Quantified User Behavior in User-in-the-Loop Spatially and Demand Controlled Cellular Systems

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***Abstract*—User-centric services are a growing concern. While the digital society definitely needs better quality-of-experience (QoE) for the user, the applications on smart mobile devices will continue to raise traffic in mobile radio networks by almost 100% per annum. Future generations of access technologies are challenged by this and the conventional over-provisioning approach will not hold anymore, especially during busy hours. Congestion will happen more and more often, leading to a much worse QoE for everyone involved. Increasing the supply side by better spectral efficiency of 5G radio networks cannot work on its own, if demand is increasing much faster than supply.**

The new user-in-the-loop (UIL) approach targets at convincing the user to participate actively in improving a common utility, instead of assuming an unconstrained traffic and homogeneous user density in a cell area. UIL can shape the demand at the user, either in space or time. Incentives are used to motivate changing location to a place of better spectral efficiency. Dynamic tariffs are one way for shifting demand out of the busy hours. We call this the smart grid of communications.

This paper provides models for the user behavior based on initial survey results. It is the first work to answer the questions about what incentive will lead to what user reaction. Thus we are now able to quantitatively describe the user block in a system-theoretic framework. Results indicate that shaping the user behavior works well and the analysis of simulation results suggest the significant gains achievable with UIL.

***Index Terms*—User-in-the-loop (UIL); IMT-Advanced; demand shaping; tariffs; spatial and temporal control; demand response; smart grid of communications**

I. Introduction

SURVEY results are required to know quantitatively how a user behaves in a system theoretic framework. His input-output function needs to be defined in order to conduct numeric studies. The user-in-the-loop (UIL) block diagram in Figure 1 shows the context. The system here includes the user, his wireless equipment and the channel in a control loop. The controller knows the system state (traffic load and channel conditions), which can potentially include every location within the wireless cell and even beyond. A decision to influence the user is based on this state. Decision means a set of incentives and instructions, to convince users to either relocate, postpone or abandon their session request. The control value can range between just informational and strongly convincing with a monotonic force depending on the severity of the congestion situation.

Previous papers studied UIL based on assumptions [1], [2]. With this contribution of first survey results it allows to give a quantitative model of the user behavior. Survey B of autumn 2011 had a sample population of around 100 university students in Ottawa, Canada. This is the first result of its kind and cannot be perfectly representative yet. However, it provides good indicators and allows further studies right away. The numbers are intuitive and confirm earlier assumptions.

Gurhan Bulu is supported under postdoctoral research fund by The Scientific and Technological Research Council of Turkey (TUBITAK).

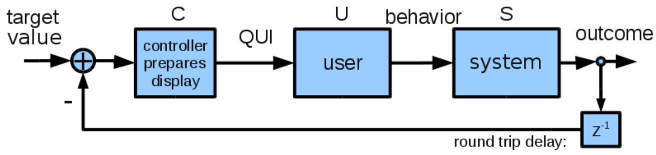


Fig. 1. User-in-the-loop (UIL): Closed loop control of user and system.

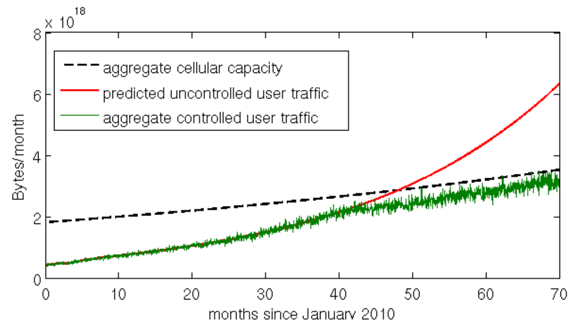


Fig. 2. Aggregate mobile traffic prediction $r(t)$, capacity limitation $\hat{R}(t)$ and UIL (temporal, dynamic price) controlled demand rate $r_C(t)$ [2].

Reasons for using UIL are manifold. In wireless communications, there is a growing problem with increasing data rates in the next 10 years [3]–[6]. Smart phones and laptop dongles will continue to increase traffic by 100% per year (Fig. 2) - a trend observed already in the last 5 years. The traditional approach to over provision capacity in order to carry all traffic will become harder as 4G, 5G and beyond [7] can never keep up with demand at this rate of increase [8]. Energy consumption and going green is also becoming more important in the future. We believe that whatever increase of capacity technology will provide, will soon be eaten up by even faster increasing traffic. New approaches require to spend even more money and power, e.g., for pico and femtocells.

The UIL approach is orthogonal and does not require more CAPEX and power. It can be used in combination with other techniques, e.g., decode-and-forward relays [9]. UIL is able to boost the spectral efficiency by substantial amounts [10].

Independent of the various ways of giving incentives and penalties (some of them studied in this paper) the outcome of the user block is either a spatial, temporal or no reaction

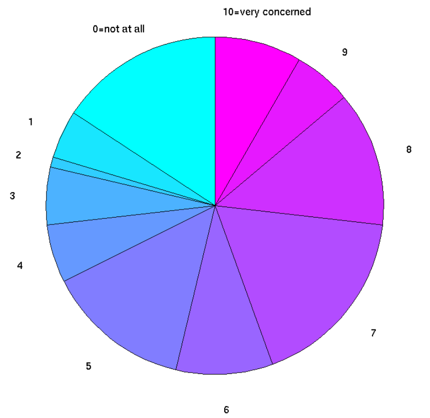


Fig. 3. Your wireless data usage has a carbon footprint proportional to your use. If you are told that for each MB that you download, you produce around 30 grams of CO_2 [2] (i.e., about 17 liters of carbon dioxide), on a scale of 0 to 10 (with 10 being the most concerned) how much do you care to adjust your data usage to be greener? Results show that rather concerned people (score 5 and above) are in the majority by almost 3/4.

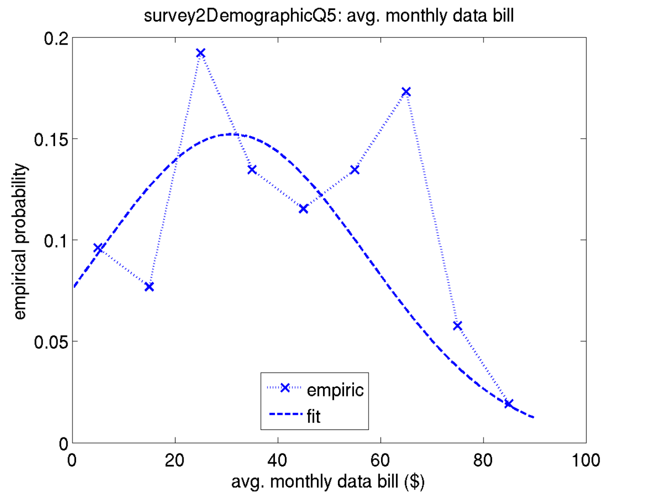


Fig. 4. Q5: Average monthly data bill. The average bill is $31 CAD (2012) with a significant amount of heavy users.

at all. Spatial UIL means the user changes location to a better one [1] (like the common practice in WiFi networks). Temporal UIL means the demand is avoided at the current time (to be continued at another time, abandoned, or offloaded to the wired network at home). The incentive usually is a fully dynamic tariff [2]. This shapes user demand during congestion. Usage-based pricing was favored by experts [11]–[15] in the past, but certain market forces have lead to the uncontrollable flat rate habit.

UIL aims at stabilizing the traffic demand to a sustainable level below the capacity. In cellular networks, it helps keeping traffic below the capacity at all times [2]. UIL applications are even possible in all fields where limited resources are consumed and where a negative impact for society or environment must be avoided, e.g., excessive consumption of energy and fossil fuel.

The paper is organized like this: The spatial and temporal UIL model are defined first. Then the results from the recent survey are presented. Finally performance results achieved in IMT-Advanced evaluation [16] scenarios are presented.

II. Spatial UIL Control

The general perspective of UIL is shown in Figure 1. In the UIL concept, the controller gives necessary information to the user, and so it is expected that the user voluntarily changes his current location from $\vec{l_1} = (x_1, y_1)$ to $\vec{l_2}$. The current signal quality $\sigma(\vec{p_1})$ and/or the spectral efficiency $\gamma(\vec{p_1})$ are known by the controller. Besides, the average signal quality and/or the spectral efficiency are known for all relevant locations of the network (from an automatically updated location-dependent database of all previous measurement statistics). After that, the network provides the necessary information and suggests better positions to the user. Before the movement, user knows his utility advantage of $\Delta u_{1,2} = u(\vec{l_2}) - u(\vec{l_1})$. This utility advantage can be financial (discount for voice calls) and/or an increased data rate (best effort data traffic). The network is providing the information where (in which direction to which location) to move. Before making his decision, the user should have all necessary information (discount rate, increased data rate, how far is the next improved step). At the end, a portion of users, p_M participates in moving and the rest of them $(1-p_M)$ stays in place. $(1-p_M)$ includes all users that cannot move, do not want to move, or do not have enough incentive to move. In previous work p_M was assumed to be constant, but in this work (after the survey) it depends on the given incentive I and the suggested distance $d_{1,2}$ to the user. The user block in Figure 1 outputs the new location $\vec{l_2}$ and it is described by a Bernoulli random process where p_M is the probability of a move from $\vec{l_1}$ to $\vec{l_2}$ for $d_{1,2}$ meters and $(1-p_M)$ of no movement. This probability depends on the distance $d_{1,2}$ and the given incentive utility u. The target spectral efficiency γ_Θ (MI_{min}) is the minimum spectral efficiency that the user should achieve after the movement (the target value must be greater than the current one). This value is not fixed and it is set by the operator, but half of the maximum or 2.5 bit/s/Hz is a good operating point.

III. Temporal UIL Control

The demand increase in cellular networks is fueled by a flat rate pricing policy. It promotes heavy-tailed traffic distributions and leads to unbounded demand increase. Nowadays the pricing policy is starting to change because of the unbounded demand increase. Eventually some operators started to charge flat-rate with a cap, but this is a temporal solution. A more elaborate solution, usage based pricing, was proposed long ago [13]–[15], but on its own it does not solve the congestion problem in the busy hours. One step further in UIL, a fully dynamic usage-based pricing is suggested [2]. This dynamic price is displayed on a user terminal (UT) so that user can decide to use or not to use the service. The main idea is very clear, the user will generate less traffic when the session price goes up. As a result the pricing method will change the user behavior and the traffic as in electricity tariffs and smart-grid applications. In the previous work [2], the user behavior is assumed as a linear with constant elasticity, but after the survey a detailed survey model is used.

The control model in Figure 1 is used to control the traffic demand. The control ratio is defined as $p = r_c/r_u$ where r_c is the controlled output rate and r_u is the uncontrolled output rate. An alternative interpretation for p is the proportion of users that do not change their original demand, while $1-p$ of the users react and do not trigger the data transmission. The controller knows the error $\epsilon(\tau) = R_{target}(\tau) - r(\tau)$, for each time

TABLE I

SURVEY B QUESTIONNAIRE: THESE QUESTIONS ARE ASKED FOR ANY OF THE SERVICES D=DATA, V=VIDEO AND S=VOICE

Question	Answer options
Q1: Assume that you are in the downtown area of a large city and you want to [use service X]. The regular cost of [using the service] is [default \$0.50 per minute for voice or \$1 for this data session]. However, due to congestion, your cell phone company will charge you an extra amount if you want to [use the service] now and in your current location. In the following table, please indicate whether you will go ahead and [use the service] despite the stated extra charge or not.	❍ use ❍ no use; for each multiplicative price increase in {1;2;3;4;5}
Q2: Assume that [the duration to use service X is between 5 to 10 minutes; or the default cost \$0.50 per minute for voice or \$1 for this data session]. Also, assume that your cell phone company provides you with discounts based on your willingness to change your location to a less congested one. In the following table, please indicate the maximum distance you are willing to walk before [using the service] in order to receive the stated discount.	❍ 0m ... ❍ 100m in 20m steps and ❍ "more" for each discount in {-20%;-40%;-60%;-80%}
Q3: Assume that [the duration of call is expected to be between 5 to 10 minutes and assume that the regular cost of your call is \$0.50 per minute; or the total regular cost of your data usage will be \$1]. Due to congestion, however, your cell phone company will charge you an extra amount if you want to make your phone call in your current location. But you can avoid this extra charge by walking to a less congested area. In the following table, please indicate the maximum distance you are willing to walk before making your phone call in order to avoid the stated additional cost.	❍ 0m ... ❍ 100m in 20m steps and ❍ "more" and ❍ "will not use" for each penalty in {+20%;+40%;...;+100%}
Q4: Assume that the total base cost of your [data or video service usage] will be \$1. Also, assume that in your current time and location, it takes approximately 12 minutes to satisfy your data demand (e.g., to complete an application download or to finish your browsing). However, assume that your cell phone company offers you a faster data access if you are willing to change your location. In the following table, please indicate the maximum distance you are willing to walk in return.	❍ 0m ... ❍ 100m in 20m steps and ❍ "more" for each speedup in {2;3;4}
Q5: Assume that [the duration of call is expected to be between 5 to 10 minutes and assume that the regular cost of your call is \$0.50 per minute; or the total regular cost of your data usage will be \$1]. Also, assume that your cell phone company provides you with discounts based on your willingness to postpone your phone call for a while. In the following table, please indicate the maximum amount of time you are willing to wait before making your phone call in order to receive the stated discount.	❍ 0min ... ❍ 60min in 15min steps and ❍ "more" for each discount in {-20%;-40%;-60%;-80%}
Q6: Assume that [the duration of call is expected to be between 5 to 10 minutes and assume that the regular cost of your call is \$0.50 per minute; or the total regular cost of your data usage will be \$1]. Due to congestion, however, your cell phone company will charge you an extra amount if you want to make your phone call right now. But you can avoid this extra charge by waiting for a period of time. In the following table, please indicate the maximum amount of time you are willing to wait before making your phone call in order to avoid the stated additional cost.	❍ 0*min* ... ❍ 60*min* in 15*min* steps and ❍ "more" and ❍ "will not use" for each penalty in {+20%;+40%;...;+100%}

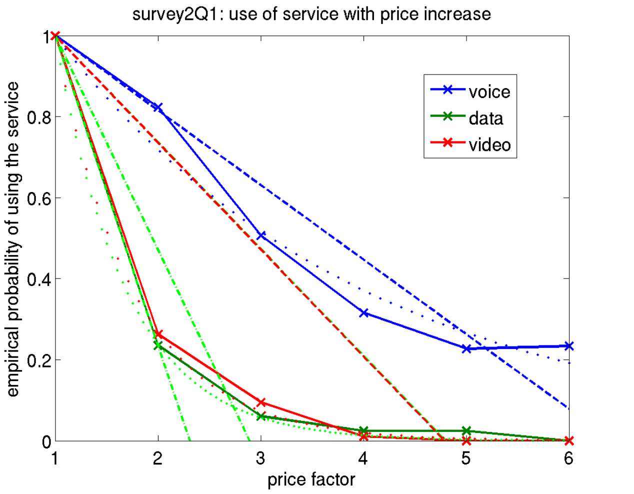


Fig. 5. Q1: Reaction to price increase $p(\chi)$ differentiated by service. The linear and exponential fits are added as dashed and dotted lines, respectively, according to the fits in Eq. 1. Data and video are quite similar while voice is less elastic. Fortunately the dominant traffic is data+video, so it will be easy to control it using the UIL method.

step τ. To reduce the uncontrolled traffic load r_u to R_{target}, the control ratio p must be chosen as $p = R_{target}/r$. Then, depending on the pricing model, an adaptation of a pricing parameter is needed. If a pricing proportional to the usage volume v is assumed, $\Pi(v) = b \cdot v$ (with one free parameter b), then b is adapted taking the inverse of the user response function (from Section IV). Now, the tariff model and price information are known and they are the inputs of the user block, so that the control loop is closed. The target value can be achieved because user is acting according to his known stochastic behavior.

IV. SURVEY RESULTS

The survey has been conducted in autumn to winter 2011 among around 100 students in Ottawa, Canada. It is based on hypothetical scenarios, since UIL is not used in the field yet.

The questions are listed in Table I and only minor variations made to explicitly name each of the three services asked for, D=data, V=video and S=voice. The original questionnaire is available on [17]. Additionally the green consciousness was assessed and results in Figure 3 show a significant interest. This allows a motivation for UIL actions even without an explicit incentive. However, in this paper we assume a zero-zero model, i.e., zero incentive ⇒ zero change compared to the uncontrolled use of mobile services. Figure 4 shows the average monthly wireless expenses for the sample group. This is representative for young professionals in Canada, a high-price market without much competition.

Figure 5 shows the UIL reaction to a dynamic price increase at the current time (e.g, busy hour). The demand response (relative price χ to control ratio p [2]) can be fitted well with exponential functions, but also linear works for $\chi \in [1, 3]$ (lin2p,lin3p):

$$\begin{aligned} p_{voice}(\chi) &= e^{-0.330\cdot\chi} \\ p_{data}(\chi) &= e^{-1.429\cdot\chi} \\ p_{video}(\chi) &= e^{-1.304\cdot\chi} \\ p^{(lin6p)}_{voice}(\chi) &= 1 - 0.184\cdot\chi \\ p^{(lin6p)}_{data+video}(\chi) &= 1 - 0.263\cdot\chi \\ p^{(lin3p)}_{data+video}(\chi) &= 1 - 0.529\cdot\chi \\ p^{(lin2p)}_{data+video}(\chi) &= 1 - 0.765\cdot\chi. \end{aligned} \tag{1}$$

The spatial UIL motivated relocation for d meters is shown as complementary cumulative distribution function (CCDF) in

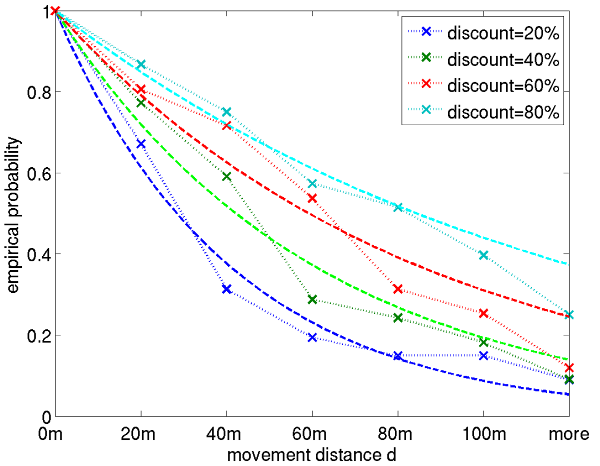


Fig. 6. Data-Q2: Empirical CCDF and exponential fit for data service and suggested UIL movement with a discount incentive (Fit: Eq. 2).

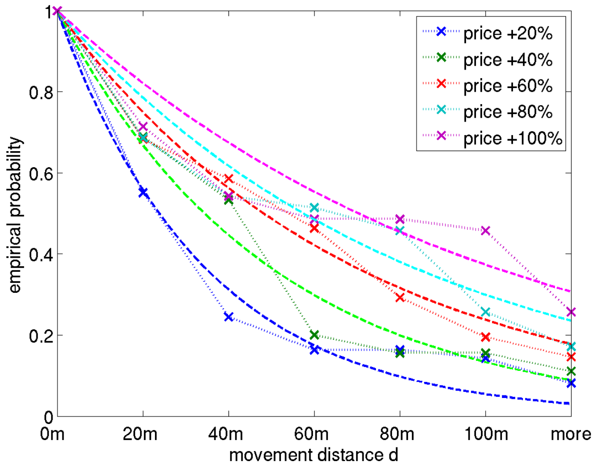


Fig. 7. Data-Q3: Empirical CCDF and exponential fit for data service and suggested UIL movement with a penalty surcharge for those users staying at their inferior location (Fit: Eq. 4).

Figures 6 and 7, first with a discount incentive δ and second with a surcharge penalty π. i is the corresponding integer index. The results show a clear control ratio. The numeric fits for the data service are

$$
\begin{aligned}
\delta_{i=1} &= -20\% \Rightarrow p = e^{-0.0244\cdot d} \\
\delta_{i=2} &= -40\% \Rightarrow p = e^{-0.0164\cdot d} \\
\delta_{i=3} &= -60\% \Rightarrow p = e^{-0.0117\cdot d} \\
\delta_{i=4} &= -80\% \Rightarrow p = e^{-0.0082\cdot d}; \qquad (2)
\end{aligned}
$$

$$p = e^{(-0.0285+0.0053\cdot i)\cdot d} = e^{(-0.0285-0.0267\cdot\delta)\cdot d}; \qquad (3)$$

$$
\begin{aligned}
\pi &= +020\% \Rightarrow p = e^{-0.0291\cdot d} \\
\pi &= +040\% \Rightarrow p = e^{-0.0202\cdot d} \\
\pi &= +060\% \Rightarrow p = e^{-0.0144\cdot d} \\
\pi &= +080\% \Rightarrow p = e^{-0.0121\cdot d} \\
\pi &= +100\% \Rightarrow p = e^{-0.0099\cdot d}; \qquad (4)
\end{aligned}
$$

$$p = e^{(-0.0311+0.0047\cdot i)\cdot d} = e^{(-0.0311+0.0233\cdot\pi)\cdot d}. \qquad (5)$$

Figure 8 shows that some users are not willing to accept the penalty and avoid using the service for the moment. The majority, however, accepts the movement and the control ratio p depends on service importance and amount of penalty $\pi \in [0.2; 1.0]$. A linear fit is appropriate:

$$
\begin{aligned}
p^{lin}_{voice}(\pi) &= 1.032 - 0.401 \cdot \pi \\
p^{lin}_{data}(\pi) &= 0.806 - 0.307 \cdot \pi \\
p^{lin}_{video}(\pi) &= 0.710 - 0.352 \cdot \pi. \qquad (6)
\end{aligned}
$$

Very remarkably, video services are not considered very important compared to voice calls. Data services range in the middle. It can be concluded that the use of video is very elastic, i.e., easy to control with slight monetary incentives or penalties. With the additional fact that video applications easily consume more data rate by one or two orders of magnitude (i.e. dominating the future traffic), it is clear that the total consumed rate can be easily controlled as well.

The temporal UIL motivated deferral (postpone the service session) for t minutes with a discount incentive δ (Figure 9)

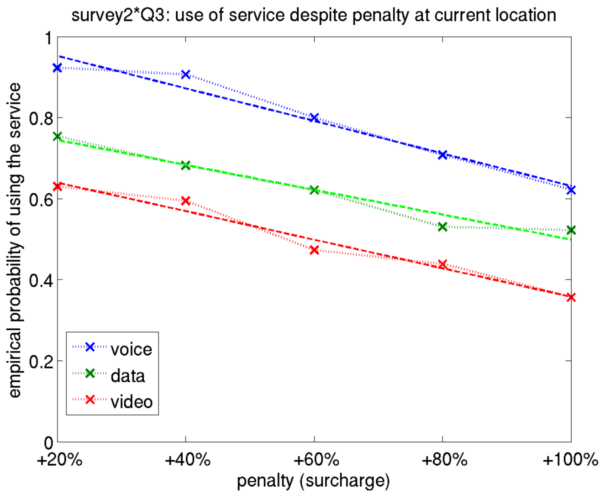


Fig. 8. Q3: This graph shows the fraction p of users which still want to use the service despite a penalty π. This includes users willing to relocate first and then use the service (Fit: Eq. 6).

or surcharge penalty π (Figure 10). i is an integer index. The results are encouraging. The numeric fits for data are:

$$
\begin{aligned}
\delta &= -20\% \Rightarrow p = e^{-0.0500\cdot t} \\
\delta &= -40\% \Rightarrow p = e^{-0.0325\cdot t} \\
\delta &= -60\% \Rightarrow p = e^{-0.0248\cdot t} \\
\delta &= -80\% \Rightarrow p = e^{-0.0190\cdot t}; \qquad (7)
\end{aligned}
$$

$$p = e^{(-0.0568+0.0101\cdot i)\cdot t} = e^{(-0.0568-0.0504\cdot\delta)\cdot t}; \qquad (8)$$

$$
\begin{aligned}
\pi &= +020\% \Rightarrow p = e^{-0.0677\cdot t} \\
\pi &= +040\% \Rightarrow p = e^{-0.0375\cdot t} \\
\pi &= +060\% \Rightarrow p = e^{-0.0320\cdot t} \\
\pi &= +080\% \Rightarrow p = e^{-0.0244\cdot t} \\
\pi &= +100\% \Rightarrow p = e^{-0.0257\cdot t}; \qquad (9)
\end{aligned}
$$

$$p = e^{(-0.0666+0.0097\cdot i)\cdot t} = e^{(-0.0666+0.0486\cdot\pi)\cdot t}. \qquad (10)$$

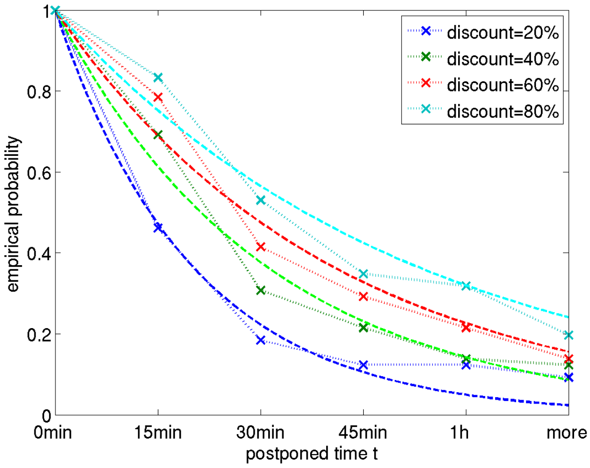


Fig. 9. Data-Q5: Empirical CCDF and exponential fit for data service and suggested UIL deferral with a discount incentive (Fit: Eq. 7).

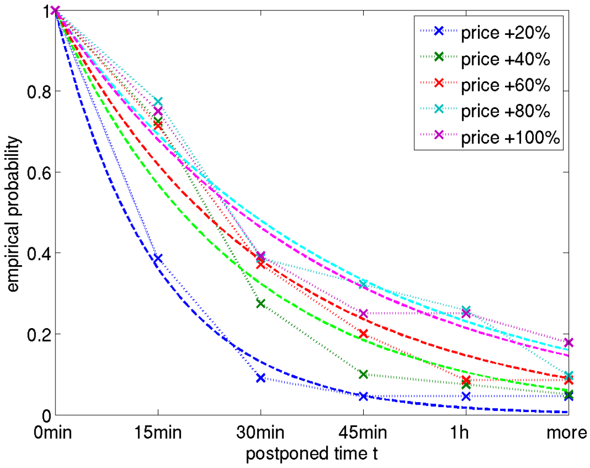


Fig. 10. Data-Q6: Empirical CCDF and exponential fit for data service and suggested UIL deferral with a penalty surcharge if used at the current time (The numeric fit is found in Eq. 9).

Respective results also exist for the voice and video service. Figure 13 contains all CCDF results for {Q2,Q4,Q5,Q6}. Important is the fact that video traffic is much more elastic than voice, i.e., video sessions can much easier be moved out of the congested times and locations. More information can be found on [17]. All the results confirm the general intuitive trends:

- The acceptance p drops with effort (distance d or wait t)
- A stronger incentive is followed with more acceptance
- A more forceful penalty also leads to more obedience
- Data traffic service is more elastic than voice
- Video service is more elastic than data
- Users are easily convinced if they understand the purpose.

V. Simulation Results

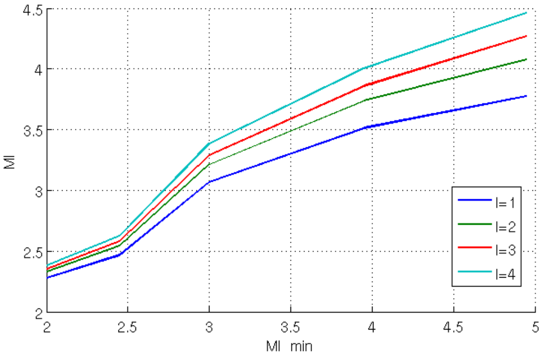
Using the survey data, an IMT-Advanced system model [16] with UIL was studied. The scenarios are defined in [16] and in Table II. They represent whole range between urban micro (UMi) and rural macro (RMa). SINR (σ) results are obtained by numeric analysis of antenna gains, path losses, interference at each location. SINR is translated into spectral efficiency γ according to the methodology in [1], [18]. The average spectral efficiency $\bar{\gamma}$ is then determined by an integration over the cell area.

TABLE II
IMT-Advanced Scenario Specifications

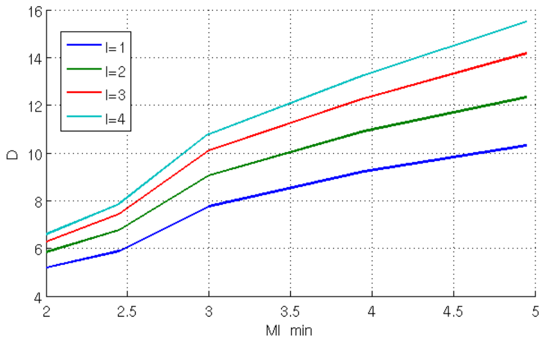
Scenario	Urban micro UMi	Urban macro UMa	Suburban macro SMa	Rural macro RMa
Inter-BS distance	200 m	500 m	1299 m	1732 m
BS height	10 m	25 m	35 m	35 m
Antenna tilt	$-12°$	$-12°$	$-6°$	$-6°$
f_C	2.5 GHz	2.0 GHz	2.0 GHz	0.8 GHz
Tx power	44 dBm	49 dBm	49 dBm	49 dBm

TABLE III
Spectral efficiency results [bit/s/Hz/Sector] without and with UIL ($\gamma_\Theta = 2.5$ bit/s/Hz), for traffic data, video, voice (from top to bottom).

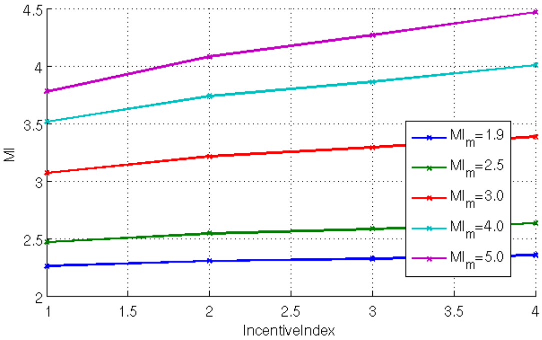
Scenario	UMi	UMa	SMa	RMa
Without UIL [10]: $\bar{\gamma}$ =	1.567	1.254	1.234	1.974
UIL proposals	80%	96%	94%	62%
UIL d_{UIL} =	8.8 m	9.4 m	15.6 m	61.4 m
UIL with constant [1]	2.170	1.995	2.836	2.509
$p_M = 0.5 \to \bar{d}$ =	4.4 m	4.7 m	7.8 m	30.7 m
Data traffic:				
UIL (Q2) data $\bar{\gamma}$ =	2.507	2.467	3.682	2.311
$\delta = -20\% \to \bar{d}$ =	6.0 m	5.9 m	10.2 m	8.8 m
participation p_{UIL} =	82%	85%	75%	36%
UIL (Q2) data $\bar{\gamma}$ =	2.590	2.543	3.899	2.363
$\delta = -40\% \to \bar{d}$ =	6.9 m	6.8 m	11.5 m	10.0 m
participation p_{UIL} =	88%	89%	82%	41%
UIL (Q2) data $\bar{\gamma}$ =	2.623	2.581	3.969	2.424
$\delta = -60\% \to \bar{d}$ =	7.3 m	7.4 m	12.1 m	13.0 m
participation p_{UIL} =	90%	91%	85%	46%
UIL (Q2) data $\bar{\gamma}$ =	2.676	2.629	4.147	2.507
$\delta = -80\% \to \bar{d}$ =	7.9 m	7.1 m	13.1 m	17.7 m
participation p_{UIL} =	94%	94%	90%	54%
UIL (Q3) data $\bar{\gamma}$ =	2.573	2.537	3.849	2.467
$\pi = +100\% \to \bar{d}$ =	6.8 m	6.9 m	11.7 m	17.2 m
participation p_{UIL} =	80%	96%	94%	62%
UIL (Q4) *data* $\bar{\gamma}$ =	2.976	3.024	3.602	2.328
$I = speedup \to \bar{d}$ =	9.1 m	10.2 m	11.9 m	15.1 m
participation p_{UIL} =	54%	44%	25%	43%
Q2: max gain for data $\bar{\gamma}$	+71%	+110%	+236%	+27%
Video traffic:				
UIL (Q2) video $\bar{\gamma}$ =	2.456	2.422	3.523	2.293
$\delta = -20\% \to \bar{d}$ =	5.5 m	5.5 m	9.5 m	8.7 m
participation p_{UIL} =	79%	82%	70%	34%
UIL (Q2) video $\bar{\gamma}$ =	2.590	2.540	3.917	2.353
$\delta = -40\% \to \bar{d}$ =	6.9 m	6.6 m	11.4 m	9.8 m
participation p_{UIL} =	88%	89%	82%	40%
UIL (Q2) video $\bar{\gamma}$ =	2.648	2.602	4.072	2.448
$\delta = -60\% \to \bar{d}$ =	7.5 m	7.5 m	12.5 m	14.6 m
participation p_{UIL} =	92%	92%	88%	48%
UIL (Q2) video $\bar{\gamma}$ =	2.680	2.635	4.174	2.511
$\delta = -80\% \to \bar{d}$ =	7.8 m	7.9 m	13.2 m	17.7 m
participation p_{UIL} =	94%	94%	91%	54%
UIL (Q3) video $\bar{\gamma}$ =	2.636	2.591	4.027	2.405
$\pi = +100\% \to \bar{d}$ =	7.4 m	7.4 m	12.3 m	10.7 m
participation p_{UIL} =	91%	92%	86%	45%
UIL (Q4) video $\bar{\gamma}$ =	2.962	2.997	3.569	2.286
$I = speedup \to \bar{d}$ =	9.0 m	9.8 m	11.3 m	14.6 m
Q2: max gain for video $\bar{\gamma}$	+71%	+110%	+238%	+27%
Voice traffic:				
UIL (Q2) voice $\bar{\gamma}$ =	2.539	2.499	3.778	2.338
$\delta = -20\% \to \bar{d}$ =	6.4 m	6.3 m	10.8 m	9.0 m
participation p_{UIL} =	84%	86%	78%	38%
UIL (Q2) voice $\bar{\gamma}$ =	2.637	2.587	4.061	2.406
$\delta = -40\% \to \bar{d}$ =	7.3 m	7.2 m	12.3 m	11.5 m
participation p_{UIL} =	91%	92%	87%	45%
UIL (Q2) voice $\bar{\gamma}$ =	2.666	2.624	4.122	2.474
$\delta = -60\% \to \bar{d}$ =	7.7 m	7.9 m	13.0 m	14.7 m
participation p_{UIL} =	93%	94%	89%	51%
UIL (Q2) voice $\bar{\gamma}$ =	2.695	2.654	4.213	2.584
$\delta = -80\% \to \bar{d}$ =	8.0 m	8.3 m	13.7 m	22.5 m
participation p_{UIL} =	95%	95%	92%	61%
UIL (Q3) voice $\bar{\gamma}$ =	2.649	2.607	4.079	2.505
$\pi = +100\% \to \bar{d}$ =	7.5 m	7.7 m	12.9 m	17.2 m
participation p_{UIL} =	92%	93%	88%	54%
Q2: max gain for voice $\bar{\gamma}$	+69%	+108%	+241%	+31%



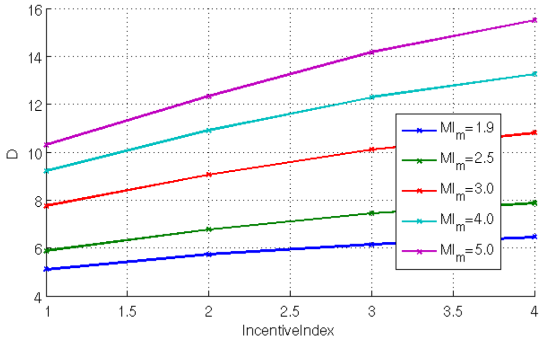
(a) Spectral efficiency in bit/s/Hz $\bar{\gamma} = f(\gamma_\Theta, I)$



(b) Average move distance in meters $\bar{d} = f(\gamma_\Theta, I)$



(c) Spectral efficiency in bit/s/Hz $\bar{\gamma} = f(I, \gamma_\Theta)$



(d) Average move distance in meters $\bar{d} = f(I, \gamma_\Theta)$

Fig. 11. Simulation results for LTE (SISO) with UIL in UMa scenario of IMT-Advanced and data traffic. Incentive $I_i|_{i=1}^{4}$ is a discount of $\{-20\%, -40\%, -60\%, -80\%\}$. The user behavior is assumed according to the survey results. Increasing the threshold γ_Θ and the incentive I both lead to higher cell spectral effiency. This leads to the conclusion that telling the user all options (different γ_Θ) is most beneficial. More powerful incentives are only required for $\gamma_\Theta \geq 3$ [11(c)]. Even with a small incentive discount $I_1 = -20\%$, $\bar{\gamma}$ can be increased from 1.254 (no UIL) to above 3 bits/s/Hz [11(a)], which economically more than compensates the impact of the incentive on the revenue in the busy hours.

More sophisticated shadowing scenarios were studied in [1], [19] and confirm previous UIL results.

Average cell spectral efficiency results $\bar{\gamma}$ for all scenarios and some parameter sets for the data service are given in Table III. The corresponding graphs are in Figure 11. They focus on the UMa scenario with incentives for data traffic. Table III also provides the fraction of *UIL proposals* which quantify those locations where a move is recommended ($\gamma < \gamma_\Theta$). Also the average distances to move $\bar{d}$ are provided, which are composed of $\bar{d}_{UIL}$, the average distance from locations of ($\gamma < \gamma_\Theta$) to the nearest proposed point if all users moved and $\bar{d}_{UIL}$, the average distance from these locations to the next better location. The real average participation p_{UIL} is observed as an outcome because it depends on the user behavior as quantified in this paper and it is averaged over all UIL-improvable positions within the cell.

As the results show, in the UMi to SMa scenarios more than 50% are motivated, even with a small incentive, and with a high incentive p_{UIL} is within [80%, 90%]. The gains for $\bar{\gamma}$ are very encouraging. The high number in the SMa scenario comes from the benefit of the special geometry, such that for many positions there is likely a very high γ nearby. Figure 11 studies the effect of the threshold γ_Θ and incentive intensity on $\bar{\gamma}$ and $\bar{d}$. Both functions are monotonicly increasing.

UIL with penalties (Q4) instead of discount incentives (Q3) leads to the same trend, but in general a −80% discount is more effective than a +100% surcharge, in terms of spectral efficiency, i.e., total capacity of the cell. It is material for further research to study the financial tradoff between the operators' outgoing incentive and incoming increase in revenue to the the much larger capacity. It is harder to quantify the financial benefit of not being in congestion, because user satisfaction is not linearly dependent on the available capacity.

The speedup scenario (Q4) is slightly different. For each location l_1 with local $\gamma(l_1)$, there are potentially locations l_2, l_3, and l_4 with distances d_2, d_3, and d_4, respectively, where $\gamma(l_i) \geq i \cdot \gamma(l_1)$. For each of the distances d_i we know the user behavior $p_{UIL,i} = f(d_i)$. A fraction of users $p_{UIL,4}$ is improving to the new location l_4 with $\gamma(l_4)$ and only if there is a higher chance $p_{UIL,3}$ the remaining ($p_{UIL,4} - p_{UIL,4}$) user fraction moves to l_3 and so on. This suits the idea of Figure 1 in [10] and the recent results in Table III confirm the optimistic assumptions.

A. Applied UIL Temporal Control

In the section above the spatial survey data has been evaluated. The survey data with temporal reaction is now studied in a future scenario where traffic demand exceeds capacity for a certain period of time each day. According to [2], the control loop can provide dynamic prices in a scenario where usage-based pricing is enabled. Figure 12 shows simulation results of 14 representative days and assumes data and video traffic only (which both have the same elasticity, see Eq. 1). The required price change is roughly +20% in the worst case here and reduces the traffic to an 80% level to be safely below the capacity. A 95% target value for the controller has been set. Very short term fluctuations also exist superimposed on the demand curve, but their effect must be handled by buffers and in the ideal case by using a proper flow control [20].

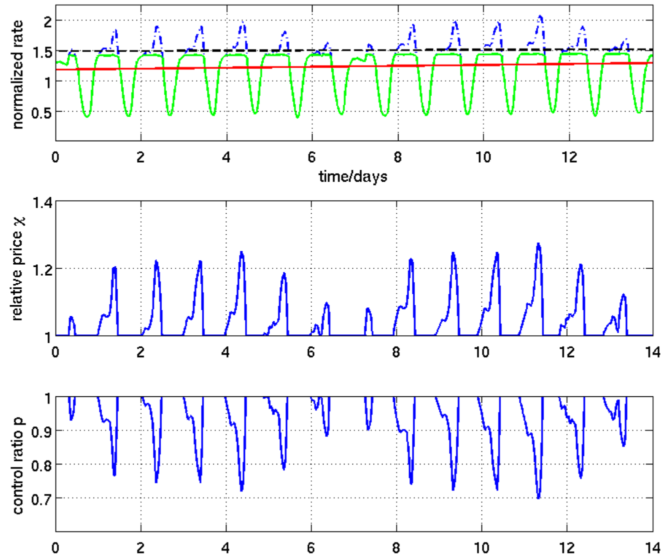


Fig. 12. UIL temporal control in times of predicted congestion during the busy hours. Here the elasticity of data and video is assumed (Eq. 1). The displayed 14 days represent typical traffic week days from a Sunday to a Saturday. The blue dash-dot line is the unconstrained traffic demand, with average shown by the red line. The black dashed line is the capacity of the system. The green line is the rate after using UIL temporal control. The UIL controller calculates the normalized price increase χ as shown as input to the user block. The user(s) - modeled like in Fig. 5 - answer with a demand reduction determined by the control ratio p.

VI. Conclusion

In this paper the new user-in-the-loop (UIL) paradigm is supported by quantitative numbers for the input-output behavior of the user in a system-theoretical model. The presented survey results for the data, video and voice services and several classes of different incentives (financial utilities or penalties or higher data rates) fill the missing link for allowing more realistic system simulations. The results indicate reactions in real application scenarios, and improve previous results which were based on assumptions. UIL is user-centric and allows active participation for improving the system performance. The incentives invoke a real motivation for the user. The IMT-Advanced scenarios were studied with the spatial UIL model and results suggest substantial gains up to 200%, independent of PHY or MAC layer algorithms. The relocation distances are easy to reach on foot. Demand shaping by UIL temporal control and fully dynamic pricing also works well, as the controlled demand stays below capacity all the time. UIL enables a greener networking by reducing the wasteful use of limited resources. Therefore new expensive infrastructure rollout can be postponed to a later time. The spatial UIL control also trains users (in long term) to understand why certain high-rate applications are prohibitive in the busy hours. More project-related information can be found on [17].

Future work will study a traffic mix situation of all three major classes in one scenario, provide details for the controller design with noisy measurements and treat relocations in heterogeneous networks, i.e., with macro and pico/femtocells.

The use of UIL in the Smart Grid is also a promising new approach. The UIL advantage is the quasi-immediate feedback to the user and the smart handheld device as interface which allows very fast learning and long-term training of the user. Potentially even bad behavior (in a game-theoretic sense) can be corrected [21], applicable in all fields where humankind shows unsustainable behavior right now. If applied globally, a good acceptance is expected because of the fair and equal treatment, where otherwise voluntary altruism is generally limited in acceptance and effect.

With all the benefits, it must be transparent to the user what is happening and why in order to avoid misuse.

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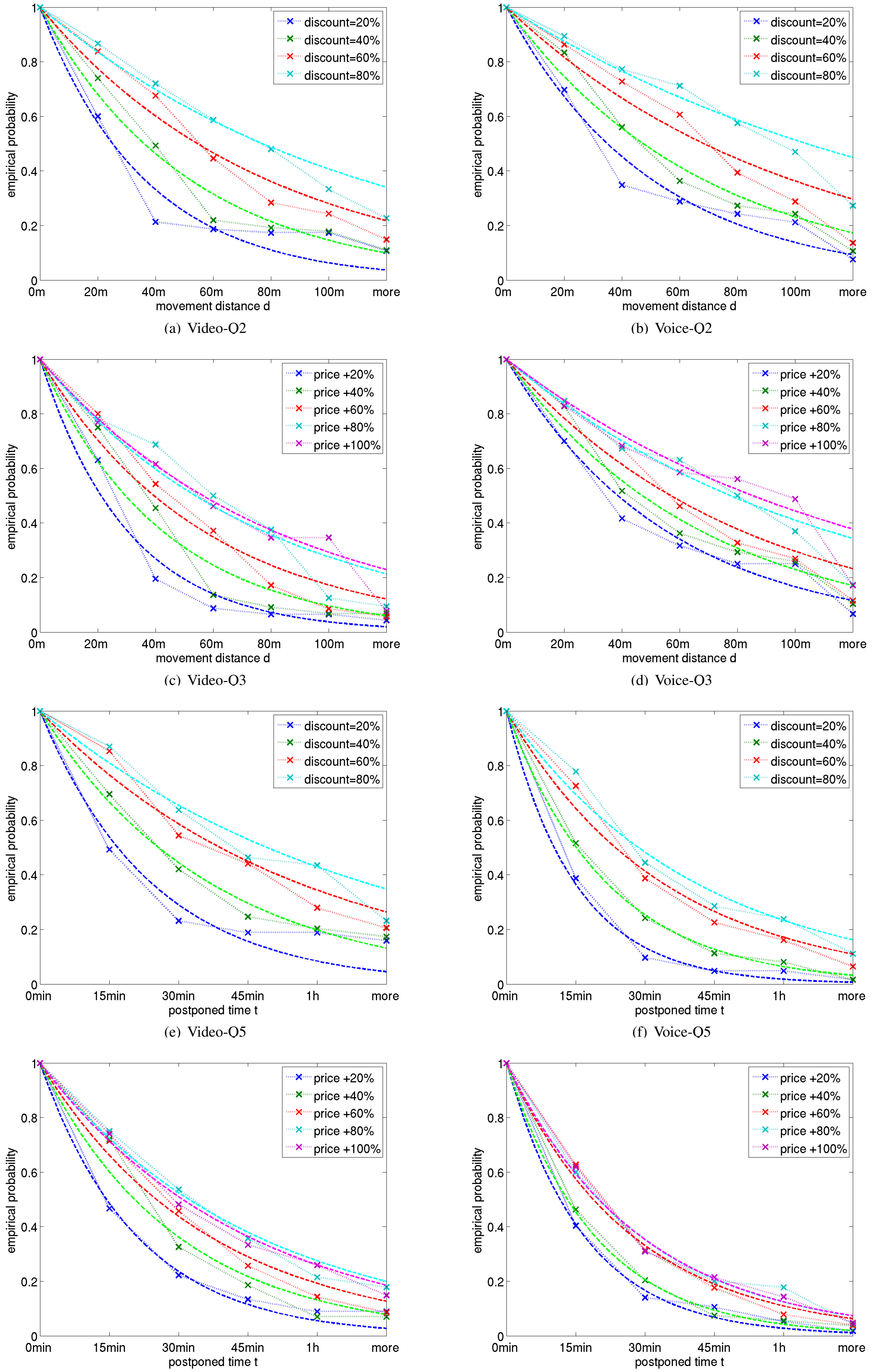

(a) Video-Q2 (b) Voice-Q2

(c) Video-Q3 (d) Voice-Q3

(e) Video-Q5 (f) Voice-Q5

(g) Video-Q6 (h) Voice-Q6

Fig. 13. Survey results for the *video* and *voice* QoS classes. Empirical CCDFs and exponential fits. Different discount options and reaction (spatial, temporal) are placed from row to row. It can be seen that video services (left column) are much more elastic than voice (right column). This comprehensive analysis also shows the different reactions, spatial (upper 4) and temporal (lower 4), as well as incentives in form of discounts (a,b,e,f) or penalties (c,d,g,h).