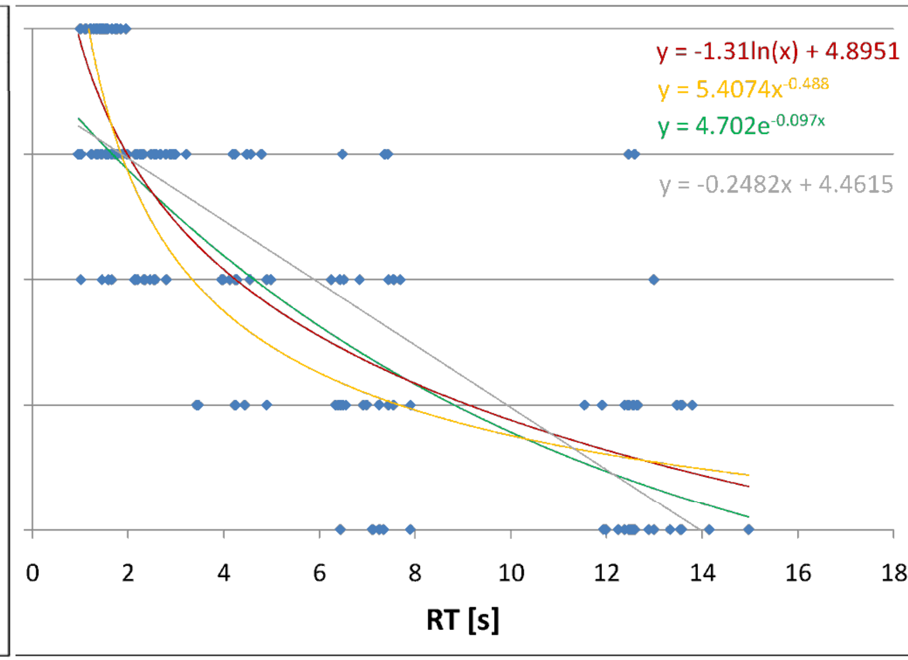
User models for QoE

Opinion scores for login, with regressions.

Complimentary study



Main study



Exponential	0.807	$y = 4.836\ e^{-0.107x}$	0.618	$y = 4.702\ e^{-0.097x}$
Logarithmic	0.720	$y = -1.687\ \ln(x) + 5.576$	0.691	$y = -1.31\ \ln(x) + 4.895$
Power	0.791	$y = 11.065x^{-0.860}$	0.643	$y = 5.407x^{-0.488}$
Linear	0.705	$y = -0.206x + 3.921$	0.966	$y = -0.2482x + 4.462$

User models for QoE

	Type	R^2	Regression
Web study	*Exponential*	0.99	**$y = 4.836\ e^{-0.150x}$**
	Logarithmic	0.988	$y = -1.426 \ln(x) + 4.469$
	Power	0.912	$y = 5.339\ x^{-0.638}$
	Linear	0.966	$y = -0.318x + 4.158$
Main study	Exponential	0.618	**$y = 4.702\ e^{-0.097x}$**
	Logarithmic	0.691	$y = -1.31 \ln(x) + 4.895$
	Power	0.643	$y = 5.407\ x^{-0.488}$
	Linear	0.966	$y = -0.2482\ x + 4.462$
Complimentary study	Exponential	0.807	**$y = 4.836\ e^{-0.107x}$**
	Logarithmic	0.72	$y = -1.687 \ln(x) + 5.576$
	Power	0.791	$y = 11.065\ x^{-0.860}$
	Linear	0.705	$y = -0.206x + 3.921$

New user models for QoE

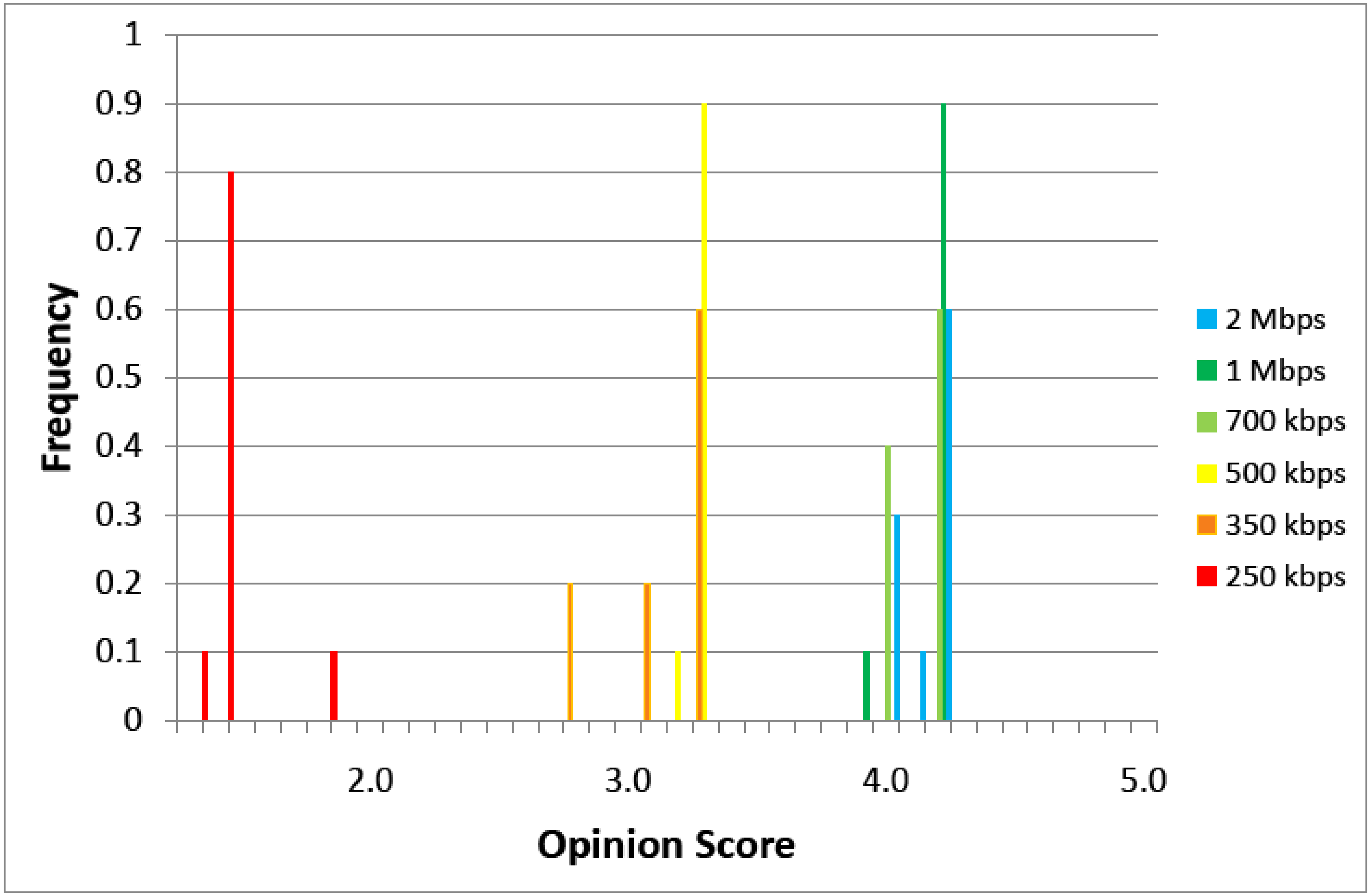
- User model for QoE considering network part and internal part: reveals critical factors
  - Exponential user model: $QoE \approx 4.7e^{-0.1T_{\mathrm{R}}/\mathrm{s}}$
  - Internal part (process): $\sum_{k=1}^{3} T_{\mathrm{I}k} \approx 1.8\,\mathrm{s}$ $(T_{\mathrm{R}} = T_{\mathrm{N}} + T_{\mathrm{I}})$
  - Resulting user model: $QoE \approx 4.7e^{-0.18}e^{-0.1T_{\mathrm{N}}/\mathrm{s}}$

$$\approx 3.9e^{-0.1T_{\mathrm{N}}/\mathrm{s}} \qquad T_{\mathrm{N}} = \sum_{k=1}^{4} T_{\mathrm{N}k}$$

- Challenge: find teletraffic models for $T_{\mathrm{N}k}$

User perception profile

Frequency of OSs (from RTs) per throughput

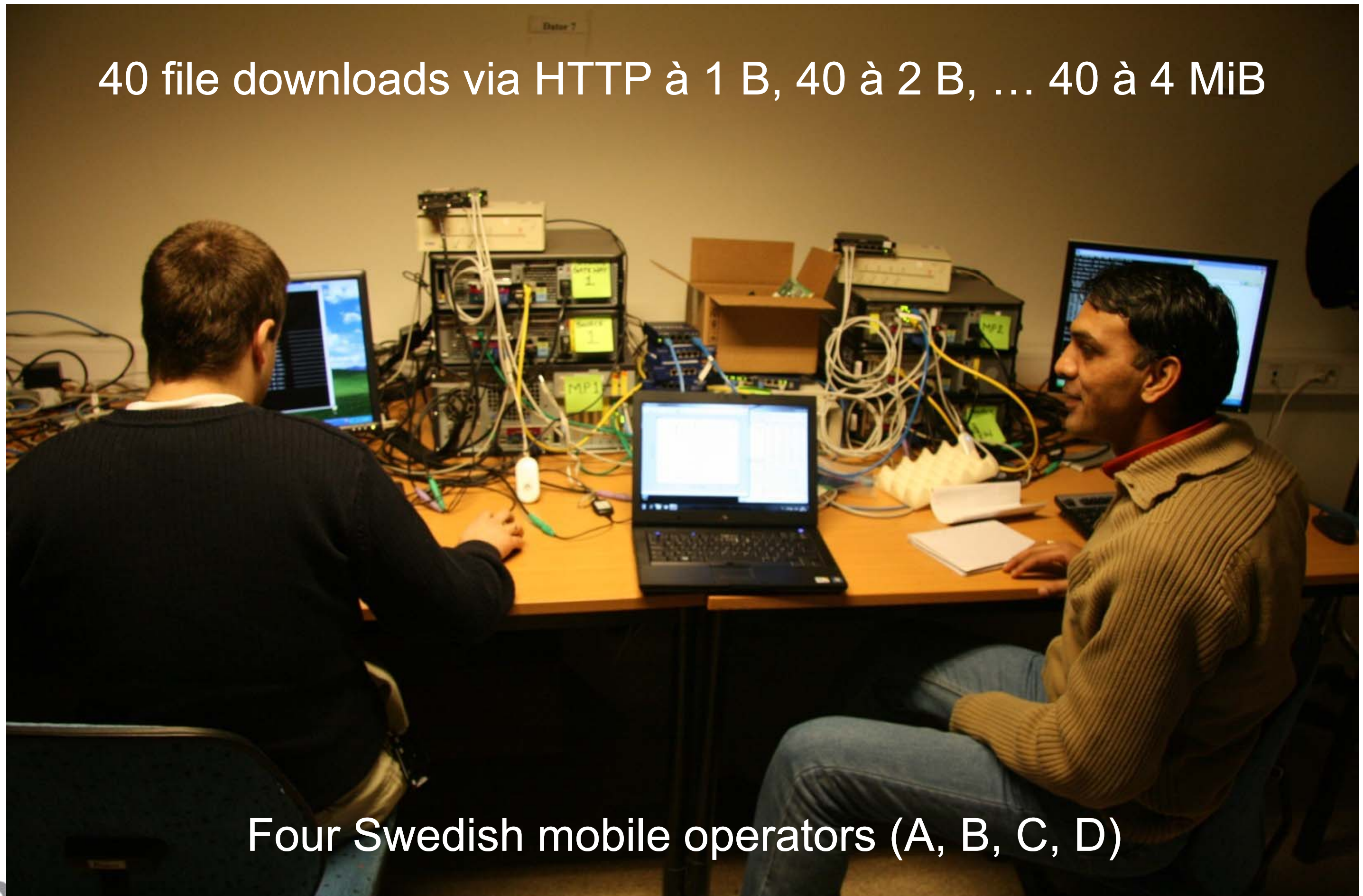


Example 4: Seamless communications

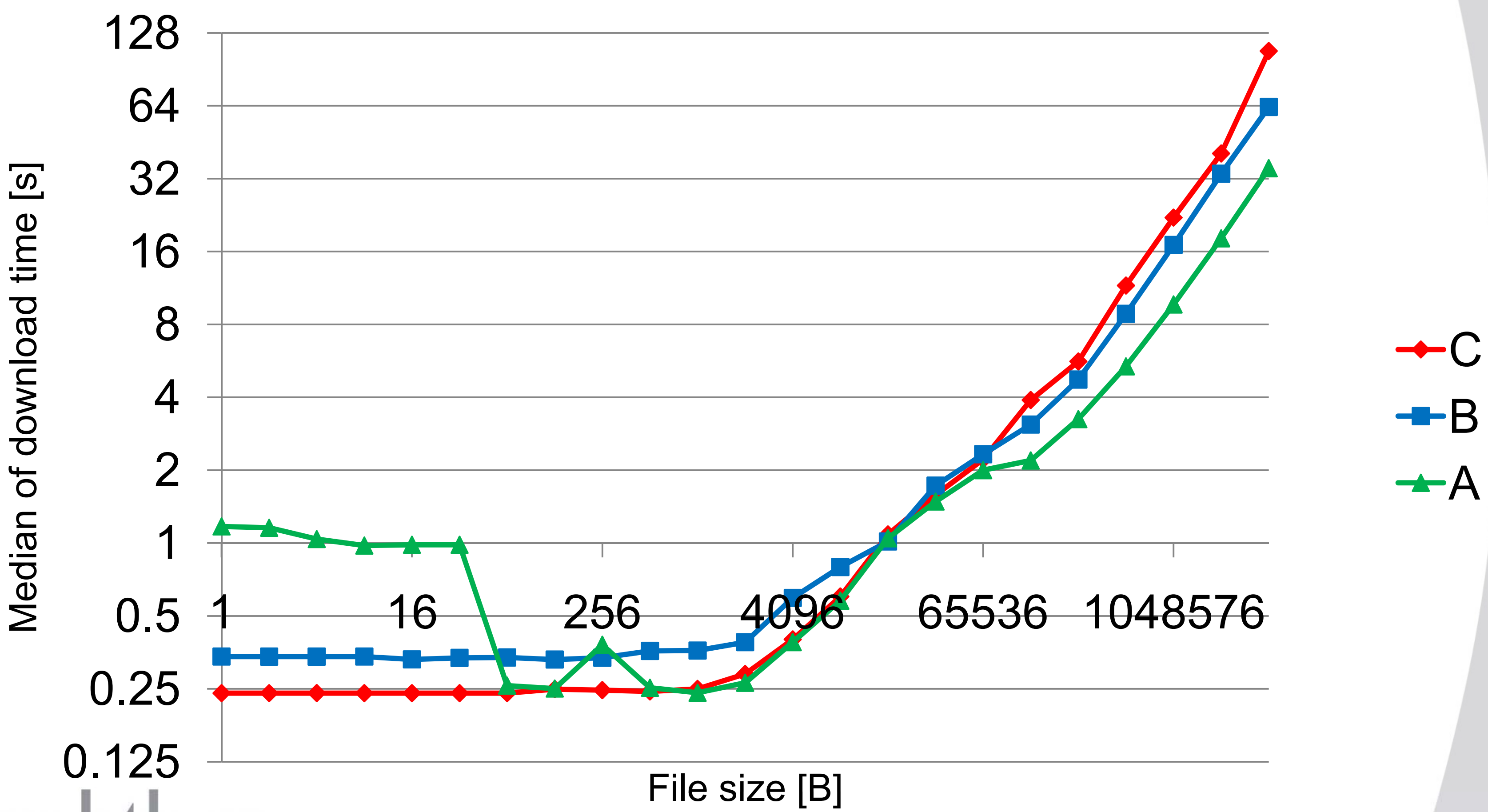
Automatic network selection
for making users
Always Best Connected

[Fiedler et al., 2011b]

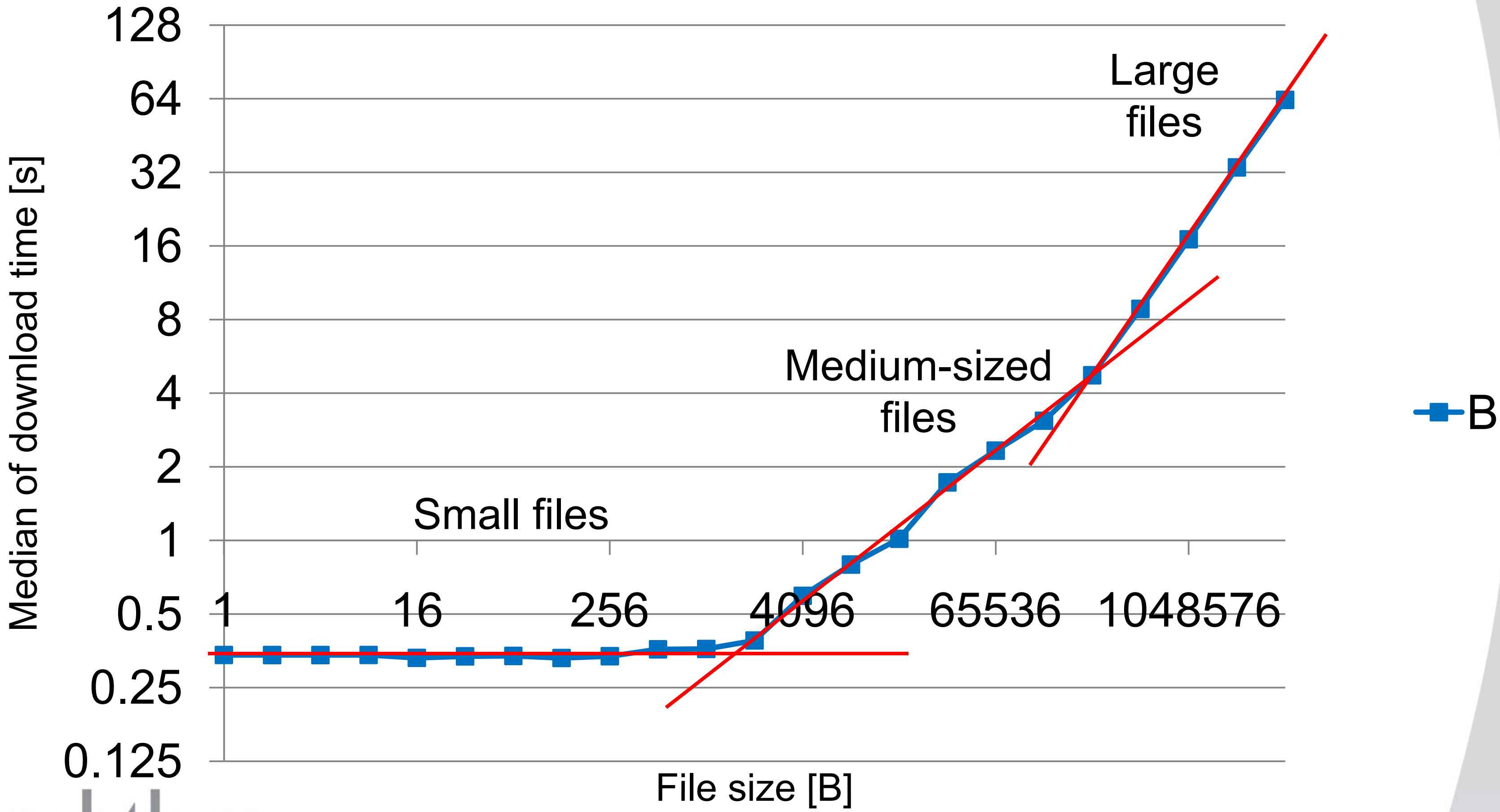
Measurements



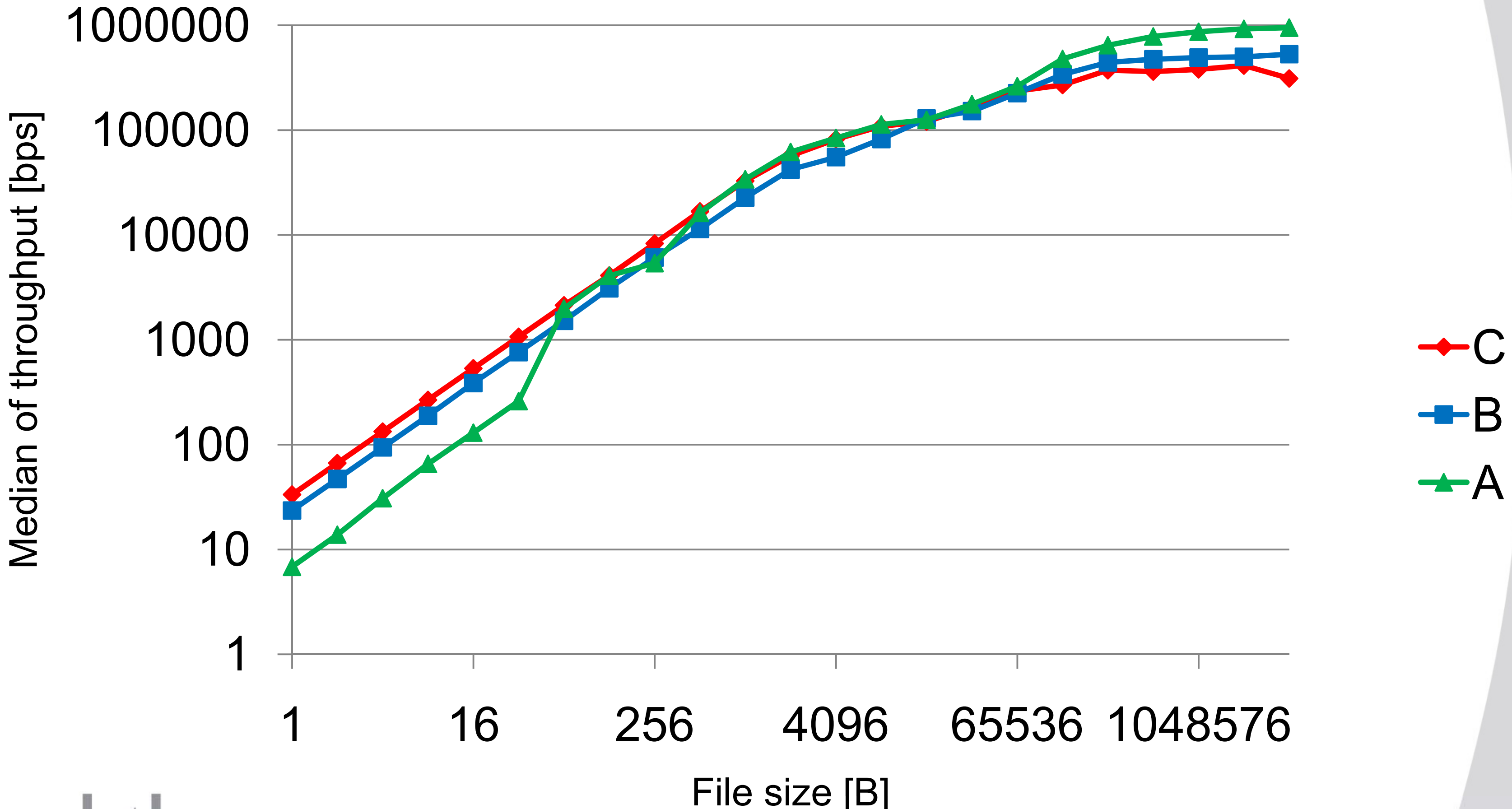
Median of download time = *f*(file size)



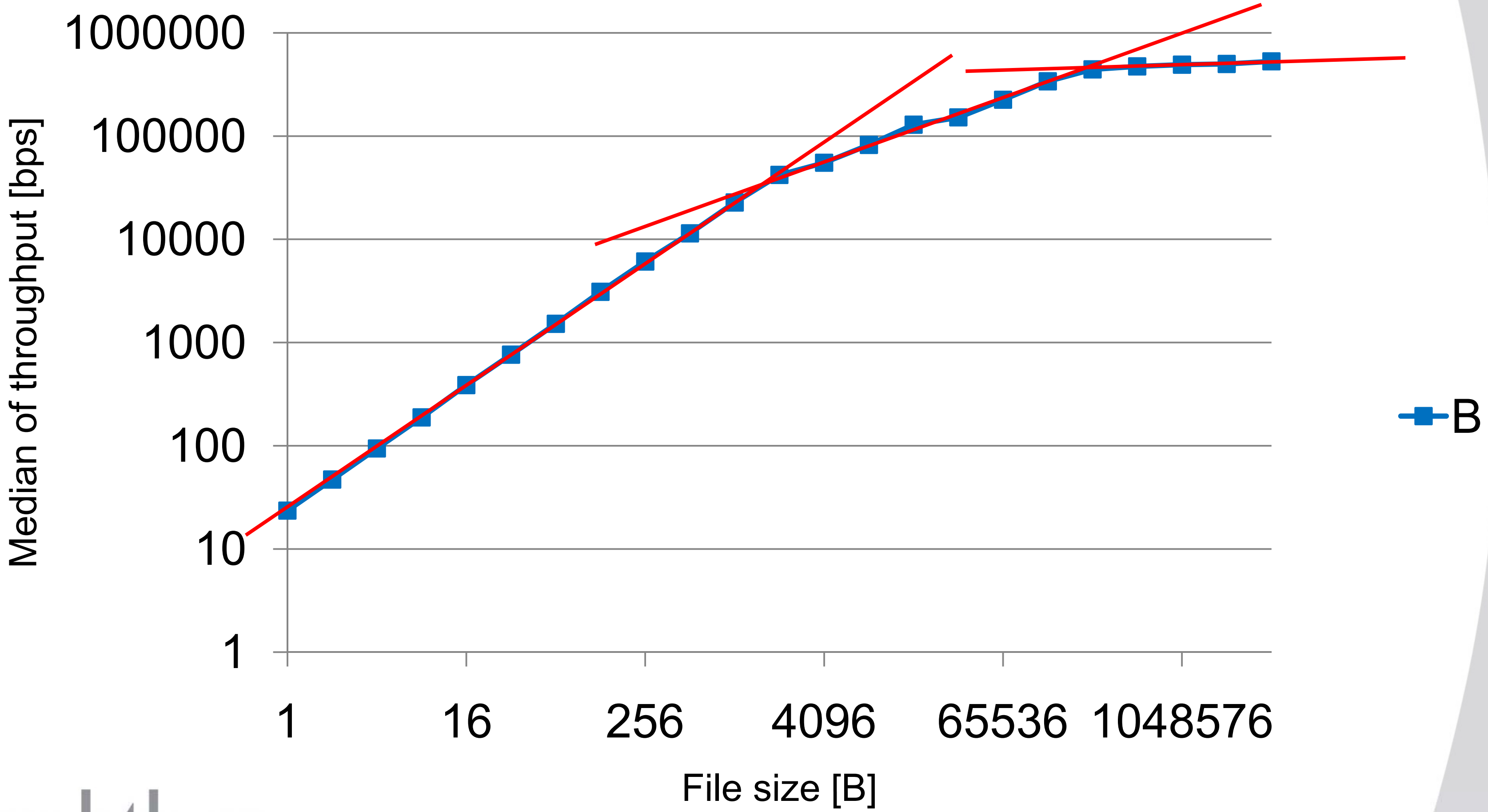
A closer look…



Median of throughput = *f*(file size)



… and again a closer look …



Quasi-stat. throughput R_∞ and RTTs

Operator	R_∞	c_V	$RTT_{0.5}$
A	950 kbps	4 %	125 ms
B	530 kbps	5 %	130 ms
C	311 kbps	13 %	336 ms
D	916 kbps	16 %	315 ms

- All operators advertise ”up to 7.2 Mbps”
- Operators A & B / C & D share networks
- RTT does not correlate well with R_∞ and download times

Regression formulae

Take maximum of the download time estimations:

- S $\hat{T}_{\mathrm{S}} = \mathrm{const.}$
- M $\hat{T}_{\mathrm{M}} = 8\left(\frac{X / \mathrm{B}}{R_\infty / \mathrm{bps}}\right)^{a_T}$ $a_T = 0.5$ (A, B)…0.625 (C)

  overestimates by 1..2 s
- L $\hat{T}_{\mathrm{L}} = 8\frac{X / \mathrm{B}}{R_\infty / \mathrm{bps}}$

QoE formulae

Basis: ITU.T Rec. G.1030 (time scale 6 s)

$$\mathrm{QoE} = \max\{\min\{4.38 - 0.9\ \mathrm{lb}(T/\mathrm{s}), 5\}, 1\}$$

$$\mathrm{QoE}_S = \min\{4.38 - 0.9\ \mathrm{lb}(\hat{T}^S/\mathrm{s}), 5\}$$

$$\mathrm{QoE}_M = \max\{\min\{1.68 + 0.9 a_T(\mathrm{lb}(R_\infty/\mathrm{bps}) - \mathrm{lb}(X/\mathrm{B}), 5\}, 1\}$$

$$\mathrm{QoE}_L = \max\{\min\{1.68 + 0.9(\mathrm{lb}(R_\infty/\mathrm{bps}) - \mathrm{lb}(X/\mathrm{B}), 5\}, 1\}$$

Role of teletraffic models

- Predict performance, in particular
  - R_∞ for downloads and streaming (average)
  - Variation of R
- TCP models: Impact of
  - Loss
  - Delay, RTT
  - Jitter, zero throughput times
- Key: Relate outcomes to user perception

Conclusions

"Classical" QoE $\Leftrightarrow$ teletraffic models

- QoE considerations provide discrimination of good / bad states in teletraffic models
  - Cf. examples 1 and 2
  - States "at the edge" might change from good to bad or vice versa
    - Memory effects captured through Hidden Markov Models [Hossfeld et al., 2011]

"Classical" QoE $\Leftrightarrow$ teletraffic models

- QoE models need output from teletraffic models
  - Cf. examples 3 and 4
  - QoS results turn into QoE results
    - Response times
    - Throughput

Building bridges …

- Lots of potential left for both teletraffic and QoE folks
  - Identify points of (real) user concern, related key parameters and thresholds
  - Build simple, yet telling models that capture the main issue(s) of concern
    - Many problems have been addressed before, but become relevant all over again $\Rightarrow$ check the literature
  - Analyse, optimise, and contribute to improved stakeholder satisfaction

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Thank you ☺
Q & A

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