Quality of Experience in LTE-A networks

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Learning outcomes

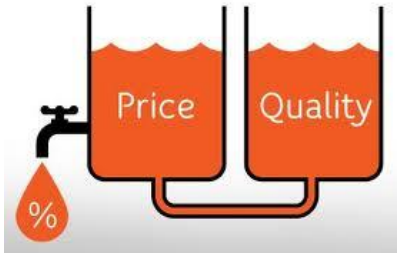
- The concept of Quality of Experience (QoE)
- Motivation behind QoE
- Quality of Service (QoS) in LTE-A
- Relationship between QoS and QoE
- Major QoE influence factors
- How can it be measured?
- How can it be controlled?
- How can it be exploited?
- Other research challenges

INTRODUCTION TO QoS & QoE

Some statistics

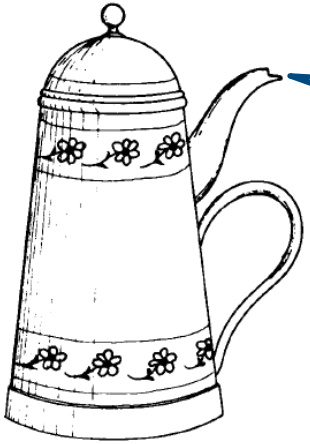
- Two "competing" entities:

Operator/Provider vs. Customer/User
↔
min(Cost) vs. max(Quality)



- Some facts:
  - **82%** of customer defections are due to frustration and the provider's inability to deal with this effectively
  - For 1 person who calls with a problem, **29** never will
  - 1 frustrated customer will tell **13** others
  - **90%** abandons a service without even complaining

Anything familiar?



Impractical

Slow

Doesn't meet expectations

Bad value for money

Unacceptable quality

Poor customer service

Unavailable

For which one would you rather pay?

- *"Unlimited internet with speed up to 24Mbps"*

  → QoS (Quality of Service)

- *"Excellent user experience guaranteed"*

  → QoE (Quality of Experience)

➢ **QoS** is "a set of technical quality requirements on the collective behaviours of one or more objects in order to define the required performance criteria". But:

- It handles pure technical aspects
- Same QoS values do not imply same customer experience
- QoS does not reflect the end-user satisfaction

Information flows in LTE-A

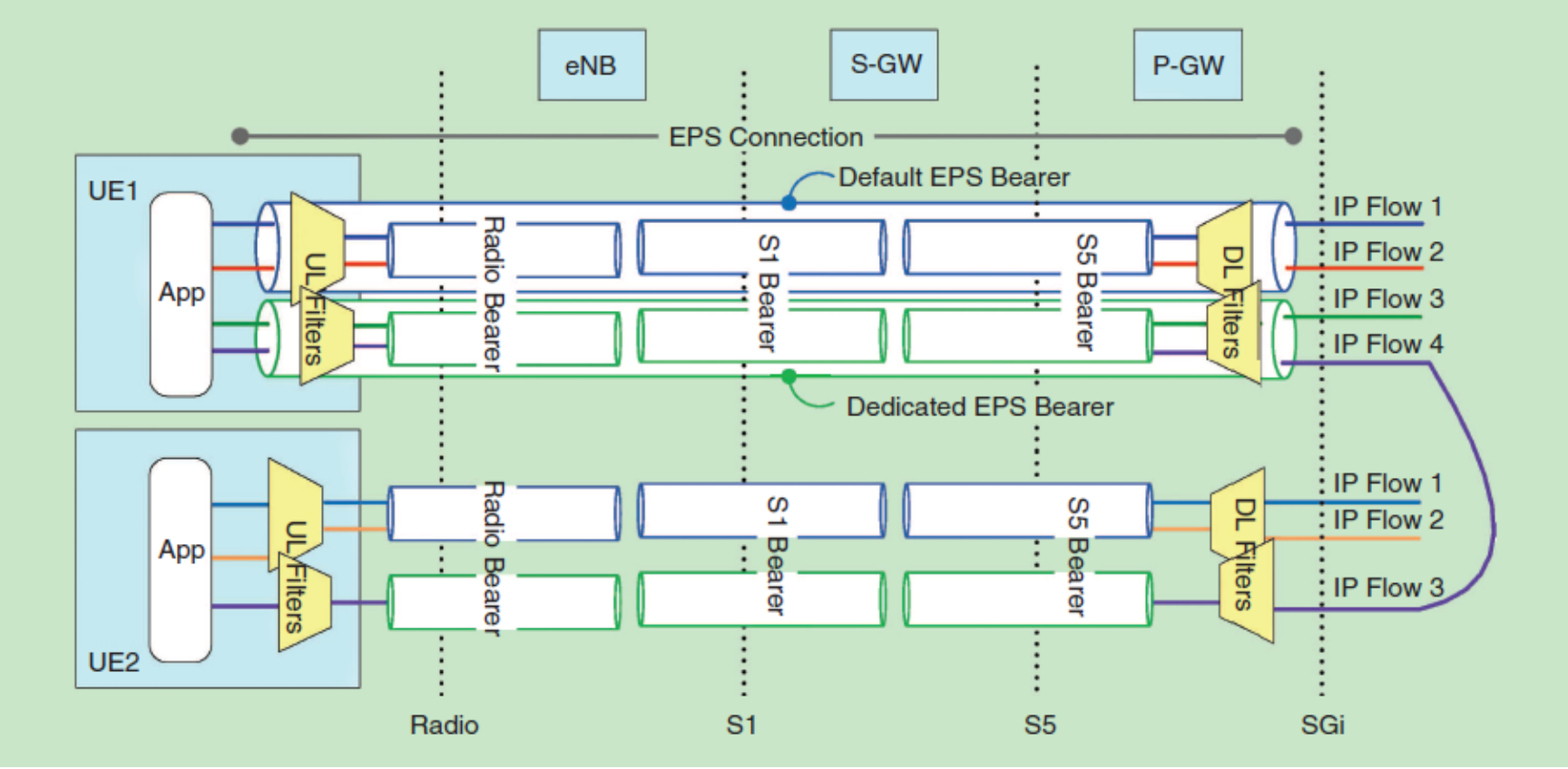
- **Bearer:** It is a virtual concept that defines how the UE data are treated across the network => a set of network parameters that defines data specific treatment
- **Channel:** Carries information between different levels of the air interface protocol stack

➢ Packet filtering into different bearers is based on **Traffic Flow Templates**:

- **Uplink TFT:** Filters IP packets to EPS bearers in the UL direction → in UEs
- **Downlink TFT:** A similar set of DL packet filters → in the P-GW

➢ End-to-end bearers are realized by the EPS bearers, which are a collection of radio, S1 and S5/S8 bearers…

Bearer architecture in LTE-A



* M. Yang, S. Lim, H. Park, and N. Park, "Solving the data overload: Device-to-device bearer control architecture for cellular data offloading," IEEE Veh. Technol. Mag., vol. 8, no. 1, pp. 31–39, Mar. 2013.

EPS bearer terminology

Criterion	Name	Explanation	Example/Attribute
QoS	GBR	A GBR bearer has a guaranteed bit rate amongst its QoS parameters	Conversational service, such as a voice call
	Non-GBR	A non-GBR bearer does not have a guaranteed bit rate	Background service, such as e-mail
Time of establishment	Default	- When the UE connects to a packet data network - Provides always-on IP connectivity	Always non-GBR bearer
	Dedicated	Additional EPS bearers for the same PDN	GBR or non-GBR bearers

QoS parameters in LTE-A

- **QoS class identifier (QCI):** Scalar that indicates the priority, the max error rate and delay associated with a service
- **Allocation and retention priority (ARP):** Determines whether a bearer will be dropped if the network gets congested

➢ GBR bearers:

- **Guaranteed bit rate (GBR):** The long-term average rate a user can expect
- **Maximum bit rate (MBR):** The max instant rate the network can provide

➢ Non-GBR bearers:

- **Per APN aggregate maximum bit rate (APN-AMBR):** Limits the total bit rate that a UE is exchanging with a particular access point
- **Per UE aggregate maximum bit rate (UE-AMBR):** Limits the total bit rate of all of the non-GBR bearers for a particular UE

QoS parameters in LTE-A

QoS Class Identifier profile

Priority of packets

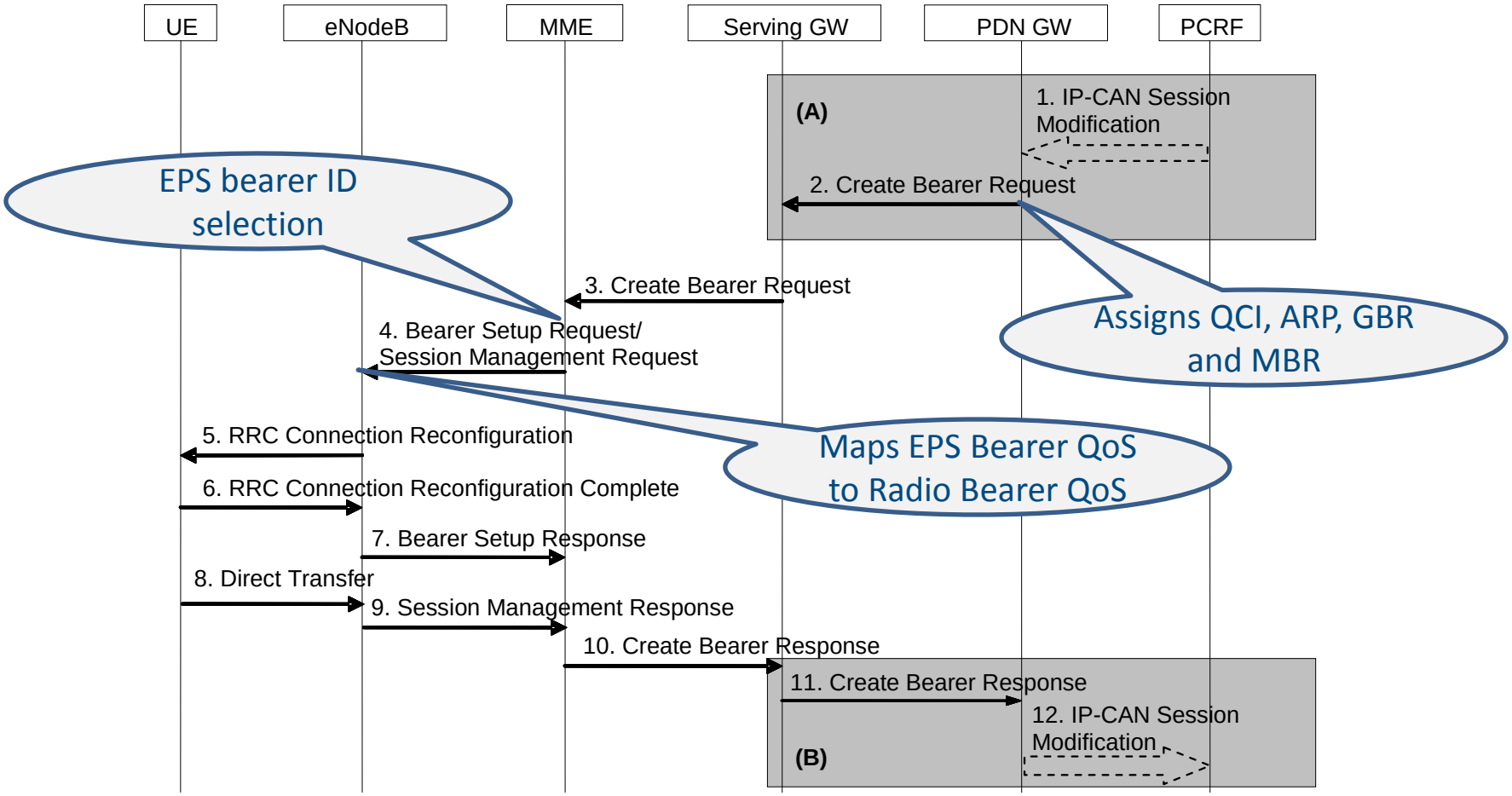
Network nodes use **QCI** as a reference, to look up the parameters that control how packets are forwarded.

QCI	Bearer Type	Priority	Packet Delay	Packet Loss	Example
1	GBR	2	100 ms	10^{-2}	VoIP call
2		4	150 ms	10^{-3}	Video call
3		3	50 ms		Online Gaming (Real Time)
4		5	300 ms	10^{-6}	Video streaming
5	Non-GBR	1	100 ms		IMS Signaling
6		6	300 ms		Video, TCP based services e.g. email, chat, ftp etc
7		7	100 ms	10^{-3}	Voice, Video, Interactive gaming
8		8	300 ms	10^{-6}	Video, TCP based services e.g. email, chat, ftp etc
9		9			

Guaranteed or not Bit Rate

Upper boundaries

Dedicated bearer activation

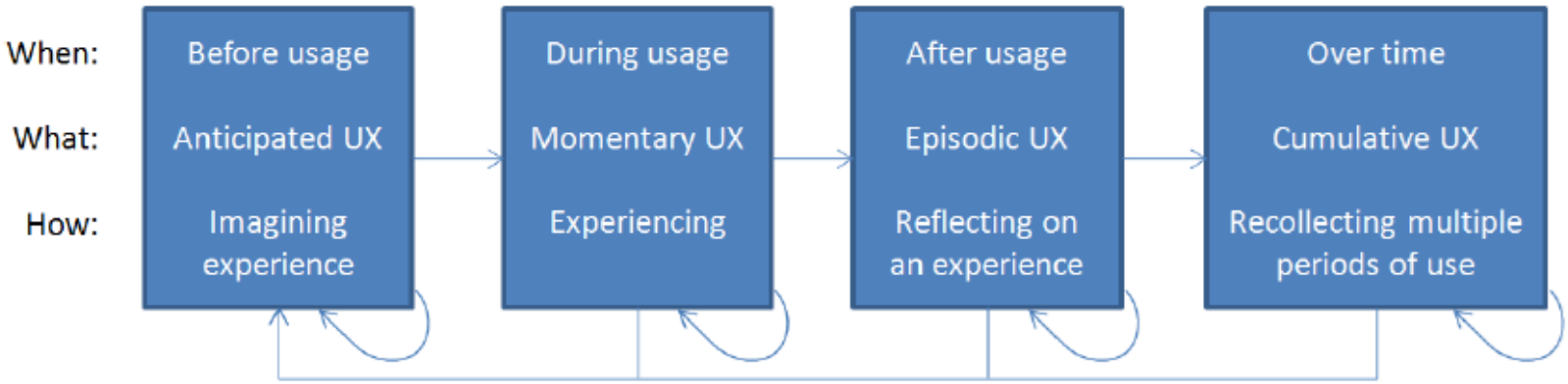


* 3GPP TS 23.401: Figure 5.4.1-1

Quality of Experience - QoE

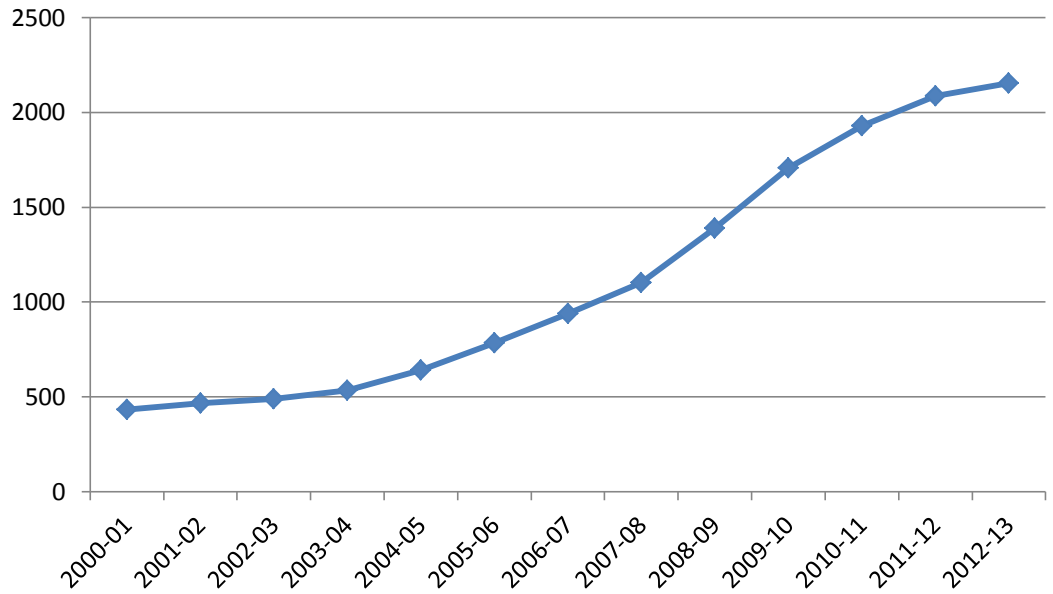
- ITU-T: "The overall acceptability of an application or service, as perceived subjectively by the end-user."
- ETSI: "A measure of user performance based on both objective and subjective psychological measures of using an ICT service or product."
- Practically: "The degree of your delight or annoyance over a product, application or service." [Qualinet]

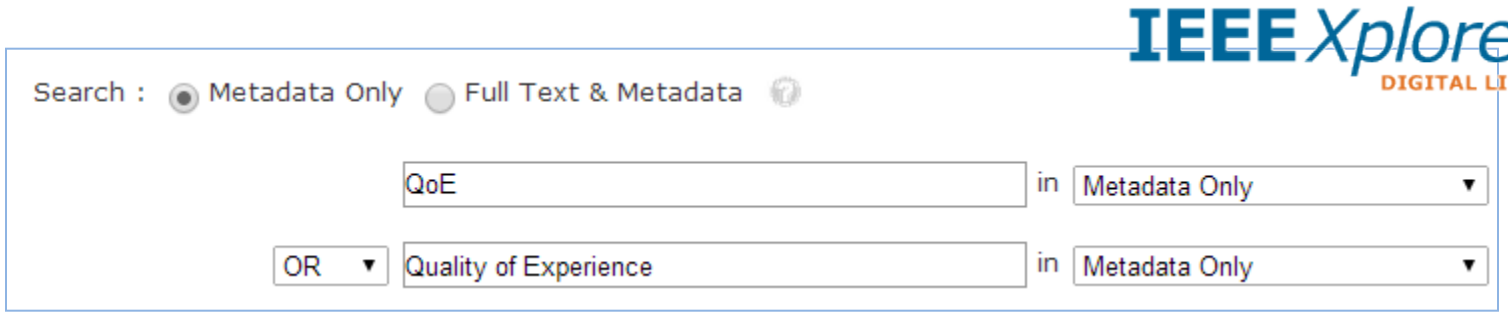
Time spans of UX



* "User Experience White Paper: Bringing clarity to the concept of user experience", Dagstuhl Seminar

QoE: An emerging topic



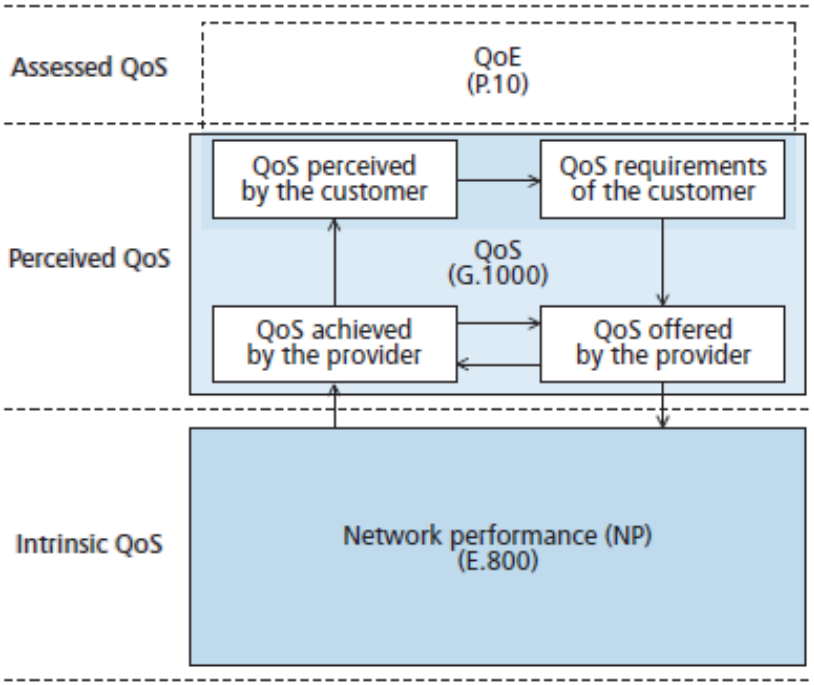


QoE: An emerging topic

QoE: An emerging topic

- **QoMEX**: Quality of Multimedia Experience
- **PQS**: Perceptual Quality of Systems
- **Qshine**: Heterogeneous Networking for Quality, Reliability, Security and Robustness
- **IWQoS**: Quality of Service
- **QoENAM**: QoE-centric Network and Application Management
- **QoEMC**: Quality of Experience for Multimedia Communications

QoE: A multidisciplinary field



- QoS: technology-centred
- QoE: user-centred

QoE encompasses:

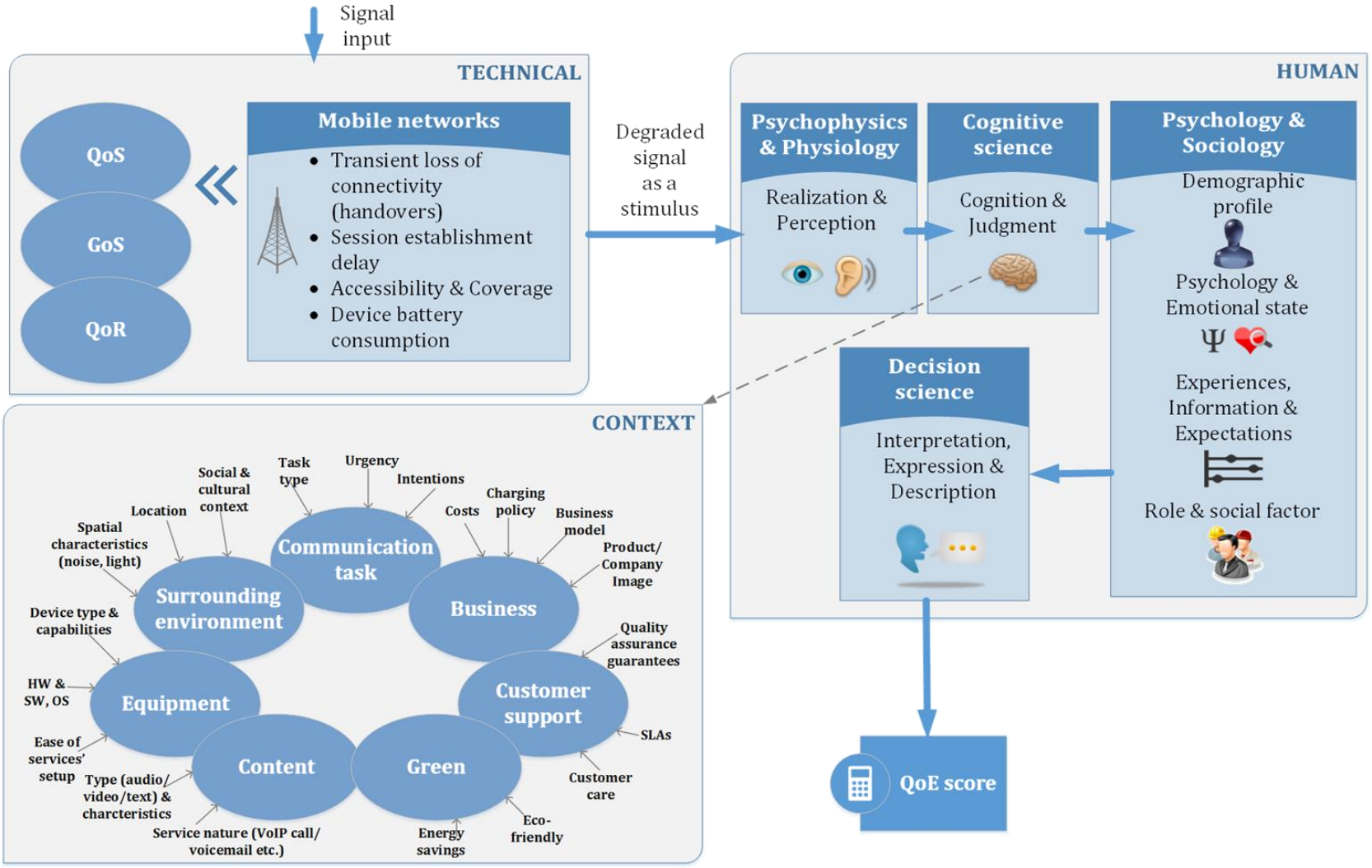
- QoS (Quality of Service)
- GoS (Grade of Service)
- QoR (Quality of Resilience)
- QoBiz (Quality of Business)
- QoP (Quality of Perception)
- QoD (Quality of Design)
- QoC (Quality of Conformance)

Main properties:

- User-dependent
- Application-dependent
- Terminal-dependent
- Time variant

* R. Stankiewicz, P. Cholda, and A. Jajszczyk, "QoX: What is it really?," IEEE Communications Magazine, vol. 49, no. 4, pp. 148–158, Apr-2011.

QoE: A multidisciplinary field



1. Human

Age, gender, education level, cultural background, sociological and psychological factors, cognitive and perceptual abilities, user expectations, experiences, emotion, mood, perception, preferences

2. Technical

Aspect	Quality Influence Factors	
Mobile networks	Vertical and horizontal handovers Battery consumption Session establishment delay	Accessibility Coverage
Service	Call setup success ratio Blocking probability Call setup time	Call cut-off ratio Availability & Reliability
Transport / Network	Round trip / one-way delay Jitter Packet loss ratio Delay burstiness distribution	Loss burstiness distribution Bottleneck bandwidth Congestion period
Physical	SNR / SIR / SINR Bit rate BLER Outage probability Packet / Symbol / Bit Error Probability Outage capacity	Ergodic capacity / rate Throughput Diversity order / coding gain Area spectral efficiency Energy efficiency

3. Context

- Environmental factors
- Terminal type
- Human role
- Communication task, Urgency
- Customer support, ease of setup & use
- Charging policy & price
- Content

Why is QoE intelligence so important?

QoE Stakeholders	
Service providers	Network operators
Network designers	Customer support
Marketing teams	Sales support
Equipment manufacturers	UX designers
Infrastructure planners	Service/SW developers
Product strategists	SLA negotiators
YOU	

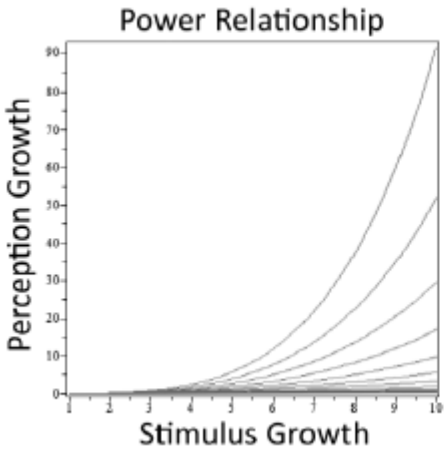
- It encompasses the issue of **your** decision on buying / retaining a service or giving it up

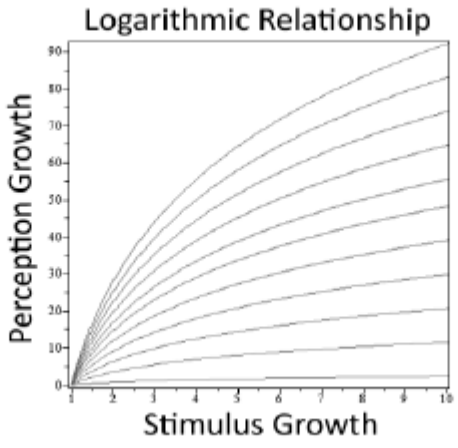
Why is QoE intelligence so important?

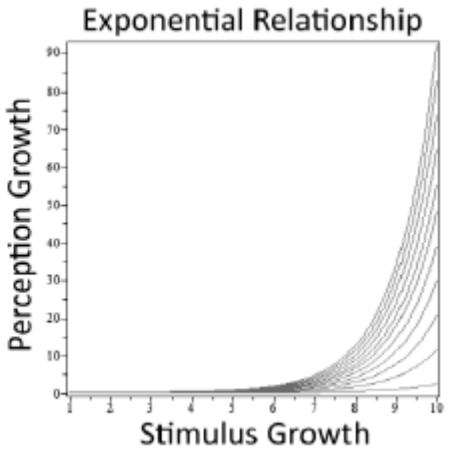
- To evaluate network quality and performance
- To test new algorithms and protocols & optimize a service
- To improve the user experience on the run (reactive)
- To predict and prevent problems in the network (proactive)
- To help the network function in a more resource-efficient way
- To provide support for: network capacity planning, identification of network bottlenecks, network reconfiguration etc.
- To enhance existing network decision-making algorithms
- To drive operations, prioritize investments, build SLAs, enable informed strategic business decisions
- For service performance benchmarking
- To improve customer care and reduce/prevent churn

QoS - QoE relationship

	Name	Trend	Relation	Form
Adopted from Psychophysics	Stevens' Power Law	Stimulus-centric	$QoE = K.QoS^{b}$	Power
	Weber-Fechner Law	Stimulus-centric	$QoE = k.\ln(QoS)$	Logarithmic
Adopted from a Hypothesis	IQX	Perception-centric	$QoE = \alpha.e^{-\beta.QoS} + \gamma$	Exponential

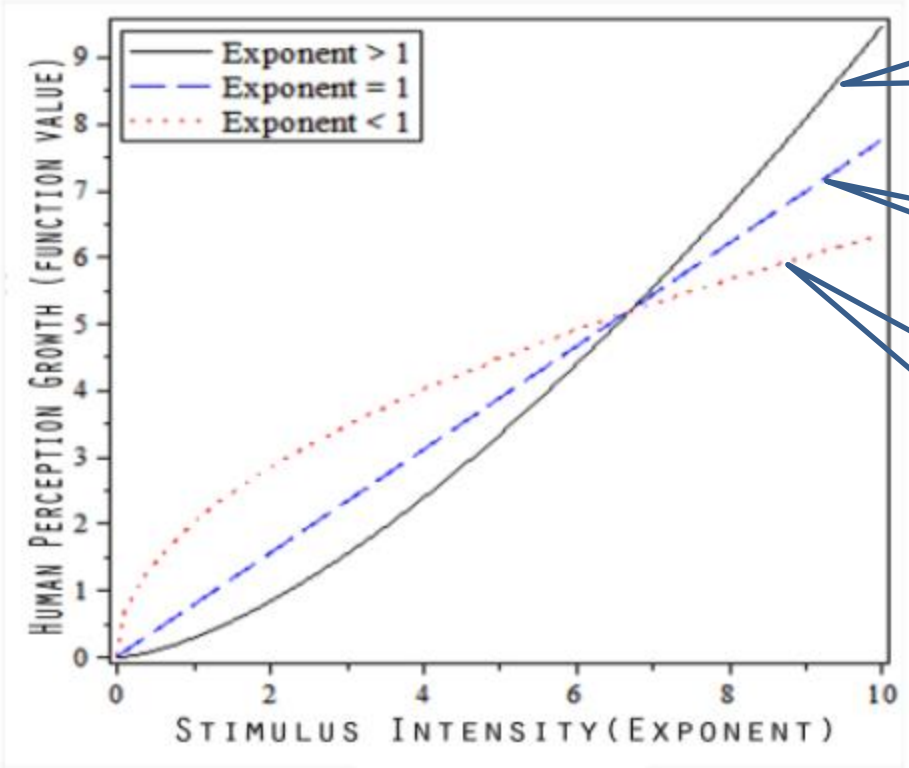






* S. Khorsandroo, R. M. Noor, S. Khorsandroo, "A Generic Quantitative Relationship to Assess Interdependency of QoE and QoS", Ksii Transactions on Internet and Information Systems, 2013.

Steven's law



Human perception growth as a function of muscle force

How humans can perceive changes in visual length

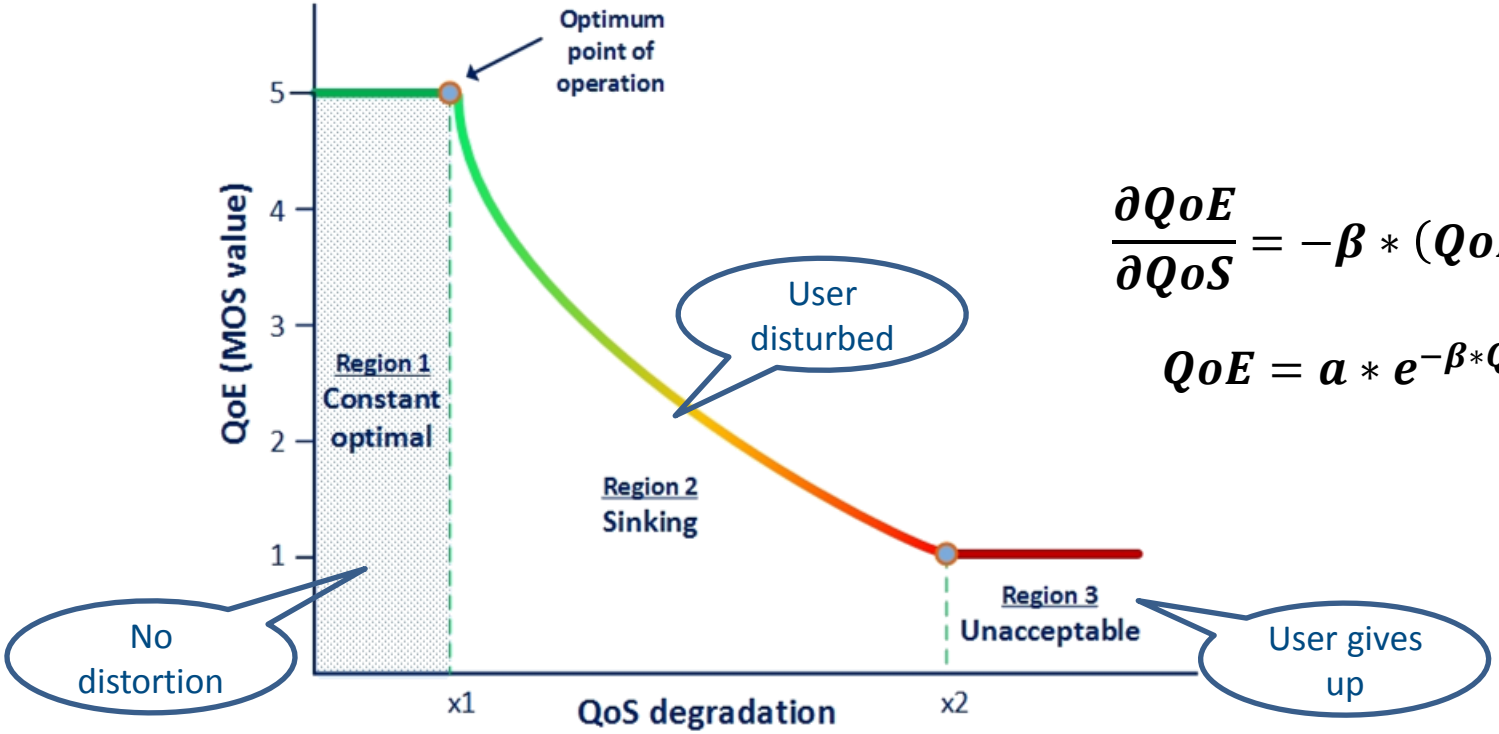
Human perception as a function of smell

$$P(S) = K * S^b$$

* S. Khorsandroo, R. M. Noor, S. Khorsandroo, "A Generic Quantitative Relationship to Assess Interdependency of QoE and QoS", Ksii Transactions on Internet and Information Systems, 2013.

The IQX hypothesis

- The change of QoE depends on its current level
- High QoE => small disturbances strong impact ≠ small QoE => unperceived



$$\frac{\partial QoE}{\partial QoS} = -\beta * (QoE - \gamma) \Rightarrow$$

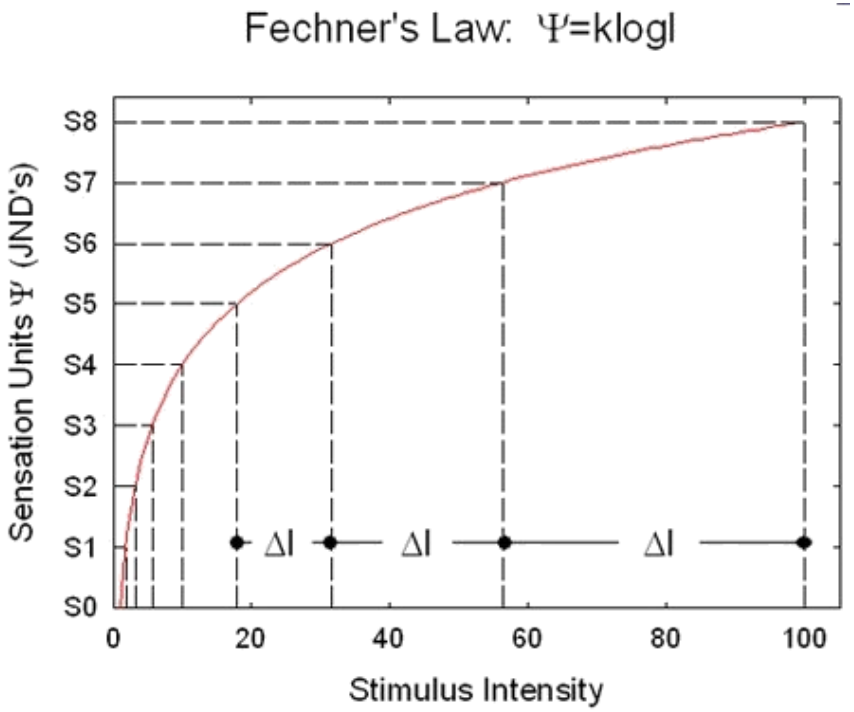
$$QoE = a * e^{-\beta * QoS} + \gamma$$

* M. Fiedler, T. Hossfeld, and P. Tran-Gia, "A generic quantitative relationship between quality of experience and quality of service," IEEE Network, vol. 24, no. 2, pp. 36–41, Mar-2010.

Weber Fechner Law

"Just noticeable differences" concept - jnd:

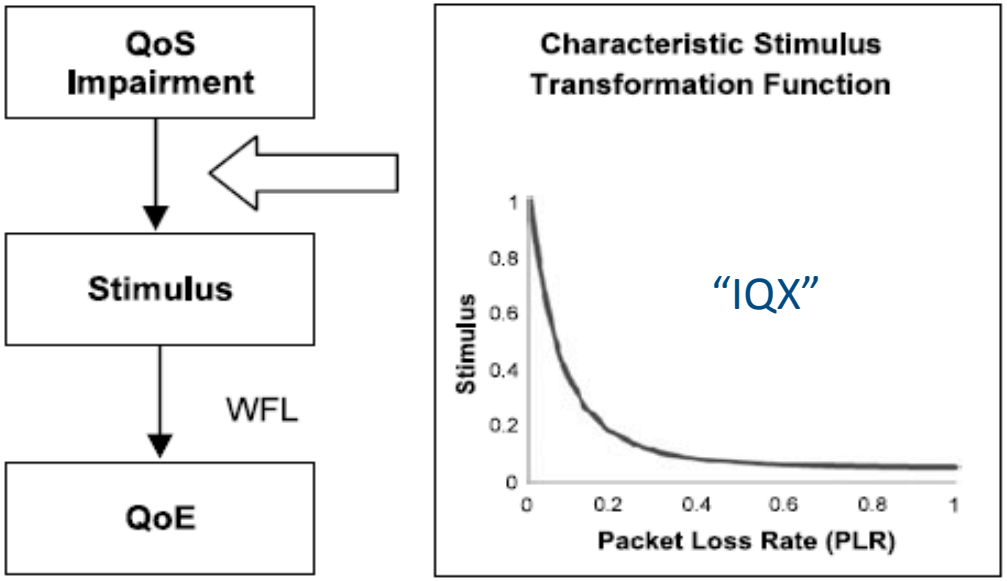
- Weight: 100gr distinguished from 105 gr, 200gr distinguished from 210gr => 5% is the "Weber fraction"
- Brightness, hearing, smelling, numerical cognition, time perception, etc.



$$dP = k * \frac{dS}{S} \Rightarrow P = k * \ln\left(\frac{S}{S_0}\right)$$

- dP = differential change in perception
- dS = differential increase in the stimulus
- S = instantaneous stimulus
- S_0 = stimulus threshold

IQX – WFL: two sides of the same coin



- The IQX hypothesis relates QoE to QoS degradation rather than to a perceivable QoS-dependent stimulus
- Transform the IQX model into a stimulus model!

* P. Reichl, B. Tuffin, and R. Schatz, "Logarithmic laws in service quality perception: where microeconomics meets psychophysics and quality of experience," Telecommun. Syst., Jun. 2011.

QoE MODELING

Research areas

QoE Management procedure	QoE impairment prediction, diagnosis	Incorporate QoE in LTE-A mechanisms	Network dimensioning & planning for QoE	Organise subjective experiments, combine
QoE-driven procedures (QoE-aware routing, resource control)	Interworking problem, HetNets	Identify KPIs (Influence Factors)	Quantify user perception (impact of stimulus)	Study quality-affecting phenomena
Map QoS to QoE, QoE to acceptance	Network-based vs. agent-based, initialisation	QoE business models, Charge for QoE	Diversification & Fairness among users	Optimise for user + provider perspective
Delivery of QoE reports, expression	Security Privacy Legal issues	SLAs Certification Labelling	QoE target, Granularity, Rating scale used	Consensus in QoE practices

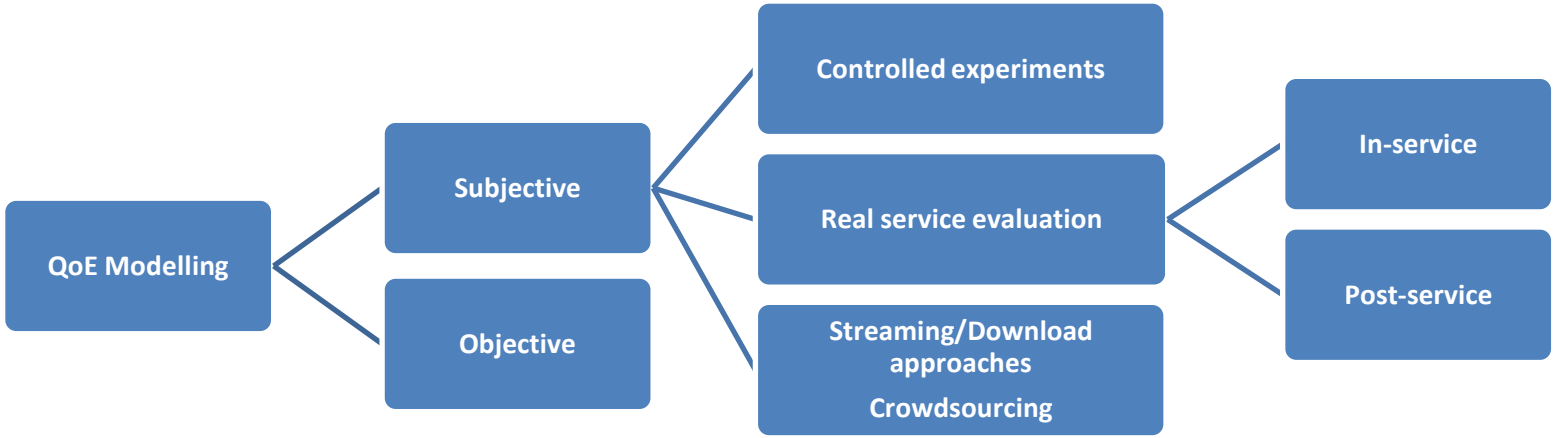
How can QoE be measured?

The answer is via: QoE modelling!

- It aims to model the relationship between different measurable QoE Influence Factors (IF) and quantifiable QoE features for a given scenario and their impact on an overall QoE score.

Any characteristic of a user, system, service, application, or context whose actual state or setting may have influence on the QoE.

A perceivable, recognized and namable characteristic of the individual's experience of a service which contributes to its quality.



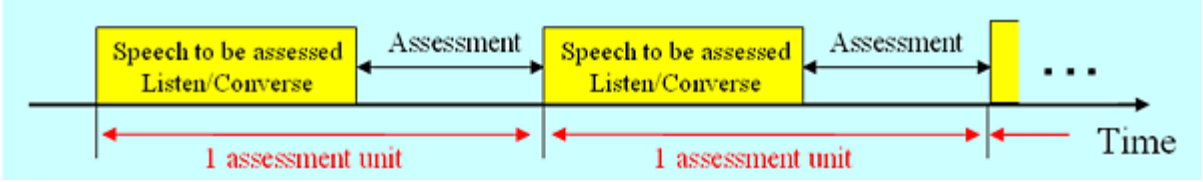
* Qualinet White Paper on Definitions of Quality of Experience

Comparison

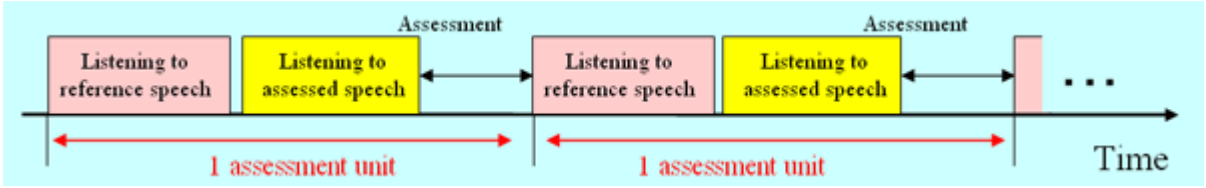
Model	Advantages	Disadvantages	Restrictions
Subjective (controlled)	+ The most reliable QoE measurement model, highly accurate and valid + Ensures uniformity between subjective scores from different laboratories	- Not real-time (requires lab setting), not reproducible on demand - Time consuming and expensive - Needs thorough planning => complex - May be biased by user opinion, assumptions or unconscious psychological factors - Users may be greedy on their QoE demands and hence evaluations - Users' tiredness and lack/loss of concentration - Participants may just want to earn money and not be concise - Difficult for users to discriminate between e.g. "Bad" and "Poor" values in MOS scale	-> Experiments need to be conducted under strict requirements and controlled conditions: isolated sound room, dedicated equipment, suitably selected panel and number of participants, specific duration of signals etc.
Objective (in general)	+ Automatically predict QoE + Same input always gives same output + Bypass the need for a human panel (the majority) + May be real-time, may be proactive	- Complexity - May not always highly correlate to reality - No universal generic quality model available, each one has a specific application scope - Need continuous validation against subjective data	-> Differ per model

Subjective: controlled experiments

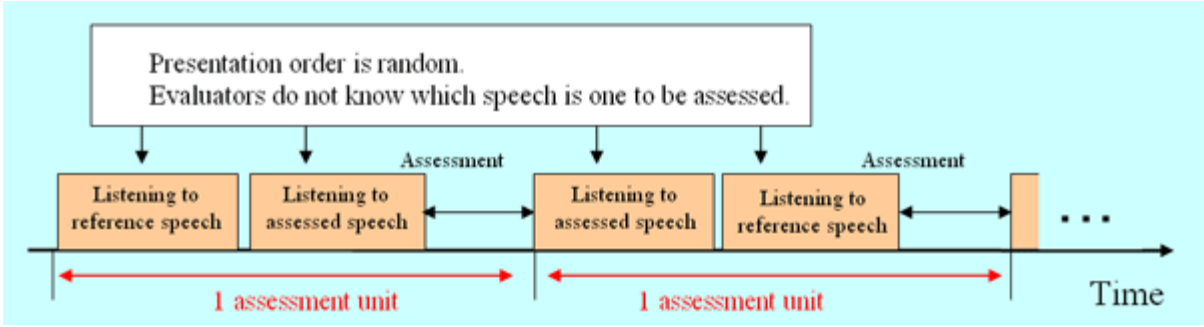
- MOS (Mean Opinion Score)



- DMOS (Degradation MOS)

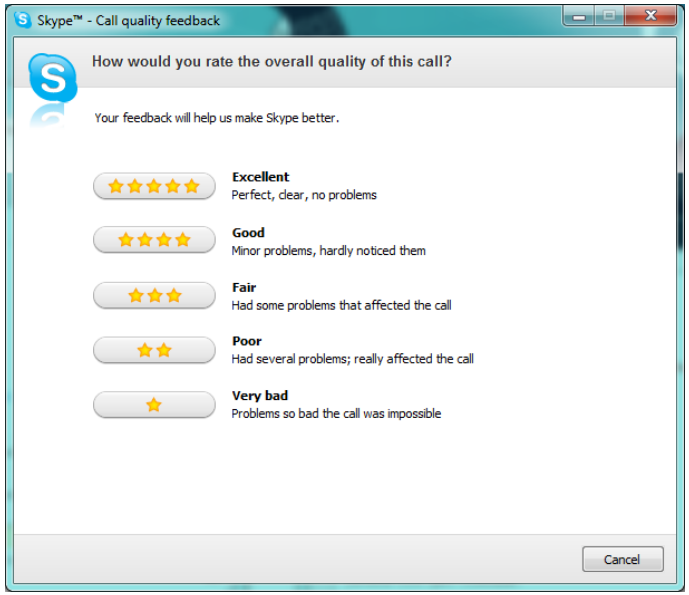


- CMOS (Comparison MOS)

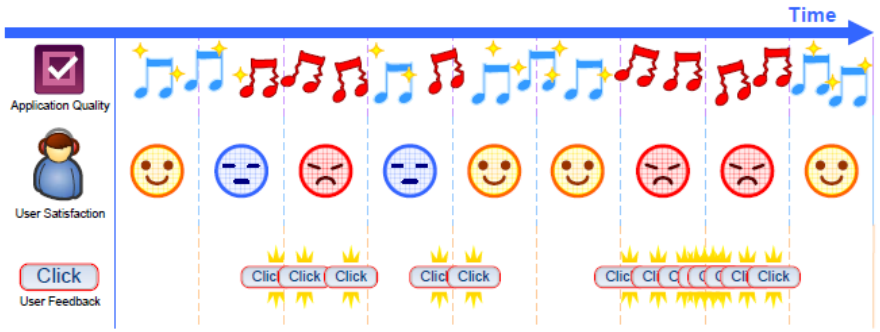


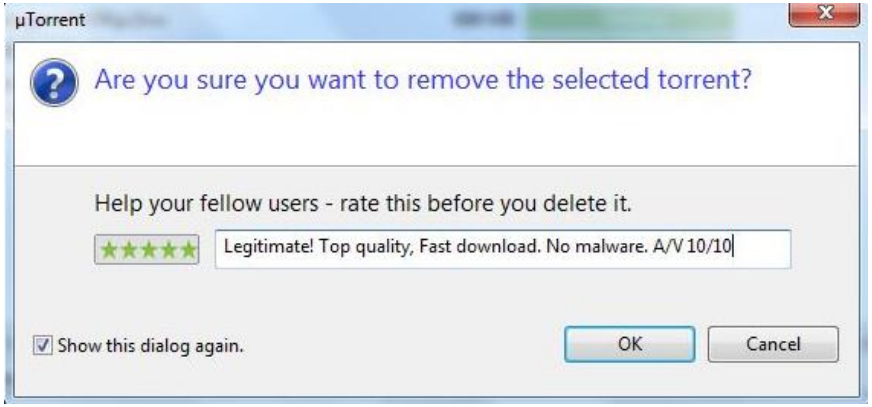
* http://www.ntt.co.jp/qos/qoe/eng/index.html

Subjective: real service evaluation

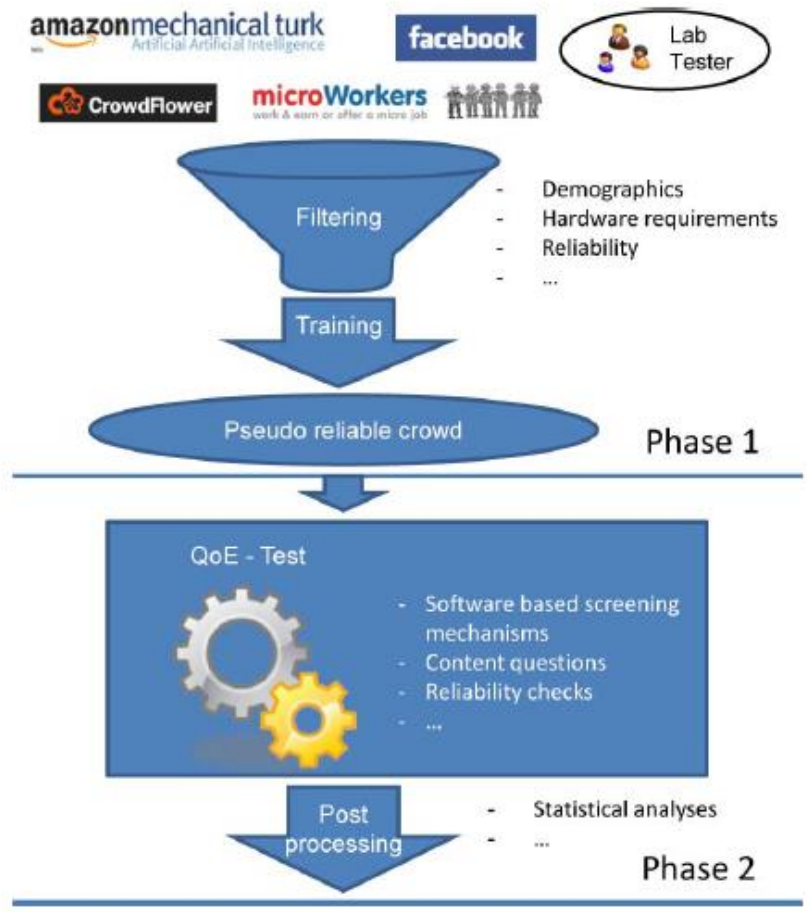


"OneClick"





Subjective: Crowdsourcing



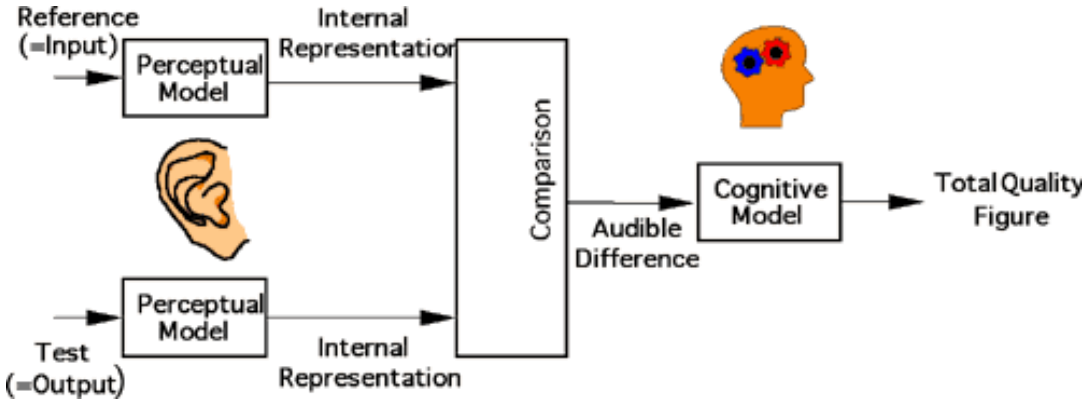
← Recommended two-stage QoE crowdtesting design

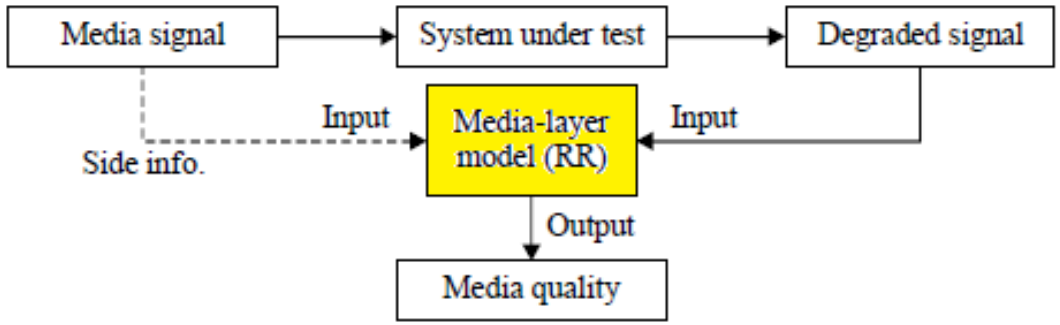
* http://mmnet.iis.sinica.edu.tw/proj/qoe/

* T. Hossfeld, C. Keimel, M. Hirth, B. Gardlo, J. Habigt, K. Diepold, and P. Tran-Gia, "Best Practices for QoE Crowdtesting: QoE Assessment With Crowdsourcing," IEEE Trans. Multimed., vol. 16, no. 2, pp. 541–558, Feb. 2014.

Objective: evaluation methods

- **Media-layer:**
  - Full / Reduced / No Reference

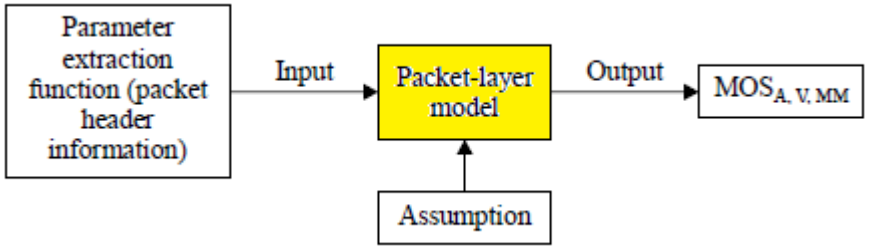




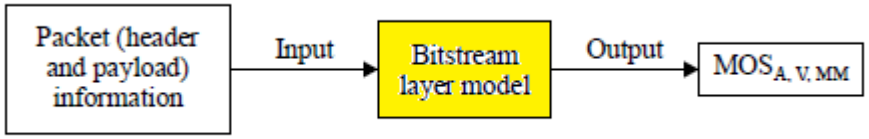
http://www.opticom.de/technology/advanced-measurements.php

Objective: evaluation methods

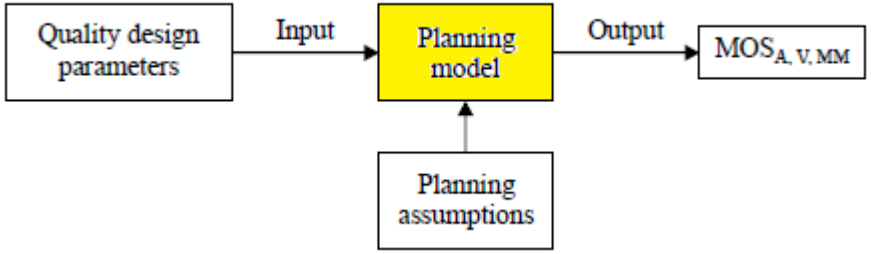
- **Packet-layer**



- **Bitstream**

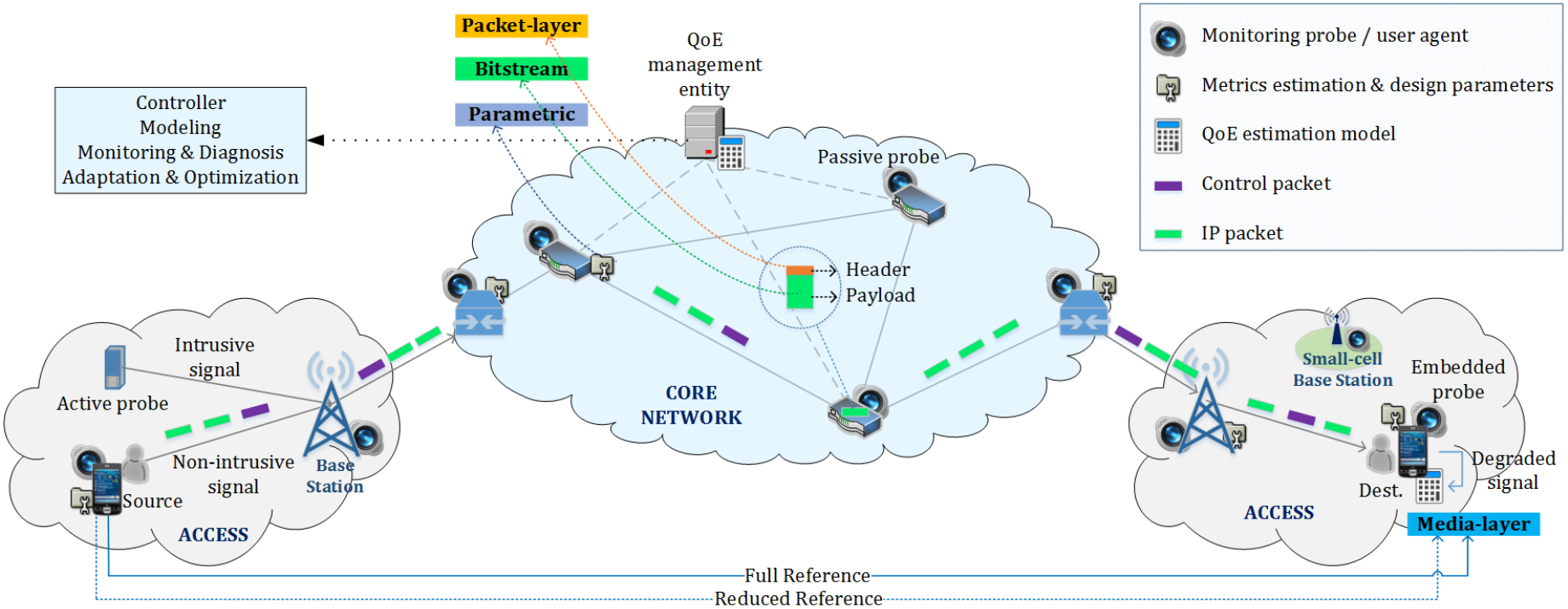


- **Parametric planning**



- **Hybrid**

Objective: Application examples



Objective: evaluation methods

Model	Advantages	Disadvantages
Media-layer: **Full Reference (e.g. PESQ)**	+ Do not require any a-priori knowledge or assumptions about the underlying network + Highly accurate and robust (based on psycho-acoustics)	- Require the reference signal (intrusive) - Very high computational effort - Practically impossible to implement at network midpoint - Do not enable insight into the internal system functionality & degradation causes (black-box) => diagnosis not possible - Neglect human dimensions, pure technical
Parametric planning: **E-model**	+ Ease of use and respect of privacy + The network is characterized by the technical specifications of its constituent elements, (non-intrusive approach) + Quantifies the human factor through the "Advantage factor", & contextual factor + Mouth-to-ear complete transmission chain => conversational + No restrictions on the network with respect to size, configuration, hierarchy, technology used, nor on the components of the network	- Intended only for the planning phase of a system (extended format) - Good in theory, but difficult to include all the model parameters online - Accurate only under strict application scenarios: new subjective tests and regression analysis needed for different conditions - Speech independent - A-priori information requirement
Packet-layer: **ITU-T P.564**	+ Enables insight into the internal system functionality (glass-box) + Light in terms of computational effort + Multiple monitoring points help identify the root of a network impairment + Used not only for speech quality predictions but also for the production of diagnostic outputs + In-service, non-intrusive (privacy) + Quality followed and pooled over time	- Not standardized, models need to be created that comply with these recommendations - The model doesn't know the characteristics of speech content to evaluate (speech level, echo, background noise etc.): assumes a generic voice payload - Only concerns impairments on the IP network (no end-to-end evaluation) - Large volume of QoE data - Models deployed require strict conformance testing

Objective: Other classifications

- **Model mode:**
  - Intrusive (active)
  - Non-intrusive (passive)
- **Model timeframe:**
  - Online = in-service evaluation
  - Offline = pre-service or post-service evaluation
- **Usage purpose:**
  - Network planning
  - Real-time service monitoring
  - Optimization
  - Maintenance
  - Codec testing, benchmarking
- **Target application & service:**
  - Voice
  - Video
  - Data
  - Audio
- **Level of interactivity of assessment:**
  - Passive perception
  - Active usage
  - Interactive usage
- **Model approach:**
  - Regression analysis
  - Machine learning
  - QoE-to-QoS mapping

A. G.107 "E-model" for voice (1/2)

- Computes the transmission quality of VoIP by estimating the mouth-to-ear conversational quality as perceived by the receiver
- A network-planning tool
- A parametric model that produces the so-called Rating factor R:

$$R = R_0 - I_s - I_d - I_{e-eff} + A$$

- R_o → basic signal-to-noise ratio, $R_o = 100$
- I_s → impairments due to the voice signal travelling in the network
- I_d → impairments caused by delay from end-to-end travelling signal
- $I_{e\text{-}eff}$ → equipment impairment factor & impairments due to packet loss
- **A** → advantage/expectation factor, in exchange for some user benefits or other factors difficult to quantify

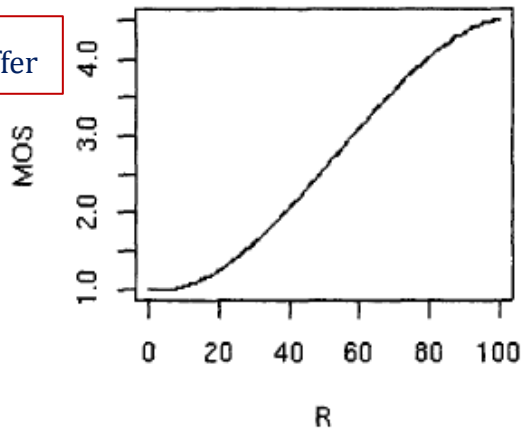
E-model: simplified version (2/2)

$$R = R_0 - I_s - I_d - I_{e-eff} + A$$

- Under specific assumptions, the model may be simplified:
  - I_s → default values, A → neglected
    $\Rightarrow R = 94.2 - I_d - I_{e-eff}$
  - $I_d = 0.024\mathbf{d} + 0.11(\mathbf{d} - 177.3)H(\mathbf{d} - 177.3)$ → G.107
  - $I_{e-eff} = 11 + 40\ln(1 + 10\boldsymbol{e})$ → G.113
  - G.729a codec
  - more…

delay = $d_{network} + d_{codec} + d_{de\text{-}jitter\_buffer}$

packet loss = $e_{network} + e_{de\text{-}jitter\_buffer}$



- Then, R [0..100] is mapped to MOS [0..5]

➢ Purpose: monitoring the conversational voice quality

➢ Delay & Packet loss are isolated

* R. G. Cole, J. H. Rosenbluth, "Voice over IP performance monitoring," ACM SIGCOMM Comput. Commun. Rev., vol. 31, no. 2, p. 9, 2001.

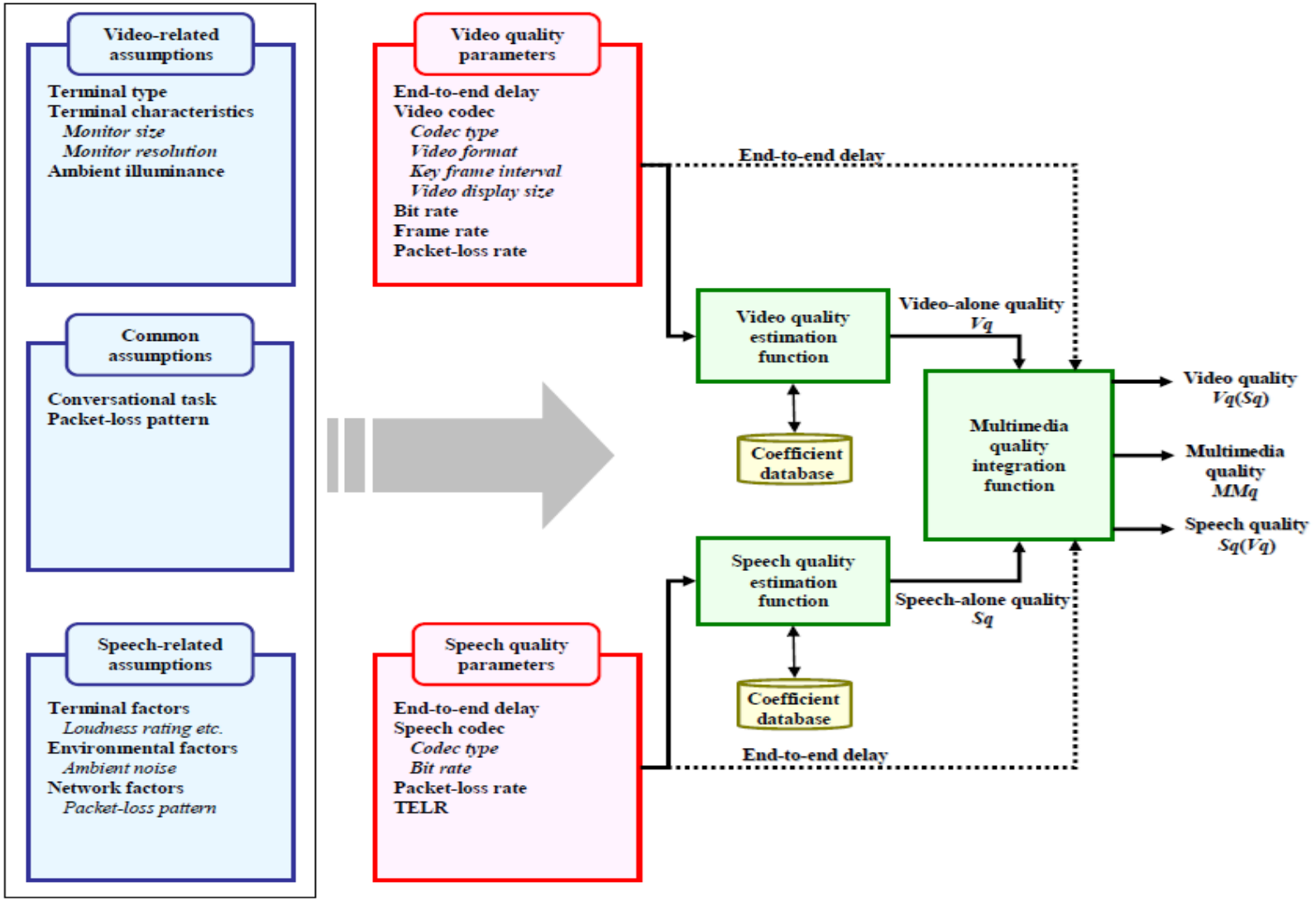
B. G.1070 "E-model" for video (1/3)

- A computational model for point-to-point interactive videophone applications over IP networks
- For QoE/QoS planning purposes (avoid under-engineering)
- Network, Application & Terminal parameters incorporated

$$V_q = 1 + I_{coding} * I_{transmission}$$

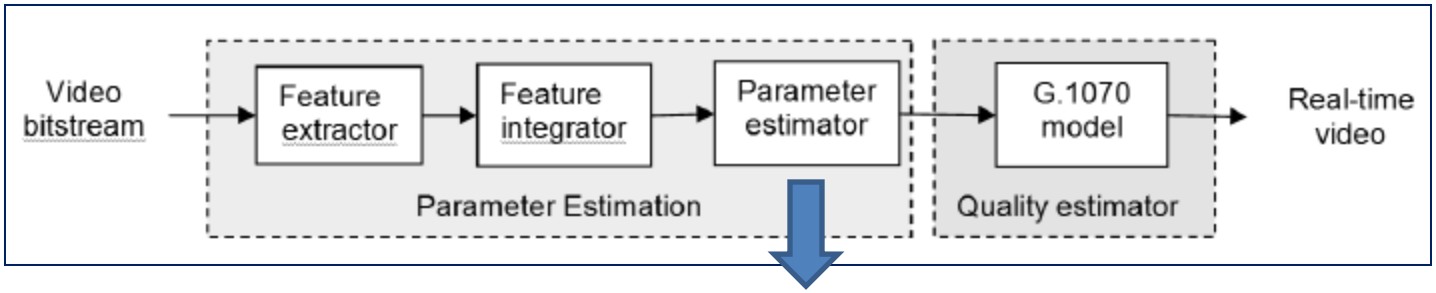
- I_{coding} represents the video quality affected by the coding distortion
- $I_{transmission}$ represents the video quality affected by the transmission process
- Ultimately everything is a function of:
  - the **video frame rate** (fps) - FR
  - the **video bit rate** (kbps) - BR
  - the **video packet loss rate** – PLR
  - 12 coefficients

Multimedia quality assessment (2/3)

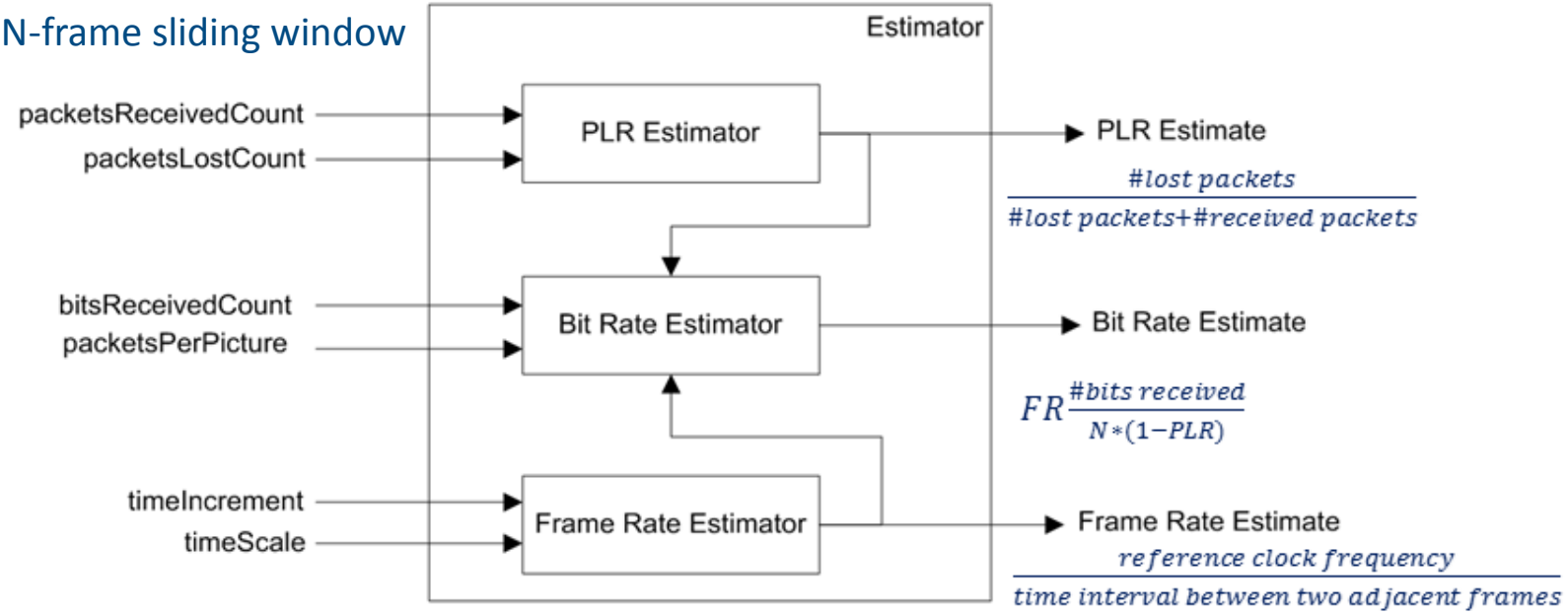


E-model: online adaptation (3/3)

Transform into a valid tool for online quality monitoring:



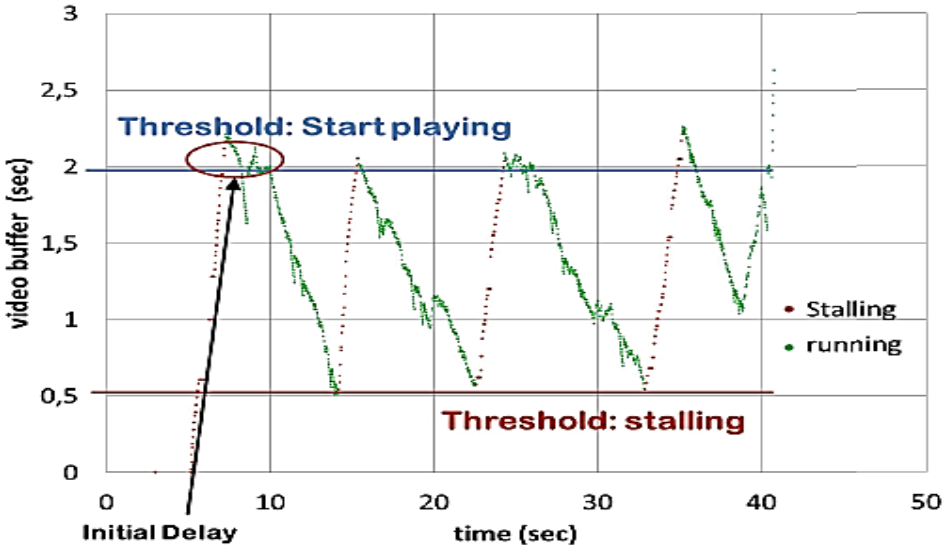
Over an N-frame sliding window



* T. Liu, N. Narvekar, B. Wang, R. Ding, D. Zou, G. Cash, S. Bhagavathy, and J. Bloom, “Real-time video quality monitoring,” EURASIP J. Adv. Signal Process., vol. 2011, no. 1, p. 122, 2011.

C. QoE for YouTube (1/3)

- Video on Demand (VoD), TCP-based connection (no losses)
- Quality influence factors (by crowdsourcing & lab tests):



- Number of stalling events, ***N***
- Duration of stalling events, ***L***
- Total video duration, ***T*** (total stalling duration over video duration)
- Initial delay (video start-up delay) → cache redirections' impact

QoE for YouTube (2/3)

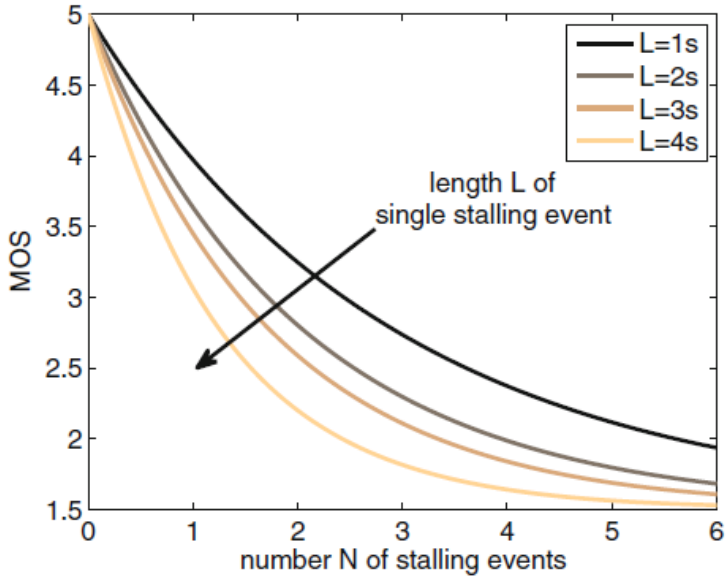
- Some conclusions:
  - The user demographics have no influence
  - Initial delays have almost no influence on MOS for videos of duration 60s and 30s compared to the influence of stalling length
  - The user ratings are statistically independent from video resolution, video motion, type of content, the usage pattern of the user, access speed
  - The number of stalling events together with the stalling length are clearly dominating the user perceived quality
  - The video duration only plays a role if there are only a very few stalling events

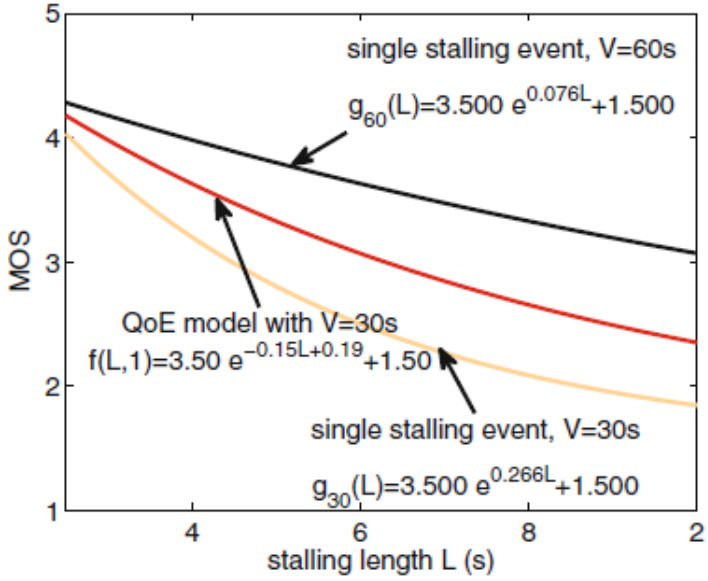
QoE for YouTube (3/3)

IQX hypothesis validation:

$$QoE(L,N) = \alpha * e^{-\beta(L)*N} + \gamma,$$

$$\alpha = 3.5, \quad \beta(L) = 0.15L + 0.19, \quad \gamma = 1.5$$





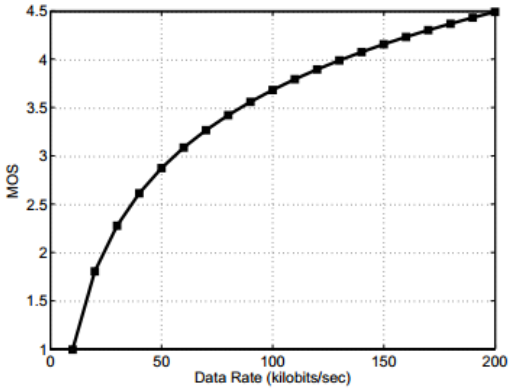
* T. Hossfeld, R. Schatz, E. W. Biersack, and L. Plissonneau, "Internet Video Delivery in YouTube: From Traffic Measurements to Quality of Experience," in Data Traffic Monitoring and Analysis, Eds. Springer Berlin Heidelberg, pp. 264–301, 2013.

D. QoE for file download services

- Elastic service, for which the utility function is an increasing, strictly concave, and continuously differentiable function of throughput
- The user satisfaction of a file transfer service is solely dependent on the provided data rate
- Logarithmic relationship between MOS and throughput:

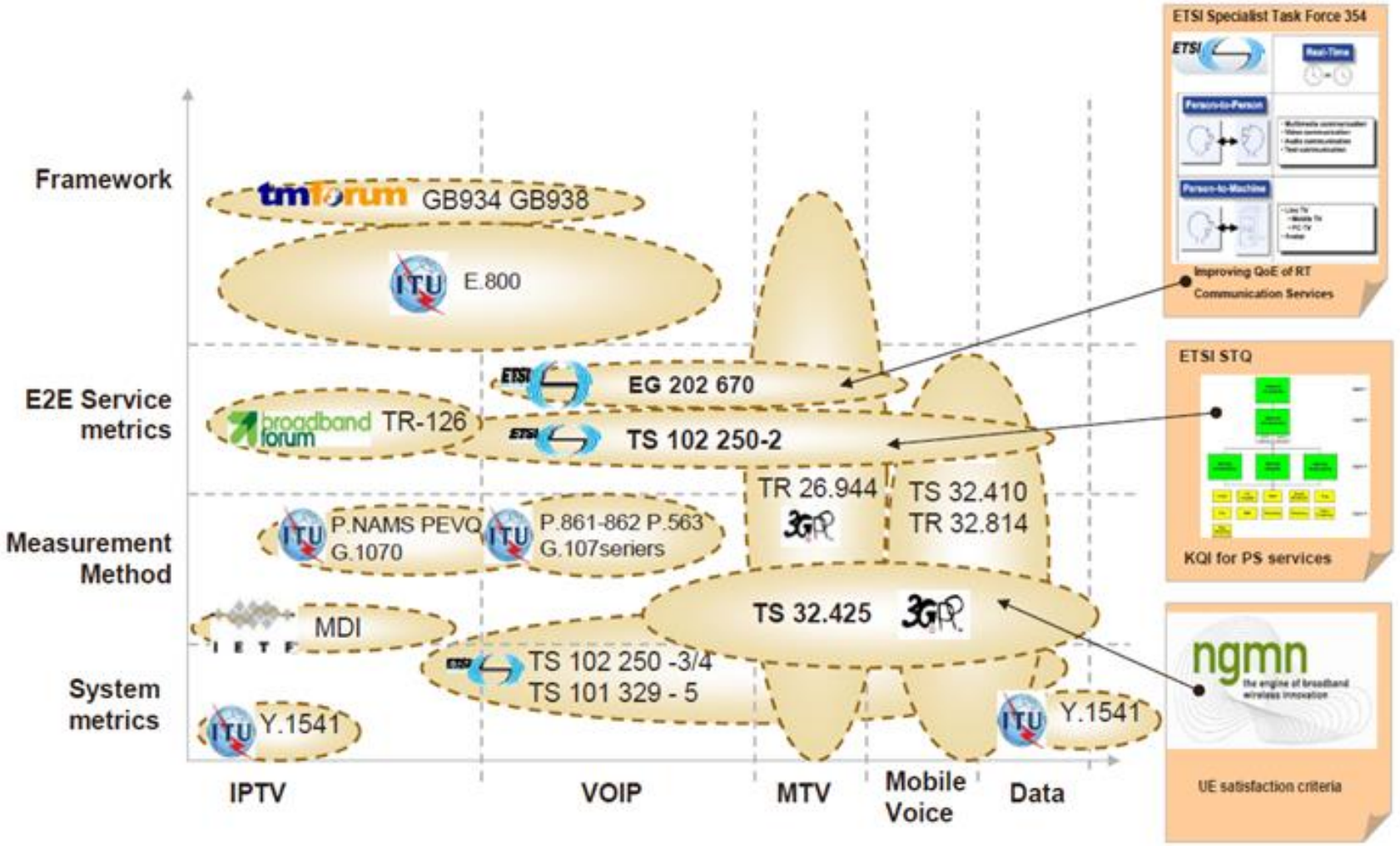
$$MOS = \begin{cases} 1, & R < 10kbps \\ \alpha \log_{10}(\beta R), & 10kbps < R < 300kbps \\ 4.5, & 300kbps < R \end{cases}$$

- R is the data rate of the service
- α and β obtained from the upper and lower user perceived quality expectations



* S. Thakolsri, S. Khan, E. Steinbach, and W. Kellerer, "QoE-Driven Cross-Layer Optimization for High Speed Downlink Packet Access," J. Commun., vol. 4, no. 9, 2009

Standardization by various bodies

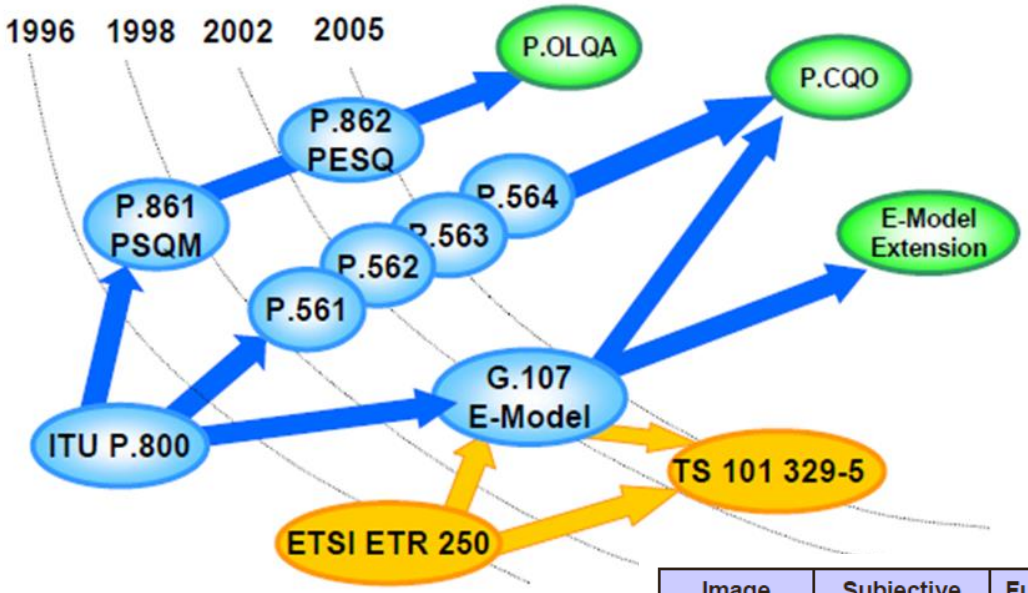


* Bridging QoE and QoS for Mobile Broadband Networks, VP Huawei European Research Centre

Standardization in ITU-T

Application	Media	Conversational (CONV)/Non-conversational (NONCONV)	Subjective test methodology	Objective test methodology		
				Model	FR/RR/NR	Primary usage
Telephony	Speech	NONCONV	[ITU-T P.800] [ITU-T P.830] [ITU-T P.835] [ITU-T P.1301]	[ITU-T P.862] + [ITU-T P.862.1] (NB) [ITU-T P.862.2] (WB) [ITU-T P.863] (NB/WB/SWB)	FR	LAB, MON
				[ITU-T P.563] (NB) [ITU-T P.564] (NB/WB)	NR	MON
		CONV	[ITU-T P.800] [ITU-T P.805] [ITU-T P.1301]	[ITU-T G.107] (NB)	NR	PLN
				[ITU-T P.561] + [ITU-T P.562] (NB/WB)	NR	MON
Video telephony	Multimedia (Note)	CONV	[ITU-T P.920] [ITU-T P.1301]	[ITU-T G.1070] (NB/WB)	NR	PLN
Video streaming (Mobile TV/IPTV)	Video	NONCONV	[ITU-T P.910] [ITU-T J.140] [ITU-R BT.500-13]	[ITU-T J.144] (SD) [ITU-T J.247] (QCIF, CIF, VGA) [ITU-T J.341] (HD)	FR	LAB, MON
				[ITU-T J.249] (SD) [ITU-T J.246] (QCIF, CIF, VGA) [ITU-T J.342] (HD)	RR	MON
	Audio	NONCONV	[ITU-T P.830] [ITU-R BS.1116-1] [ITU-R BS.1285] [ITU-R BS.1534-1]	[ITU-R BS.1387]	FR/RR	MON/PLN
	Multimedia	NONCONV	[ITU-T P.911]	[ITU-T P.1201.1] (QCIF, QVGA, HVGA) [ITU-T P.1201.2] (SD, HD) [ITU-T P.1202.1] (QCIF, QVGA, HVGA) [ITU-T P.1202.2] (SD, HD)	NR	MON
Web browsing	Data			[ITU-T G.1030]	NR	PLN
NOTE – For individual media (i.e., speech and video), the Recommendations used in telephony and video-streaming applications are applicable.						

Evolution of QoE models



Voice QoE assessment

Video QoE assessment

Image resolution	Subjective Estimation	Full Reference	Non Reference		Reduced Reference
SDTV	ITU-R BT.500 ITU-T J.140 ITU-T J.245	ITU-T J.144 ITU-R BT.1683	ITU-T SG12: **P.NAMS** **P.NBAMS** **G.OMVAS**	VQEG: **RRNR-TV** **HDTV**	ITU-T J.147 ITU-T J.249
HDTV					
VGA	ITU-T P.910 ITU-T P.911	ITU-T J.247		VQEG: **MM Project**	ITU-T J.246
CIF					
QCIF					

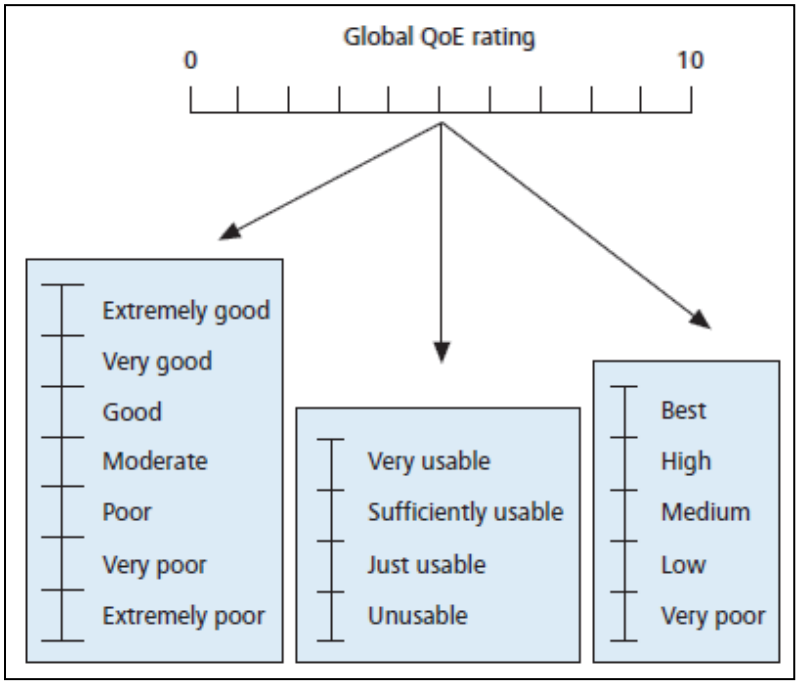
Completed Ongoing projects

* Bridging QoE and QoS for Mobile Broadband Networks, VP Huawei European Research Centre

Quality scales

Absolute Mean Opinion Scores (**MOS**) / comparative

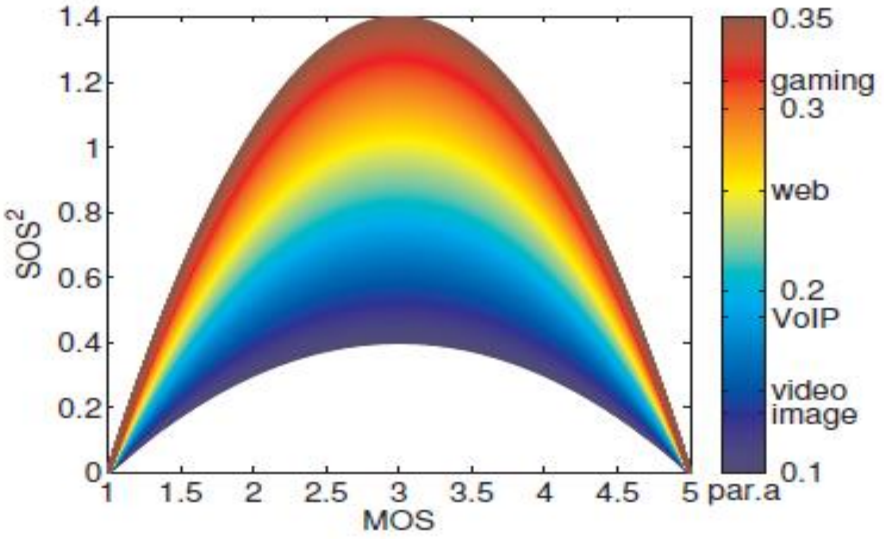
MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying



Score	Description
3	Much Better
2	Better
1	Slightly Better
0	About the Same
–1	Slightly Worse
–2	Worse
–3	Much Worse

SOS – The MOS is not enough

- Standard deviation of Opinion Scores (SOS)
- Statistical summary of subjective user tests
- Reflects the level of rating diversity
- A square function of MOS → SOS hypothesis
- No diversity at the edges and maximal diversity at MOS = 3

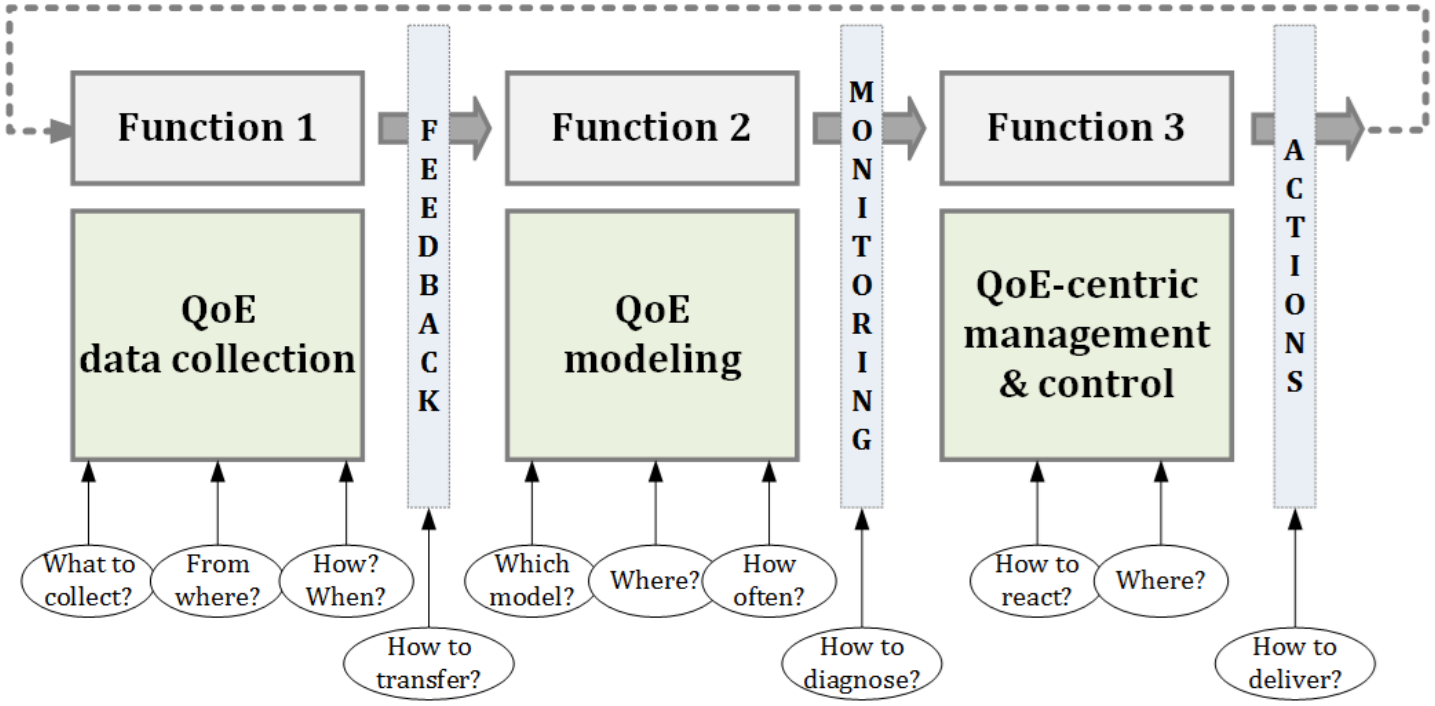


* T. Hossfeld, R. Schatz, and S. Egger, "SOS: The MOS is not enough!," in 2011 Third International Workshop on Quality of Multimedia Experience, 2011, pp. 131–136.

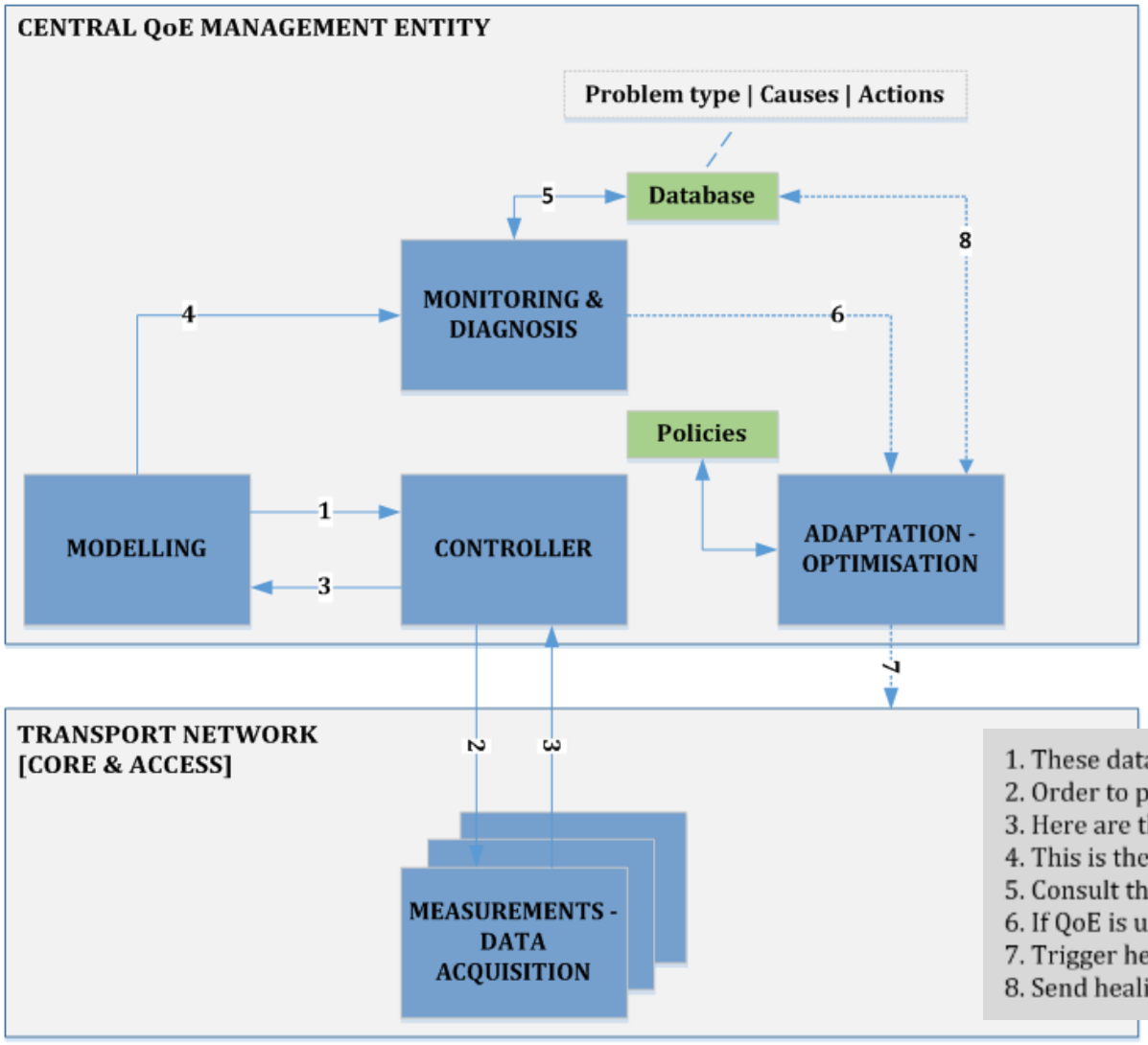
QoE MANAGEMENT

QoE research stages & management

Goal: Optimize end-user QoE, while making efficient use of network resources & maintaining a satisfied customer base



A generic QoE management framework



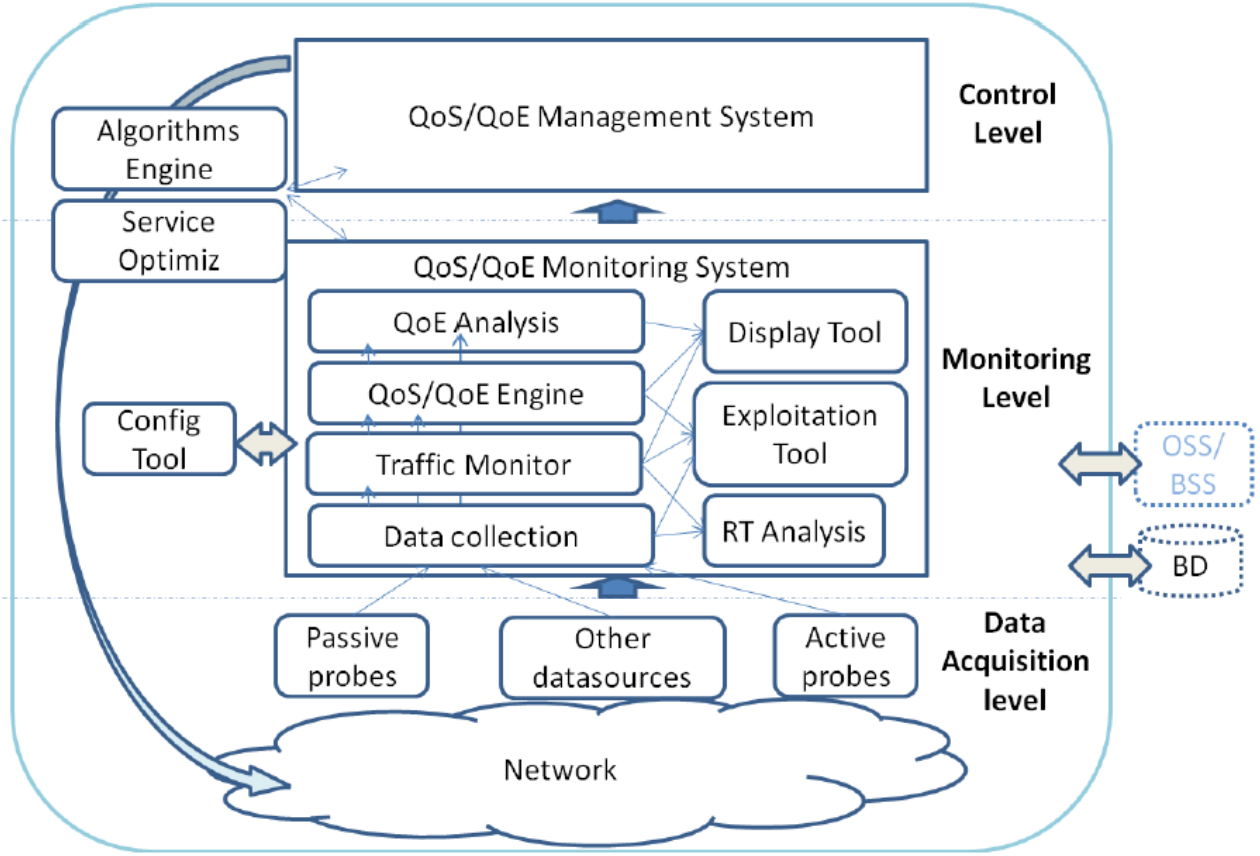
The Doctor-Patient Analogy

MODELING ↔ Medicine science
CONTROLLER ↔ Hospital staff
TRANSPORT NETWORK ↔ Patients
MEASUREMENTS ↔ Exams, Samples, Patients' descriptions etc.
MONITORING & DIAGNOSIS ↔ Doctor
DATABASE ↔ Doctor's knowledge & experience, other consulting doctors, books, medical records
ADAPTATION-OPTIMIZATION ↔ Pills, operations, other procedures

1. These data are required as an input
2. Order to provide these data periodically
3. Here are the requested data
4. This is the estimated output QoE value
5. Consult the database and diagnose problems, if any
6. If QoE is unsatisfactory, prepare a diagnosis report
7. Trigger healing actions (consulting database)
8. Send healing report to Database

A network-centric framework

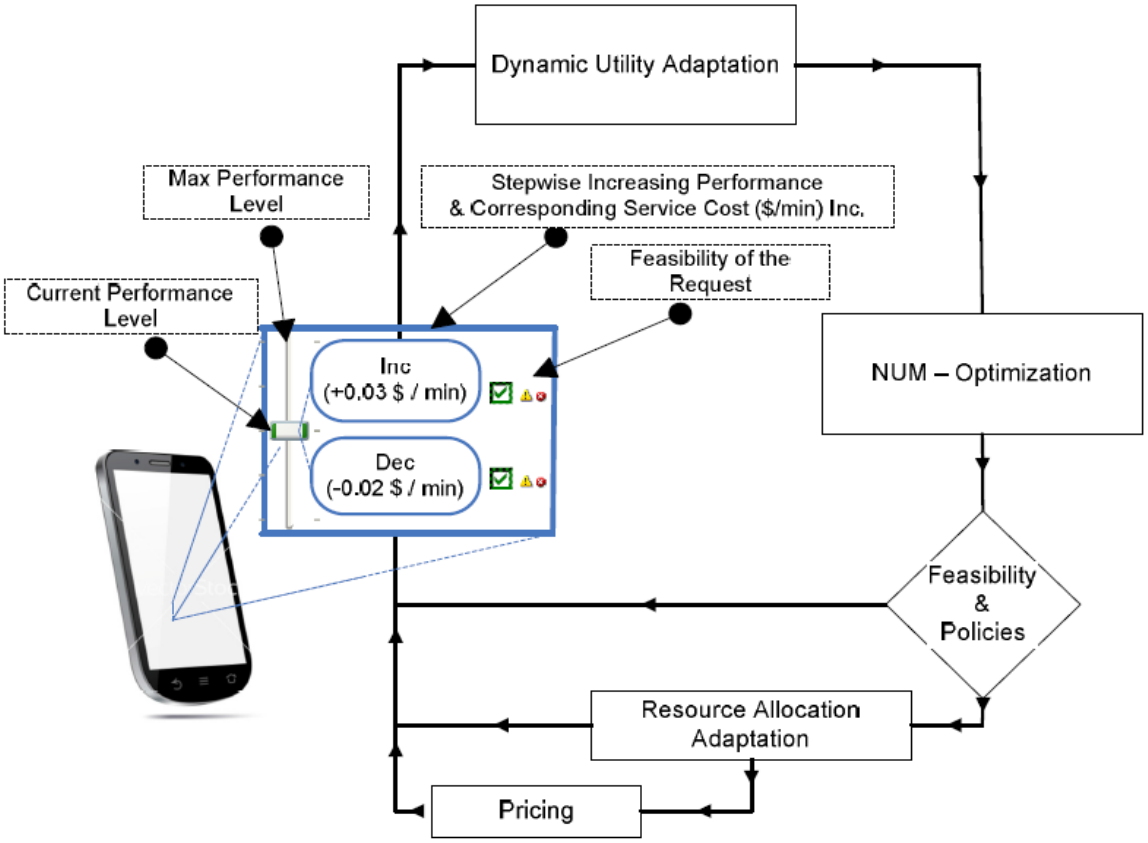
A global Customer Experience Management System (CEMS) architecture



* A. Cuadra-Sanchez, M. Cutanda-Rodriguez, et al., "A global customer experience management architecture," in Future Network & Mobile Summit (FutureNetw), 2012, pp. 1–8.

A user-centric framework

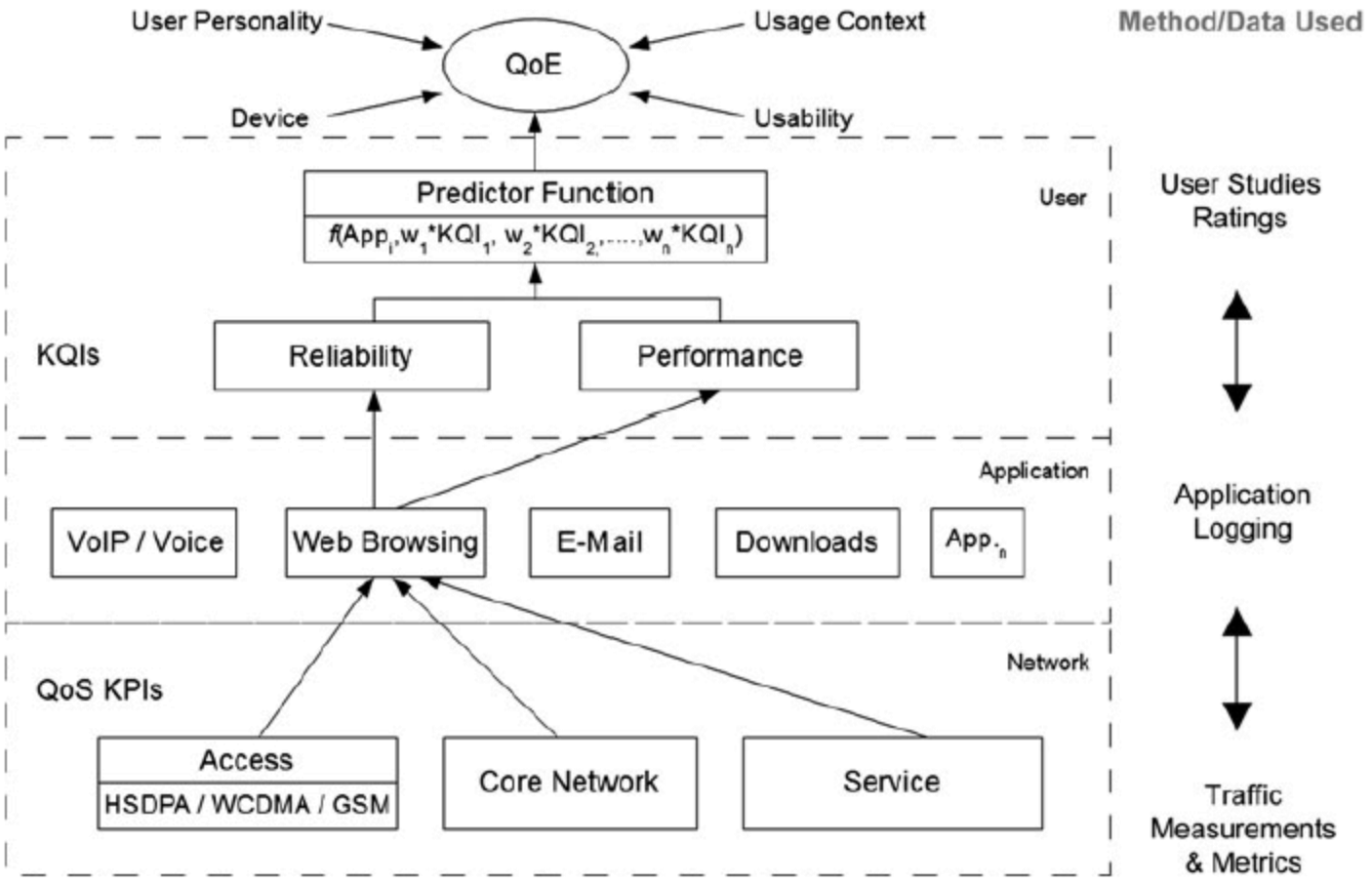
Network Utility Maximization for user-centric QoE provisioning



* L. Skorin-Kapov, K. Ivesic, et al., "Approaches for Utility-Based QoE-Driven Optimization of Network Resource Allocation for Multimedia Services", Data Traffic Monitoring and Analysis book, Computer Communications and Networks, Springer, 2013.

General framework for QoE modelling

Utility function = relative satisfaction derived from consumption of services

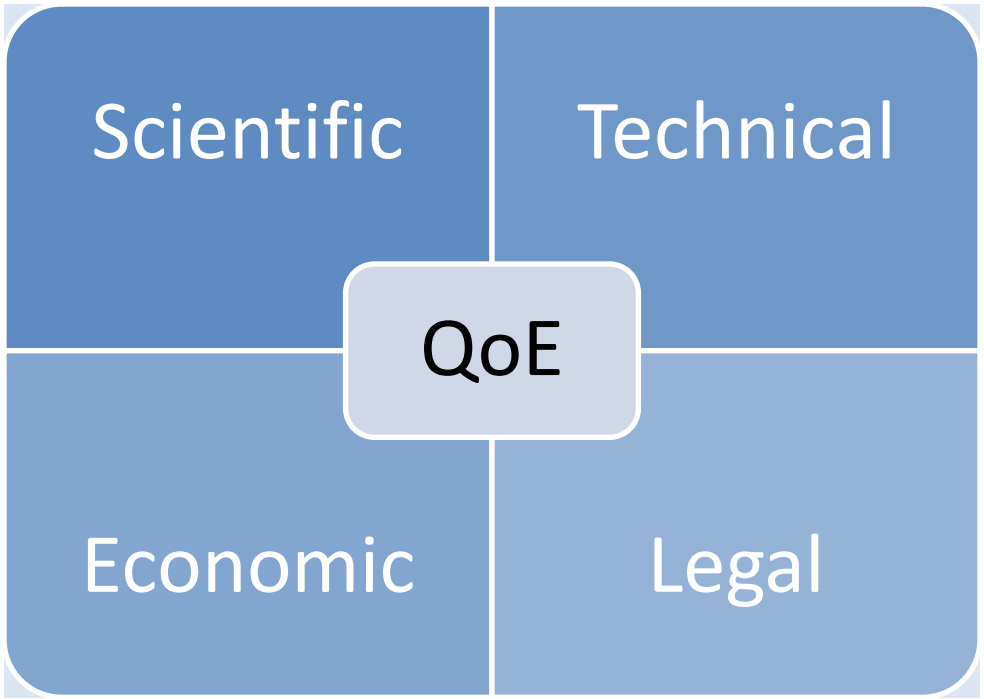


* ACE project series

QoE CHALLENGES IN LTE-A

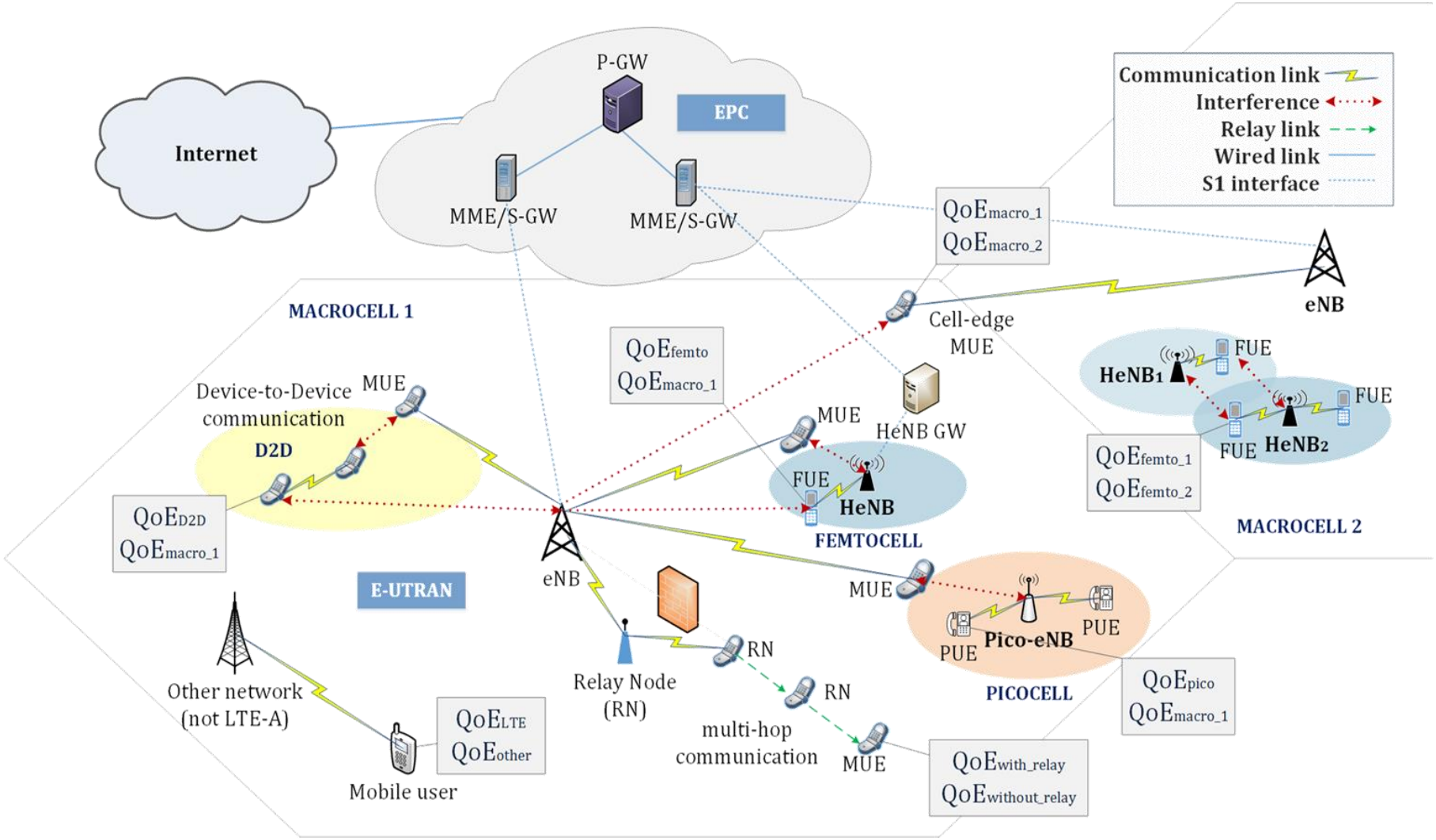
Research challenges

- Feasibility
- Scalability
- Complexity
- Competition
- Market issues
- Business model



- Heterogeneity
- Security
- Signalling
- Net neutrality
- Double selling
- Standardization

Challenges in LTE-A: heterogeneity



Challenges in LTE-A: more

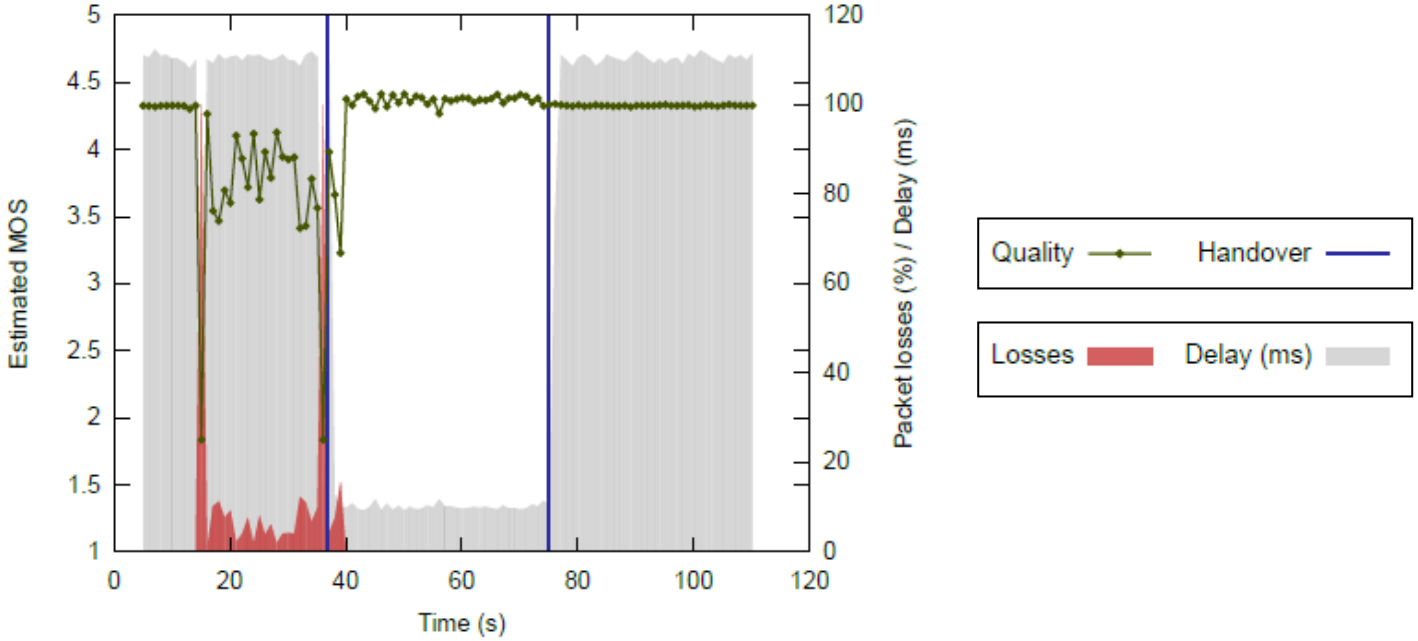
- Monitoring: Network-centric vs. user agent-based approaches
  - Agent-based:
    - + Capture the HUMAN, CONTEXT, and WIRELESS medium aspects
    - - Do not offer diagnosis information
    - - Depend on manufacturer, not scalable
    - - Privacy, security, energy concerns
- User vs. provider benefits
- Scalability & complexity issues
  - QoE feedback, control and modeling per user session
- Network diversity
  - Different operators or vendors, networks, mobile technologies (e.g., 2G or 3G), or even different countries or continents
- Energy consumption
  - QoE-awareness and provisioning: monitoring, signaling, processing, memory requirements, new network entities

QoE in LTE-A mechanisms

- In access network selection - mobility management
- In scheduling
- In interference management
- In power allocation
- In routing
- In traffic offloading
- In any other network control mechanisms
- In network planning & configuration

QoE-driven access network selection

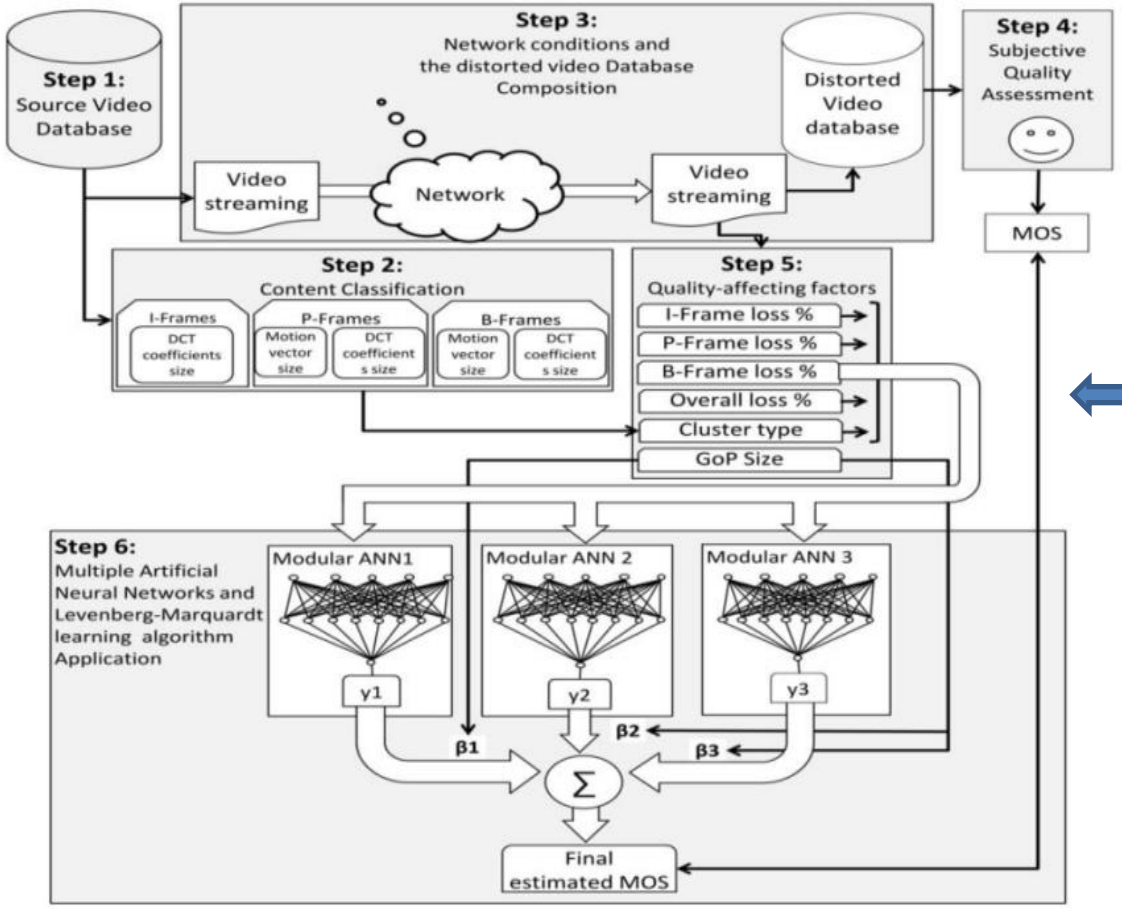
- **Idea:** Network congestion reduces QoE => a handover is triggered
- Passive network QoS monitoring fed to PSQA model
- Sliding weighted average of MOS estimations over a time window
- The device roams back into the original network after some time



* M. Varela and J.-P. Laulajainen, "QOE-driven mobility management — Integrating the users' quality perception into network — Level decision making," in 2011 Third International Workshop on Quality of Multimedia Experience, 2011, pp. 19–24.

QoE-driven handover architecture

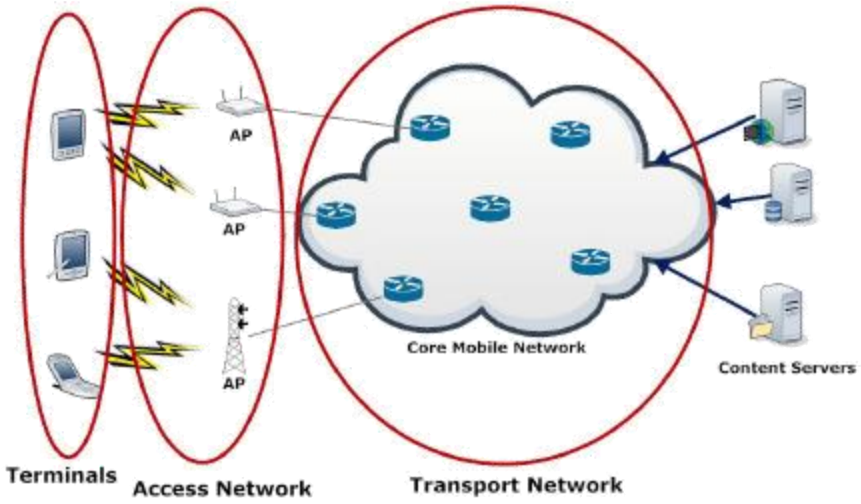
"**QoEHand**": users always-best connected in converged heterogeneous wireless networks



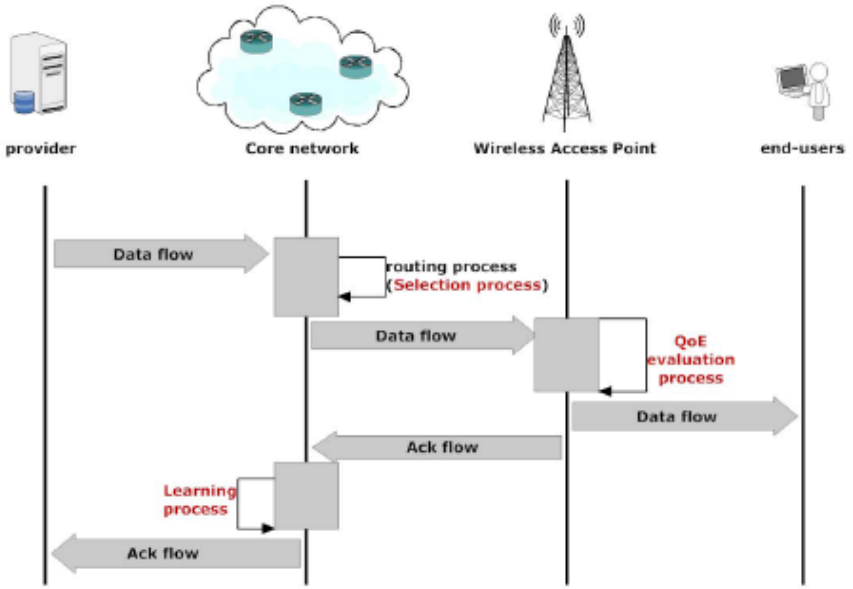
1. Quality estimation
2. Mapping
3. Adaptation

* C. Quadros, E. Cerqueira, et al., "A quality of experience handover system for heterogeneous multimedia wireless networks," in International Conference on Computing, Networking and Communications (ICNC), 2013, pp. 1064–1068.

QoE-dependent routing



- **DOQAR**: Dynamic Optimized QoE Adaptive Routing
- Router = state, Link = action

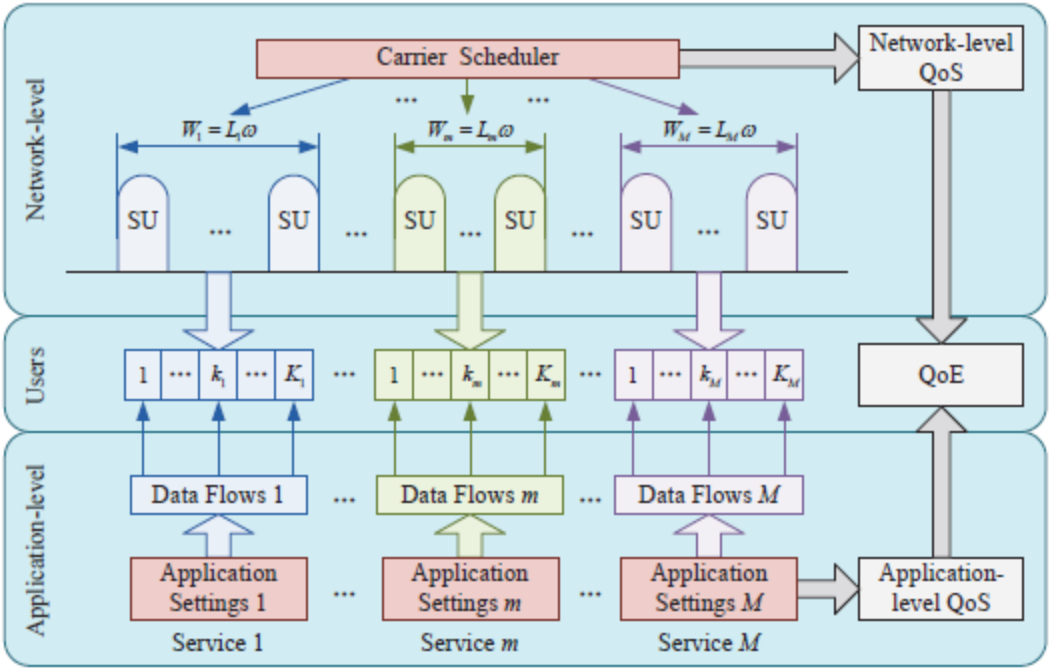


- Based on experience and feedbacks, an agent is able to learn control policies -Reinforcement Learning (RL)
- Neural Multi-Layer Perceptron concept

* H. A. Tran, A. Mellouk, S. Hoceini, and B. Augustin, “Global state-dependent QoE based routing,” in 2012 IEEE International Conference on Communications (ICC), 2012, pp. 131–135.

QoE-aware scheduling

- QoE-based carrier scheduling scheme for multiple services in LTE-A
- Dynamic optimization algorithm based on the multi-choice knapsack problem (MCKP) → max the sum MOS in the system



- MOS is function of throughput, delay and application-level settings
- Different model per service (VoIP, IPTV, file download, web browsing)

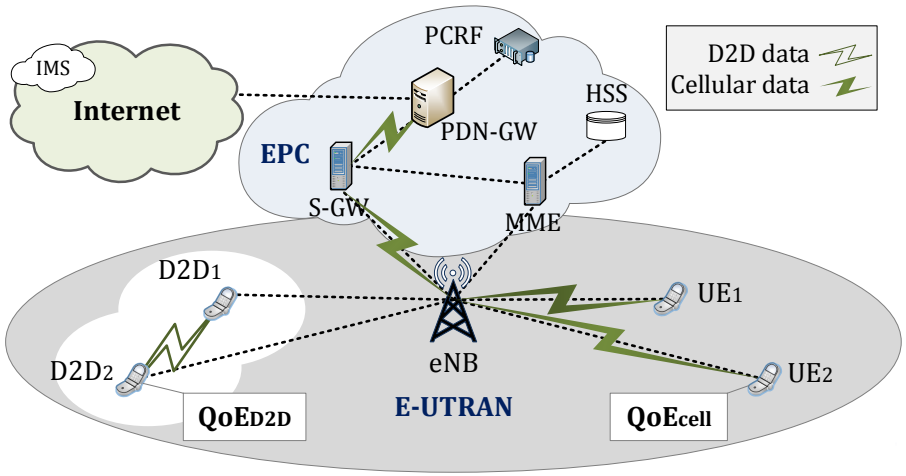
$$max \sum_{m \in M} K_m \bar{\eta}_m ,$$

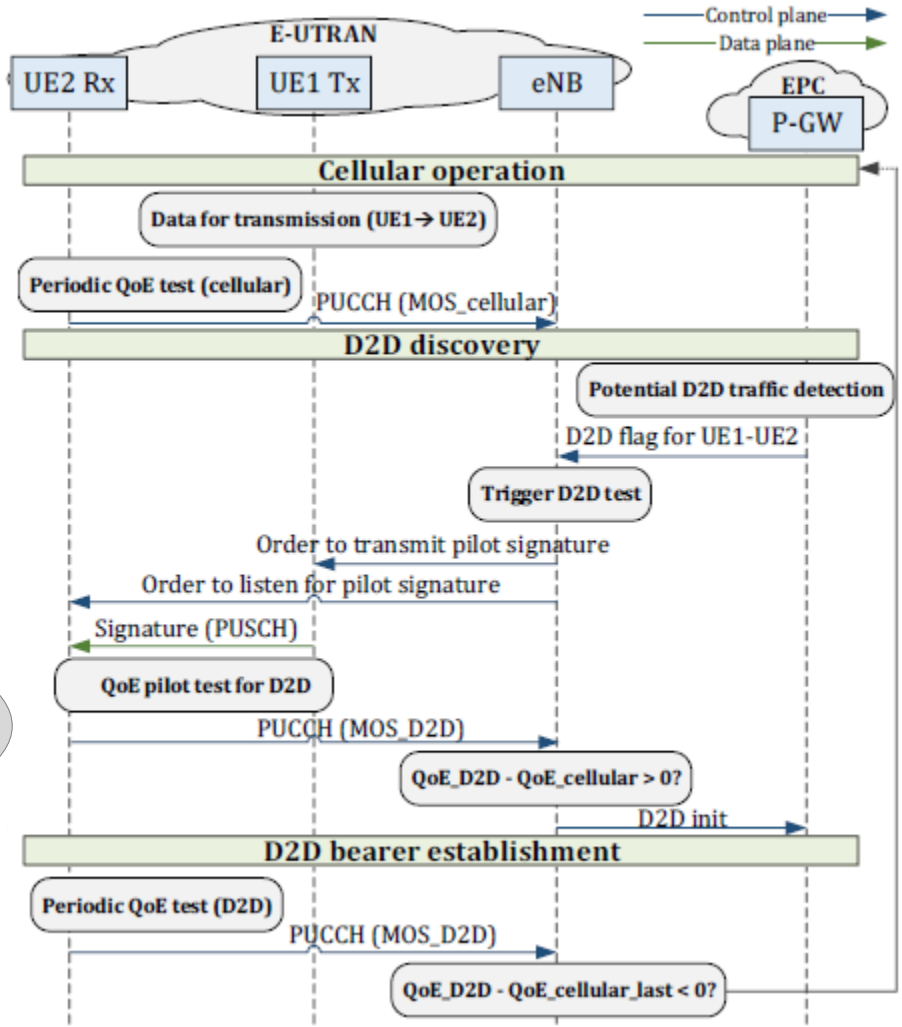
$$\sum_{m \in M} \mathbf{L}_m \leq L$$

* F. Liu, W. Xiang, Y. Zhang, K. Zheng, and H. Zhao, "A Novel QoE-Based Carrier Scheduling Scheme in LTE-Advanced Networks with Multi-Service," in 2012 IEEE Vehicular Technology Conference (VTC Fall), 2012, pp. 1–5.

QoE-driven D2D communications

- How QoE awareness can control cellular ↔ D2D mode transitions

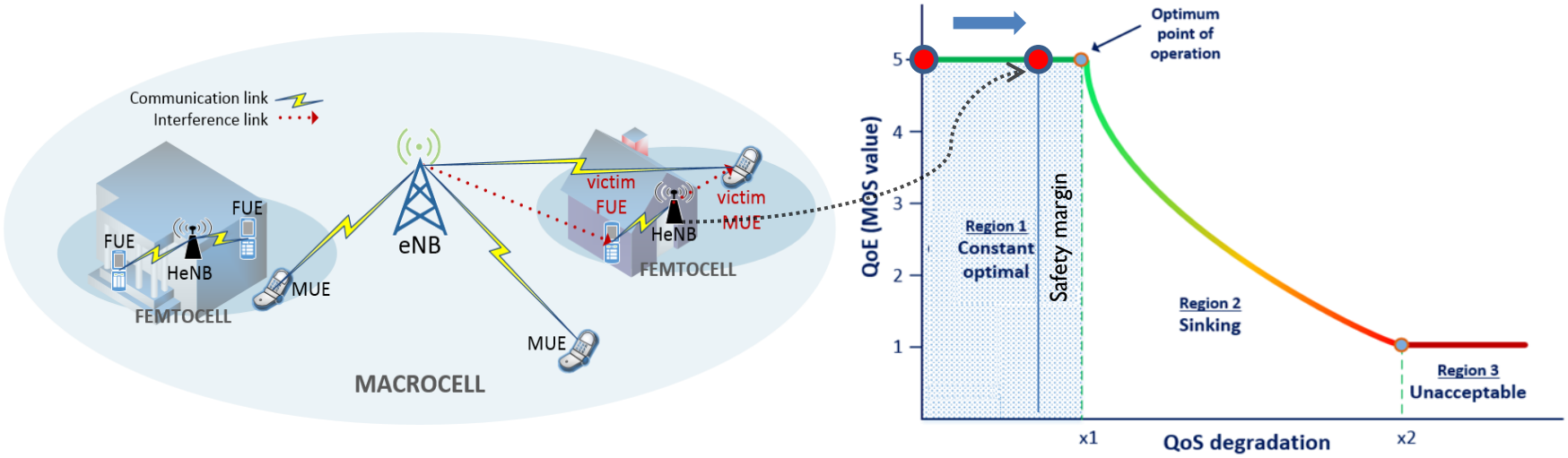




* E. Liotou, E. Papadomichelakis, N. Passas and L. Merakos, "Quality of Experience-centric management in LTE-A mobile networks: The Device-to-Device communication paradigm", in International Workshop on Quality of Multimedia Experience (IEEE QoMEX), 2014, submitted.

QoE-aware Interference Management

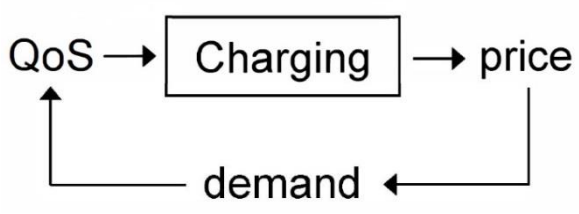
- How QoE can drive Power Controlled (PC) IM scheme in femto-LTE-A
- Methodology:
  - Quantify the QoE of VoIP users in the co-presence of macro- and femtocells
  - Examine the relation between SINR and perceived QoE at target user
  - Propose QoE-aware PC: Reduce HeNB transmit power, with no loss in FUEs' QoE

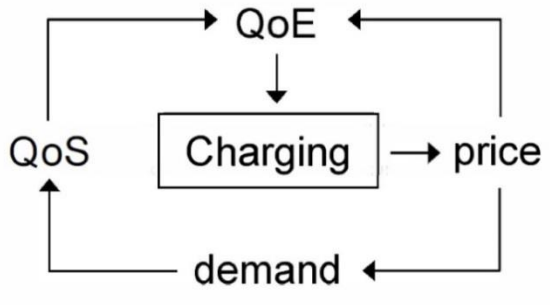


* D. Tsolkas, E. Liotou, N. Passas, and L. Merakos, "The Need for QoE-driven Interference Management in Femtocell-Overlaid Cellular Networks ", in 10th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services, Tokyo, 2013.

QoE charging model

QoE estimation may heavily depend on the expected price itself!





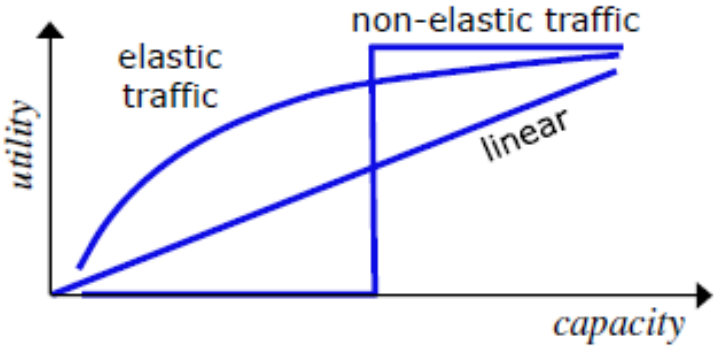
Charging for QoS vs. charging for QoE

$price\ function$: $p = p(q)$
$demand\ function$: $d = d(p)$
$QoS\ function$: $q = q(d)$

$demand\ function$: $d = d(p)$
$QoS\ function$: $q = q(d)$
$price\ function$: $p = p(x)$
$QoE\ function$: $x = x(q, p)$

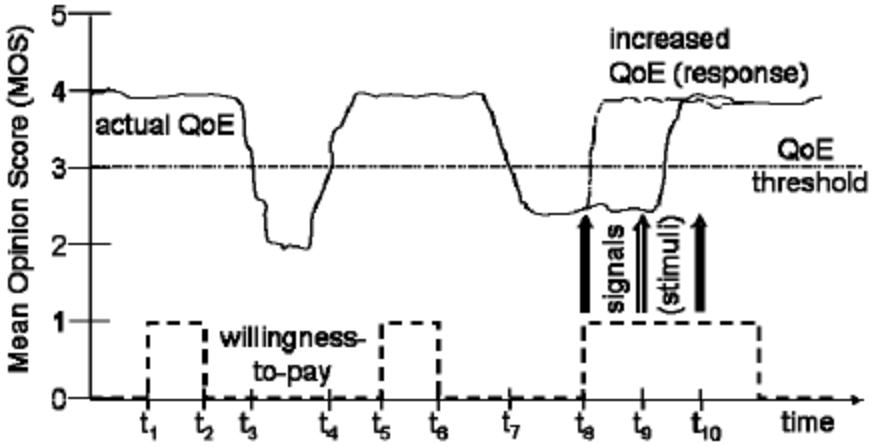
* P. Reichl, P. Maillé, P. Zwickl, and A. Sackl, "A Fixed-Point Model for QoE-based Charging," in the ACM SIGCOMM 2013 Workshop on Future Human-Centric Multimedia Networking (FhMN 2013), Hong Kong, 2013.

QoE charging model



Microeconomic utility theory tools:

$u_i(x)$ = the consumption of resource "x" by user i



A stimulus-response charging mechanism

Legal issues

- Network Neutrality
  - "Quality" may be considered as a public good
- Double selling
  - Sold as an add-on service to existing network connections?
  - How profits will be distributed to involved parties?
- Service Level Agreements (SLAs)
  - Define the delivered quality in terms of QoE
  - Find a "common vocabulary"
- Privacy and fidelity
  - Transfer of user-sensitive information in an E2E path
- Agreements among operators
  - Collaborations, especially at interconnections

SYNOPSIS

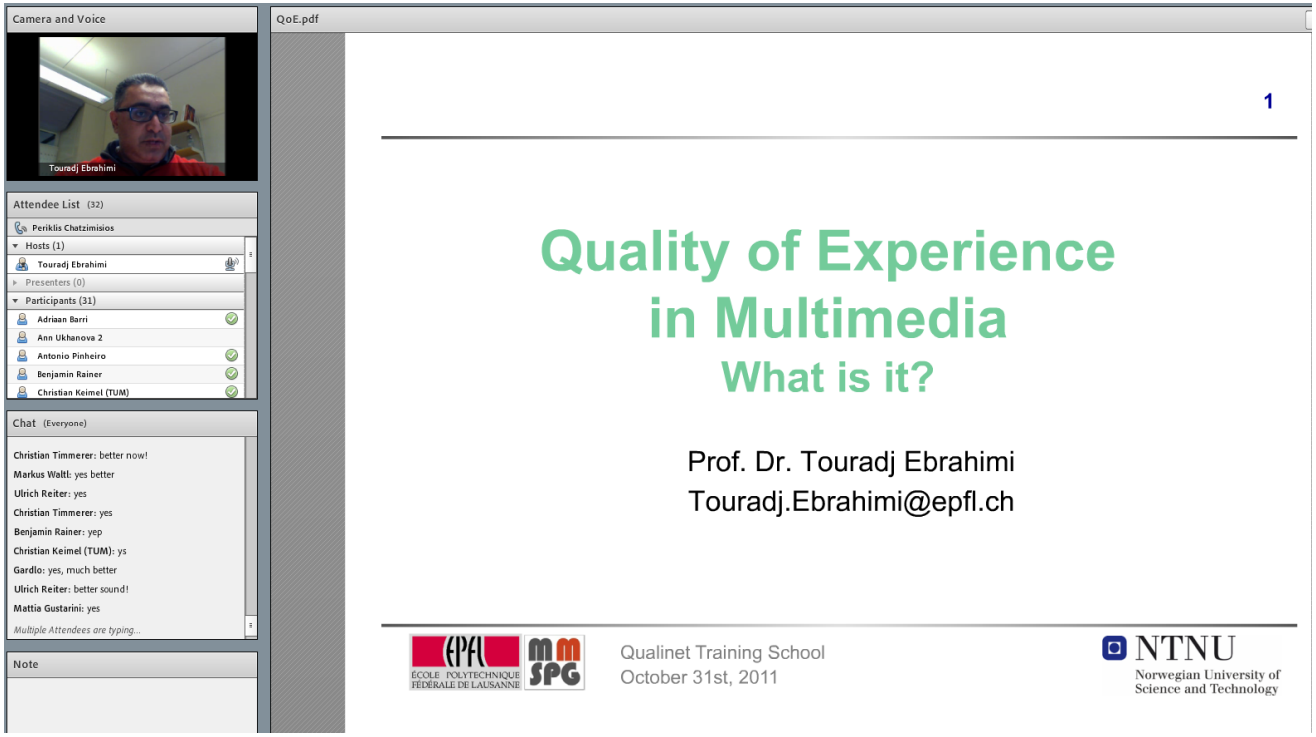
Good to remember

- The multidimensional definition of QoE
- The relationships between QoS and QoE
- QoE modeling evaluation methods
- QoE management required building blocks
- How QoE can assist LTE-A mechanisms
- Main challenges

If you want to get more involved…

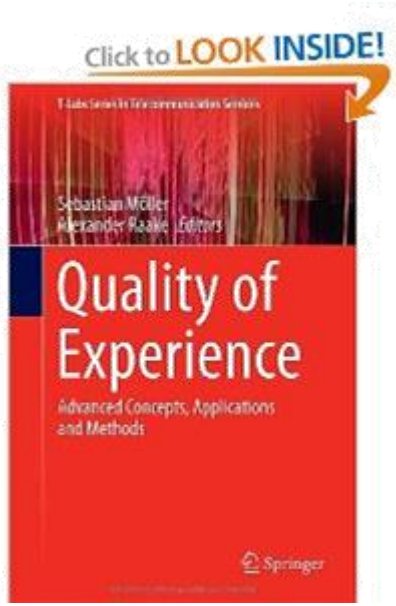
- Qualinet online training platform:

https://collab.switch.ch/qualinet-training (6 lectures available)



If you want to get more involved…

- Specialist Task Force 354: ”Guidelines and Tutorials for Improving the User Experience of Real-time Communication Services”
- ITU-T SG 12: Performance, QoS and QoE
- euroNF NETWORK OF EXCELLENCE http://www.bth.se/com/ccs.nsf/pages/materials-qoe
- QUALINET cost IC1003 European Network on Quality of Experience in Multimedia Systems and Services http://www.qualinet.eu/ https://www.facebook.com/groups/qualinet/
- New book available (2014): http://www.amazon.com/Quality-Experience-Advanced-Applications-Telecommunication/dp/3319026801



- Dissertations in GAIN group: http://gain.di.uoa.gr/

Thank you!