



Budapest University of Technology and Economics
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On Pricing, Incentives and Congestion Control in Heterogeneous Networks

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Collection of PhD theses

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1 Introduction

Designing the next-generation global network is a complex task. What was once considered a pure engineering problem has become cross-disciplinary: engineers, economists, sociologists and legal experts cooperate to propose efficient methods for future networked systems. While performance enhancing techniques – like congestion control – are still very important as the popularity of bandwidth-hungry and real-time applications and services (file sharing, streaming video, etc.) is ever-growing, socio-economic aspects are becoming increasingly significant [1].

On the other hand, heterogeneity is inherently present in multiple aspects of the wired and wireless Internet. As access technologies, network-enabled devices and end-users themselves are more and more diversified, heterogeneity will only gain even more momentum in future networks. Therefore, understanding, overcoming or even exploiting this heterogeneity at different levels is a fundamental goal for researchers.

Heterogeneous networks are managed by a diverse collection of network operators: Internet Service Providers, community wireless providers, micro-providers (end-users themselves), cellular mobile operators, etc. These operators face various challenges both at the socio-economical and technical levels. This work focuses on a subset of these challenges. First, the dissertation aims to quantify the impact of user-behavior on Internet access pricing, and to propose a directly user-influenced pricing mechanism. Second, incentive schemes are studied which enable the global proliferation of a community wireless network. Third, a novel TCP extension is proposed and analyzed; this extension enables mobile operators and content providers to utilize efficient congestion control in dynamic mobile environments.

Starting with the emergence of commercial Internet Service Providers (ISPs), continuing in the dotcom era, culminating in today's feature-rich, application-driven, multimedia services network, profit-making is the single most-important driving force behind the evolution of the Internet. Understanding the economic processes of the Internet is therefore essential [2]. There is broad literature in the area of modeling interactions between ISPs, most of these employ game-theoretical tools [3] [4] [5]. While these papers introduce and analyze complex models on the interaction of ISPs at different levels of the hierarchy, they mostly assume a very simple user behavior model when investigating the market for last-mile ISPs: end-users choose the cheapest provider assuming that the quality of the service is the same. This assumption could be plausible in certain scenarios, but it could be misleading if there are loyal customer segments present in the market. On the other hand, economists are well aware of the notion of consumer or brand loyalty, which is very much existing in realistic markets [6]. Practically speaking, a customer is loyal to a brand if she purchases the product of that brand, even if there are cheaper substitutions on the market. If user loyalty is given consideration when pricing Internet access, higher profits can be achieved by the service providers. Also, the ongoing network neutrality debate [7] is driving a change in pricing schemes used by players of the Internet ecosystem [8]. Access ISPs are thinking about taxing content providers for carrying their content to end-users, furthermore, they want to cap user's data traffic in order to operate profitably. While certainly advantageous for access ISPs, these schemes may not be optimal or even acceptable for users and content providers. Furthermore, the global economic crisis left providers worrying about their revenues and users trying to cut down on their costs. Given the circumstances, designing a pricing mechanism, which lets ISPs plan their income and gives users the possibility to save some money, is highly relevant.

User-provided networking has seen its stock rising recently. While some see this concept as an interesting but only moderately viable alternative to the traditional Internet Service Provider centric paradigm, others believe it has the potential to induce a complete shift in Internet communication patterns. The latter view can be justified by four important disruptive aspects of user-provided networking. First, since the end-user can share or sell her own resources (e.g., connectivity), the

distinction between end-user device and network device disappears. Second, the nature of wireless media, human mobility [19] and the rise of micro-operators create the need for protocols that inherently handle intermittent connectivity, opportunistic relaying and smooth roaming. Third, user-provided services require traditional trust relationships to be transformed: social networks of trust should be formed to ensure the willingness to cooperate and to maintain network growth. And last, swift adoption of new technologies is possible as adopters are the end-users themselves. It is reasonable to believe that these novel characteristics and functionalities could enable user-provided wireless networking to be the foundation of the future wireless Internet. Existing work on wireless community networks focuses on user participation and community pricing [16] [17] [18]. Although FON [15] and wireless community networks in general show great promise, their ultimate success depends on properly designed incentive mechanisms for both users and ISPs. These networks should be as much user-provided as ISP-endorsed: a dual support is essential to achieve global wireless connectivity.

With the proliferation of wireless cellular and community networks, and more specifically their integration into the global network, the inherent heterogeneity of the Internet has become even more dominant. High-speed wireless technologies like UMTS, HSPA, LTE [21] and WiMAX are becoming reality, bringing broadband experience to mobile users. The data rates of these technologies were already realized and surpassed in wired networks a decade ago, even triggering a flurry of research for making TCP (the dominant transport protocol of the Internet) capable of utilizing high-bandwidth, high-delay network connections [22] [23] [24] [25]. Also, there is a significant amount of work on making TCP wireless-friendly [26] [27][28][29][30]. However, since new, broadband wireless networks are deployed in an island-like manner, inter-system handovers are becoming commonplace. A handover between a GPRS and an LTE network means a link capacity increase of several orders of magnitude. This could significantly impact a number of applications, e.g., multimedia streaming over TCP [31] [32]. Understanding the limitations of existing TCP variants and proposing a new mechanism which can handle these scenarios well is important, because user experience can suffer from inefficient transport protocols, driving people away from using mobile Internet. Mechanisms with explicit signaling introduce the need for network support and additional overhead, and also have a low chance of deployment [33]. In order to ensure deployability and facilitate adoption, the proposed scheme should be a simple, easily implementable, server-side algorithm, adhering to the end-to-end concept.

2 Research Objectives

The objective of my research is threefold.

- (1) Quantify the impact of customer loyalty on the pricing competition between Internet Service Providers. Propose a pricing mechanism for Internet access, which enables network providers to plane their revenues, while users can directly influence the implemented billing policy.
- (2) Understand the economic interactions in wireless community networks. Show that proper incentive design facilitates the emergence of a truly global wireless community, while both users and network providers profit from the network.
- (3) Understand the limitations of existing TCP versions in scenarios of sudden capacity increase. Propose a simple non-congestion detection mechanism which solves this problem effectively.

3 Methodology

The results presented in Theses 1 were obtained mainly by game-theoretical analysis [9]. Quantification of the impact of customer loyalty on Internet access pricing was done by applying noncooperative game theory, specifically one-shot (Nash equilibrium) and repeated games (subgame-perfect equilibrium, Nash reversion). For proving the properties of the novel user-influenced pricing mechanism, I have used cooperative game theory (transferable payoffs, core, ψ -stable pairs, Shapley value).

Economic interactions in global wireless community networks (Theses 2) were also modeled and evaluated with the help of noncooperative (one-shot game, Nash equilibrium, Stackelberg game, subgame-perfect equilibrium, backward induction) and evolutionary game theory (fitness, mutation, evolutionarily stable strategies) [20]. Probability theory was used for modeling the geographic relevances of users. Extensive simulations were utilized for evaluating the extended model including user mobility, heterogeneous payments and temporal evolution. Real-world data sets were used as input to the simulations, e.g., GPS coordinates of the users' homes, population density and user mobility behavior.

The main results of Theses 3 were derived from testbed measurements with a working Linux kernel implementation of the proposed methods. The lower bound in Thesis 1.1, and the method for parameter tuning was derived by analytical calculations. Larger scale throughput and fairness evaluation was done by simulations in the well-known ns-2 framework using the exact kernel implementation code.

4 New Results

My contributions are divided into three theses.

Theses 1: Pricing Internet Access under User Influence [J2] [C5] [C6]

In these theses I have investigated the pricing of Internet Service Providers competing for users of different loyalty intentions through a game-theoretic framework. I have shown how loyalty facilitates cooperation and maximum possible prices. I have also proposed a novel pricing mechanism allowing users to explicitly impact the tariffs of their respective providers.

Definition 1.1 (Stage game with user loyalty, G_0). Consider a market with two local ISPs competing in prices for a fixed number of customers. Customers are split into three partitions upon their brand loyalty: the first group consists of l_1 customers who are all loyal to ISP₁ in the sense that if ISP₁'s price p_1 is less than or equal to a reservation value α , they choose ISP₁ as their service provider, otherwise they do not purchase Internet access. The second group consists of l_2 loyal customers of ISP₂, while the third group contains n "switchers", who buy service from the cheapest provider, if its price is not greater than α . If the providers announce the same price ($p_1 = p_2 < \alpha$), then half of "the switchers" chooses ISP₁ and the other half chooses ISP₂. The flow of the game is that ISPs announce their prices simultaneously, then customers make their choices.

The basic idea of this game was proposed in [10]. Note, that though values $l_1 > 0$, $l_2 > 0$ and $\alpha > 0$ are common knowledge, group membership of a given customer cannot be determined, so there is no price discrimination possible. Furthermore, for simplicity we assume a constant unit cost of zero for both firms, and that ISP₁ has the larger loyal user base, $l_1 > l_2$.

Given the above and that $p_1 \leq \alpha$ and $p_2 \leq \alpha$, ISP₁'s payoff can be expressed as

$$\pi_1(p_1, p_2) = \begin{cases} (l_1 + n)p_1 & p_1 < p_2 \\ (l_1 + 0.5n)p_1 & p_1 = p_2 \\ l_1 p_1 & p_1 > p_2 \end{cases} \quad (1)$$

It can be shown (see [10] and [11]) that this game has a unique Nash equilibrium in mixed strategies. In this case, equilibrium profits are $\pi_1 = l_1 \alpha$ and $\pi_2 = \frac{l_2 + n}{l_1 + n} l_1 \alpha$.

Thesis 1.1 (Equilibrium analysis of a repeated game model for Internet pricing with user loyalty). *I have formulated the repeated game G_r as the infinitely repeated extension of G_0 . I have shown by analysis that the strategy profile "Set price to reserve price α until the other player deviates and then play according to the equilibrium in G_0 " is a sub-game perfect Nash equilibrium for the repeated game G_r , if $n > l_1 - 2l_2$ and*

$$\Theta > \frac{1}{2} + \frac{l_1 - \frac{n+l_1}{n+l_2} l_2}{2n}$$

where $\Theta < 1$ is the discount factor for future payoffs.

This result means that cooperation between the two ISPs yield higher profits for both thus there is a strong incentive to cooperate. Note, that in a number of markets there are only two access ISPs to choose from.

The optimal decision of ISPs lies in evaluating the assumption inequalities. For Player 1 (larger loyal user base) it is always better to cooperate and try to achieve sub-game perfection. For Player 2 it is a matter of loyal user base size: if $n > l_1 - 2l_2$, Player 2 will also cooperate. If not, then she will play the G_0 equilibrium strategy, while Player 1 will play the cooperative strategy for one round. Then from round 2 (because of Nash reversion), player 1 will also play the G_0 equilibrium strategy.

Definition 1.2 (Stage game with user loyalty and differentiated reserve prices and inelastic demand, G_1). G_1 is constructed from G_0 by introducing α_1 , the reservation value for “switchers”, and α_2 , the reservation value for loyal users ($\alpha_1 < \alpha_2$), instead of the single reservation value α . Thus the demand function for G_1 is the following:

$$D(p) = \begin{cases} n + \sum_{j=1}^N l_j & 0 \leq p \leq \alpha_1 \\ \sum_{j=1}^N l_j & \alpha_1 < p \leq \alpha_2 \\ 0 & p > \alpha_2 \end{cases} \quad (2)$$

where p is the price charged to users and N is the number of competing ISPs. From that, the payoff function $\Pi_i(p_i)$ of ISP_i can be defined:

$$\Pi_i(p) = \begin{cases} p_i \left(l_i + \frac{n}{m} \right) & p_i = \min_j p_j \leq \alpha_1 \\ p_i l_i & \min_j p_j < p_i \leq \alpha_2 \\ 0 & p_i > \alpha_2 \end{cases} \quad (3)$$

where m is the number of ISPs charging the same minimum price, therefore sharing “switchers” equally.

Note that G_1 models the situation, when loyal users have a higher threshold for the service price than switchers. Furthermore, demand is inelastic which is characteristic of a product that is uniformly needed—this is the case with Internet access in advanced countries.

Definition 1.3 (Stage game with user loyalty and differentiated reserve prices and elastic demand, G_2). Game G_2 is constructed from G_1 by substituting the demand function in G_1 with the commonly used linear demand function:

$$D(p) = \begin{cases} n \frac{\alpha_1 - p}{\alpha_1} + \sum_{j=1}^N l_j & 0 \leq p \leq \alpha_1 \\ \sum_{j=1}^N l_j & \alpha_1 < p \leq \alpha_2 \\ 0 & p > \alpha_2 \end{cases} \quad (4)$$

From that, we can define the payoff function $\Pi_i(p_i)$ of ISP_i , which has a form of

$$\Pi_i(p) = \begin{cases} p_i \left(l_i + n \frac{\alpha_1 - p_i}{\alpha_1 m} \right) & p_i = \min_j p_j \leq \alpha_1 \\ p_i l_i & \min_j p_j < p_i \leq \alpha_2 \text{ or} \\ & \alpha_1 < p_i \leq \alpha_2 \\ 0 & p_i > \alpha_2 \end{cases} \quad (5)$$

where m is the number of ISPs charging the same minimum price.

Note that G_2 is different from G_1 since the demand is price-sensitive, i.e. elastic. This models the demand for Internet access in developing regions: people treat Internet access as a luxury product. The two different demand functions are depicted in Figure 1.

Thesis 1.2 (Equilibrium analysis of stage games with dual reserve prices: inelastic and elastic demand). *I have shown by analysis that*

(i) G_1 with two players has the following Nash equilibria:

- (a) $(p_1, p_2) = (\alpha_2, \alpha_2)$ is a pure strategy Nash equilibrium, if $A < B_1$ and $A < B_2$;
- (b) $(p_1, p_2) = (\alpha_2, \alpha_1)$ is a pure strategy Nash equilibrium, if $A < B_1$ and $A > B_2$;

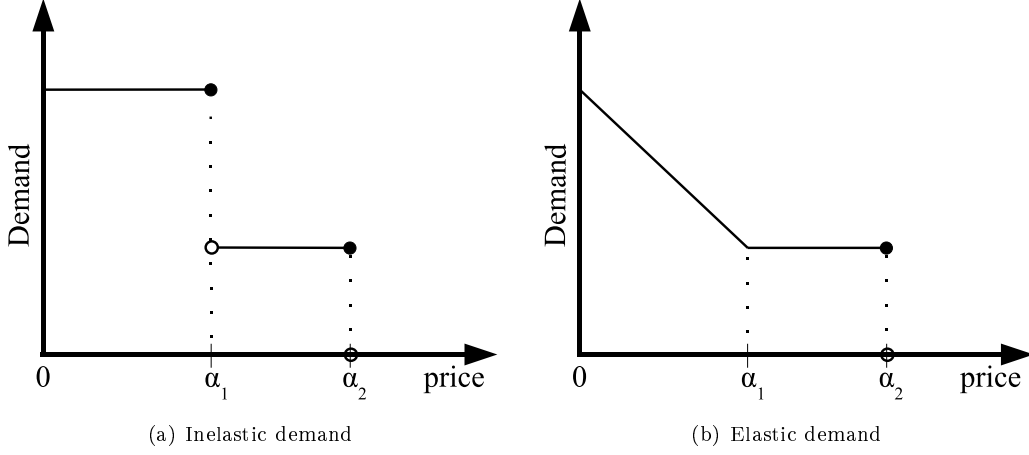


Figure 1: Demand functions for G_1 and G_2

- (c) $(p_1, p_2) = (\alpha_1, \alpha_2)$ is a pure strategy Nash equilibrium, if $A > B_1$ and $A < B_2$;
(d) There is no pure strategy Nash equilibrium if $A > B_1$ and $A > B_2$.

where $A = n\alpha_1$ and $B_i = (\alpha_2 - \alpha_1)l_i$ for $i = 1, 2$;

(ii) G_2 with two players has the following Nash equilibria:

- (a) $(p_1, p_2) = (\alpha_2, \alpha_2)$ is a pure strategy Nash equilibrium, if $A' < B'_1$ and $A' < B'_2$;
(b) $(p_1, p_2) = (\alpha_2, p_{max})$ is a pure strategy Nash equilibrium, if $A' < B'_1$ and $A' > B'_2$;
(c) $(p_1, p_2) = (p_{max}, \alpha_2)$ is a pure strategy Nash equilibrium, if $A' > B'_1$ and $A' < B'_2$;
(d) There is no pure strategy Nash equilibrium if $A' > B'_1$ and $A' > B'_2$.

where $p_{max} = \operatorname{argmax}_{p \in [0, \alpha_1]} p_i \left(l_i + n \frac{\alpha_1 - p_i}{\alpha_1 m} \right)$, $A' = n \frac{\alpha_1 - p}{\alpha_1} p_{max}$ and $B'_i = (\alpha_2 - p_{max})l_i$ for $i = 1, 2$;

(iii) the above results for G_1 and G_2 can be generalized for an arbitrary number of players and a wide range of plausible demand functions.

The main result of Thesis 1.2 is that if the loyal part of an ISP's user base is large and has a high enough reserve price, the ISP does not have to engage in a price war for getting other users. Rather, the ISP is interested in pushing the price to the limit. Note that this holds regardless of being in a developing or an advanced country. Also note that independent studies researching user loyalty in the ISP sector revealed [12] that ISPs with the most loyal users have the highest profits, thus every ISP is interested in building a large loyal user base.

One can observe how user behavior impacts the pricing decisions of ISPs selling Internet access *implicitly*. Next, I propose a novel pricing mechanism, which enables the user to affect pricing policies *explicitly*.

Thesis 1.3 (UIP: a user-influenced pricing mechanism for Internet access). *I have proposed UIP, a novel, user-influenced pricing scheme for Internet access providers, which enables providers to plan their revenues and users to affect pricing policy.*

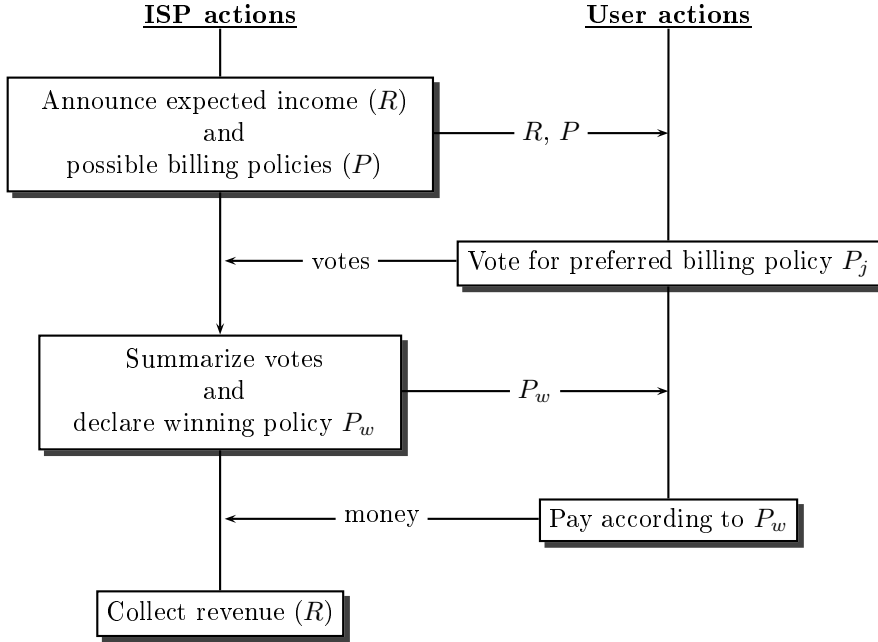


Figure 2: User-Influenced Pricing mechanism (UIP)

Furthermore, I have proposed a model of the UIP pricing mechanism as a three-player, cooperative, majority voting game with quarreling. I have derived the characteristic function, the equilibrium solutions of the game (as ψ -stable pairs) and expected costs for different user groups for all possible user regimes.

The User-Influenced Pricing mechanism (UIP) is depicted in Figure 2. As a first step, the ISP has to set a goal for the next billing cycle (e.g., one month), how much revenue R it wants to collect. Second, the ISP announces R to its users along with the possible billing options (flat-rate and usage-based schemes are considered in this work). Then users vote for the billing scheme they like. We assume that voting is mandatory, non-voting users are punished to pay according to the pricing scheme that is worse for them (e.g., usage-based for non-voting heavy users). The ISP summarizes the votes and announces the chosen pricing scheme for the upcoming billing cycle. During the vote, users can motivate other users to vote with them. We assume that users can utilize financial incentives (side-payments) to sweeten the deal for others, while still profiting from the outcome of the vote. Third, users use their subscription and pay according to the implemented pricing scheme chosen by the user community.

The idea behind the game-theoretical model is the following: users can be split into groups based on their preferred billing policy. This preference is closely related to their monthly traffic demand. Heavy users (file sharing, multiplayer online games, video streaming) want flat-rate fees, while light users (web browsing, e-mail) would prefer usage-based pricing. And there are the medium users, who occasionally download a movie or two, watch some YouTube videos and use social networking sites. They are close to indifferent between choosing flat-rate or usage-based pricing. These three user groups are modeled as three players (Player 1: heavy, Player 2: medium, Player 3: light users) [13].

Table 1: ψ -stable pairs in the balanced regime

Side-payment parameters	Core solution	Coalitional structure
$0 < s_3^{\max} < s_1^{\max}$	$(s_1^{\max} - s_1, s_1, 0)$	$(\{12\}, \{3\})$
$0 < s_3^{\max} = s_1^{\max}$	$(0, s_1^{\max}, 0)$	$(\{12\}, \{3\})$ or $(\{1\}, \{23\})$
$0 < s_1^{\max} < s_3^{\max}$	$(0, s_3, s_3^{\max} - s_3)$	$(\{1\}, \{23\})$

In a balanced regime, where neither heavy nor light users have absolute majority, the game will be decided by side-payments: which group can provide better incentives to medium users to vote along with them. The upper bound of a sensible side-payment is the expected profit coming from the preferred billing scheme over the other one. The solution of the user-influenced pricing game is given as ψ -stable pairs in Table 1. Note that the ψ -stable concept does not restrict the possibilities. In the first row of the table heavy users win (flat-rate pricing is chosen), but a side-payment of at least the maximum sensible payment of the light users (s_3^{\max}) has to be paid. According to the third row, light users win by paying at least the maximum sensible payment of the heavy users (s_1^{\max}) to medium users. If the maximum side-payments are equal, the outcome is indeterminate.

Thesis 1.4 (Distribution of power). *I have derived the distribution of power in the voting game (as modified Shapley values) for all possible user regimes. Specifically, I have shown that users with medium traffic demand are pivotal in the outcome, in the case of a balanced user regime.*

As heavy and light users would never vote together (they would not be in the same coalition), a *modified Shapley value* incorporating quarreling has to be utilized [14]. This modified value represents an expected distribution of side-payments (x_1, x_2, x_3) in the game, when the players arrive in random fashion to join coalitions, and receive their marginal worth to the coalition. The modified Shapley value employs the constraint of a quarreler not joining a coalition where another quarreler is already present: then he receives no payoff. Formally for Player j :

$$\phi_j^*[Q, \nu] = \sum_{S \cap Q = j} \gamma(n, s) V_j(S) + \frac{q-1}{q} \nu(j), \quad j \in Q \quad (6)$$

and

$$\phi_j^*[Q, \nu] = \sum_{S \cap Q = \emptyset} \gamma(n, s) V_j(S) + \sum_{|S \cap Q|=1} \frac{\gamma(n-q, s-1) - \gamma(n, s-1)}{q} V_j(S), \quad j \notin Q \quad (7)$$

where Q is the set of quarrelers and $q = |Q|$.

In the balanced regime the power is shared with a modified Shapley value of $(\frac{s_1^{\max}}{6}, \frac{s_1^{\max} + s_3^{\max}}{3}, \frac{s_3^{\max}}{6})$. Note that for $s_1^{\max} > s_3^{\max}$ heavy users have more power than light users, and for $s_3^{\max} > s_1^{\max}$ the opposite is true. Most importantly, irrespective of the maximum offered side-payments, Player 2 is the most powerful since he is a *pivotal* player. His power grows twice as fast as the other players if side-payments begin to grow.

Remark (Usefulness of the results). *Although highly theoretical results are presented in Theses 1, they could also have practical impact. Theses 1.1 and 1.2, together with the simulation study and the discussion on service bundling presented in [J2], can serve as a predictive loyalty sensitivity report for large ISPs. As such, it can be an important input for the complex pricing decision process of the ISPs. Furthermore, these results could encourage researchers to further study user behavior and incorporate more realistic user models in their work. Theses 1.3 to 1.4 propose and analyze a user-influenced pricing scheme for real application by service providers. Naturally, a number of questions regarding its actual implementation arise; a number of these questions are discussed in [C5].*

Theses 2: Incentives for Wireless Community Networks [J1] [C3]

In these theses, I have proposed a game-theoretic model for global wireless community networks. This model incorporates users, ISPs and community network providers, therefore describes community networks fully. I have analyzed the different levels of the model and shown how an effective incentive scheme can ensure participation from both users and ISPs. I have also investigated the temporal evolution of user participation and shown that a steady technology diffusion is likely in realistic scenarios.

Definition 2.1 (A Stackelberg game model for global wireless community networks). I have proposed a novel model of the economic interactions in global wireless communities as a Stackelberg (leader-follower) game. Specifically, I have constructed the game hierarchy, the respective payoff functions, and introduced technology penetration.

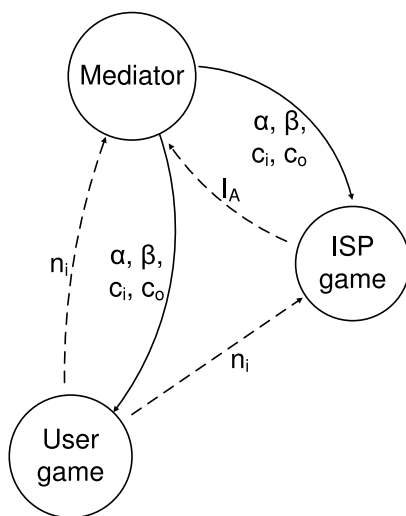


Figure 3: Representation of the Stackelberg model

In this model, the *mediator* (community provider) operates as the leader of the leader-follower game. At the first stage, the mediator decides on cost parameters and the distribution of income among the other participants (followers), i.e., ISPs and users. At the second stage, Internet Service Providers (ISPs) play a one-shot game, then in the last stage Internet subscribers (users) play a game among themselves (we consider both a one-shot and an evolutionary model for the users' game in our analysis).

Deriving the subgame-perfect equilibrium of this extended game setting leads to an optimal design. The leader (mediator) opts for the strategy with which the second stage's (ISPs) reactions (in the view of the third stage's expected decision) and then the best response of the users leads to the highest possible payoff. This line of thoughts holds for each stage, as the definition of sub-game perfection states. The game-theoretic model is illustrated in Figure 3 with the anticipated strategies of lower stages to be taken into account. Note, that in the second and third stages the strategy choices are not made by individuals, but embedded games of multiple players on each. Please refer to Table 2 for notations.

Definition 2.2 (One-shot game for user participation, G_u). The user participation game G_u is constructed as follows:

n	number of users/subscribers
n_i	number of insiders
n_o	number of outsiders
s	strategy
π	payoff
u	roaming utility of a user
c_i	insider entry cost
c_o	outsider roaming cost
c_s	Internet subscription cost
c_t	ISP traffic cost due to roaming alien users
c_a	ISP adoption cost
c_m	mediator operational cost
G	user roaming activity
T	community penetration
S_j	share of income of the j -th insider
α	insider's share of roaming income
β	ISP's share of the roaming income
I_a	indicator of adopter ISP

Table 2: Notations

- Players: the n users in the system;
- Strategies: s_i become a community member (insider) or s_o : not to become a community member(outsider);
- Payoffs:

$$\pi_u(s_o) = GT(u - c_o) - c_s; \quad (8)$$

$$\pi_u(s_i^j) = GT(u + S_j n_o c_o \alpha) - c_i - c_s. \quad (9)$$

Note, that $S_j \in [0..1]$ denotes the share of income of the j -th insider from the roaming outsiders' contributions. Two different settings of this parameter is investigated; a homogeneous case, where the income from the outsiders' roaming costs is shared evenly between the insiders, and a heterogeneous case, where the income is shared as a function of the geographic relevance of the insiders' home locations.

Thesis 2.1 (Equilibrium analysis of user participation as a one-shot game). *I have derived the equilibrium properties of G_u . Specifically, I have shown the following:*

(i) Let

$$Gc_o T n_i \left[\alpha \frac{n}{n_i} - \alpha + 1 \right] > c_i. \quad (10)$$

Then G_u with homogeneous payments can result in the following stable outcomes:

- Every user playing the insider strategy is a pure strategy Nash equilibrium, if (10) has at most one real root or it has two real roots $n_{i_1}^*, n_{i_2}^*$ in increasing order, but $n_{i_1}^* > n$.
- Every user playing the mixed strategy $P(\text{insider}) = \frac{n_{i_1}^*}{n}$ and $P(\text{outsider}) = 1 - P(\text{insider})$ is a mixed strategy Nash equilibrium, if (10) has two real roots and $n_{i_1}^* \leq n$ ($n_{i_1}^* > 0$ always holds).

- (c) There are at least two Nash equilibria at $n_i = n_{i_1}^*$ (mixed, see previous) and $n_i = n$ (pure, every user is insider), if both real roots exist and $n_{i_2}^* < n$.
- (ii) Consider G_u with homogeneous payments. If user home relevances can be described by a Pareto distribution with an exponent less than $\frac{1}{1-\alpha}$, then if a Nash equilibrium, where users with the highest relevance constitute the team of insiders, exists, then full penetration cannot be achieved.
- (iii) Let

$$GTn_i \left(u + \frac{R_{n_i}}{T_{n_i}} c_o \left(\frac{n}{\Delta n_i} - \frac{n_i}{\Delta n_i} \right) \alpha \right) - GT_{n_i - \Delta n_i} (u - c_o) > c_i. \quad (11)$$

Then G_u with heterogeneous payments can result in the following stable outcomes:

- (a) Every user playing the insider strategy is a pure strategy Nash equilibrium, if (11) has at most one real root or it has two real roots $n_{i_1}^*, n_{i_2}^*$ in increasing order, but $n_{i_1}^* > n$.
- (b) Every user playing the mixed strategy $P(\text{insider}) = \frac{n_{i_1}^*}{n}$ and $P(\text{outsider}) = 1 - P(\text{insider})$ is a mixed strategy Nash equilibrium, if (11) has two real roots and $n_{i_1}^* \leq n$ ($n_{i_1}^* > 0$ always holds).
- (c) There are at least two Nash equilibria at $n_i = n_{i_1}^*$ (mixed, see previous) and $n_i = n$ (pure, every user is insider), if both real roots exist and $n_{i_2}^* < n$.

The first statement shows an important characteristic of the system: under certain circumstances an equilibrium state may stall the growing insider population. This phenomenon hinders technology diffusion and it can impact future payoffs in a negative way. Dynamically tuning parameters during the different life cycles of the system may alleviate the problem; this is an interesting topic for future work.

The second statement has important consequences regarding economically feasible game scenarios. The equilibrium state, when all users join the community is clearly not favorable, since in this setting all income from roaming vanishes. In case of heavy-tailed user relevance distributions the game naturally transforms into a scenario, where the all-insider equilibrium cannot be present in the system. The heavy-tailed relevance distribution also ensures that there is a relatively large number of insiders even when considering lower α values.

The impact of the payment structure on the users' willingness to join the community can be seen in Figure 4. While equal incomes motivate more users to join (even users at low-relevance locations), a heterogeneous revenue structure allows high-relevance users to generate higher profits. Here lies a management possibility for the mediator: whether she wants to share the wealth evenly in the community, or to provide incentives for highly relevant users to join and thus facilitate the quick diffusion of the technology.

Thesis 2.2 (Equilibrium analysis of user participation as an evolutionary game). *I have derived the stable strategies (ESS) of the evolutionary extension of G_u . Specifically, I have shown that the ESS is exactly one of the Nash equilibria of the original G_u .*

The relation between $c_o G$ and c_i always determines the ESS. If $c_o G > c_i$, then the “trivial”, full participation is the ESS. On the other hand, if $c_o G < c_i$, the non-trivial, mixed strategy equilibrium is the ESS. This state provides a healthy balance for the system: participation is high, but there are also outsiders, who pay for roaming. Note, that even if there are multiple Nash equilibria in the one-shot game model, only one of them is evolutionarily stable.

Definition 2.3 (One-shot game for ISP participation, G_i). The ISP participation game G_i is constructed as follows:

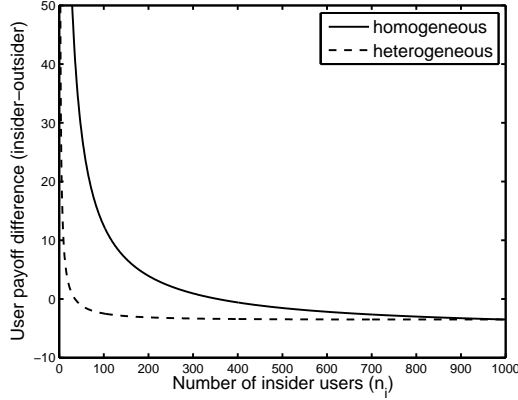


Figure 4: Expected revenue for users: heterogeneous vs. homogeneous payment structure (all other parameters fixed)

- Players: the ISPs in the system (for analytical tractability 2 ISPs are assumed);
- Strategies: A adopt and allow connection sharing for users or D : defect and disallow connection sharing;
- Payoffs: see Table 3. Payoffs are symmetric.

	A^2	D^2
A^1	$\frac{n}{2}c_s + GT\frac{n_o}{2}c_o\beta - GT\frac{n}{2}c_t - c_a$	$\frac{n+n_t}{2}c_s + GTn_o c_o\beta - GTnc_t - c_a$; $\frac{n_o}{2}c_s$
D^1	$\frac{n_o}{2}c_s$	$\frac{n}{2}c_s - GT\frac{n}{2}c_t$

Table 3: Simplified payoff matrix for the ISP game

Thesis 2.3 (Equilibrium analysis of ISP participation as a one-shot game). *I have derived the Nash equilibria of the game G_i , and shown how the mediator decides the outcome by setting parameters accordingly. Specifically (let $K = \frac{nGTc_t + c_a - n_i c_s}{n_o GT}$):*

- if $c_o\beta > K$, the strategy profile (A,A) is a pure-strategy Nash equilibrium.
- if $c_o\beta < K$, The strategy profile (D,D) is a pure-strategy Nash equilibrium.

The effect of revenue share β on ISP payoffs can be seen in Figure 5. The gap between (A,A) and (D,D) payoffs increases with β : a higher revenue share makes supporting the global wireless village concept more favorable for ISPs. On the other hand, there is an intersection of (A,A) , (A,D) and (D,A) in both cases: it points out the number of insiders that satisfies $c_o\beta = K$. To the left of this point it is better to defect, on the contrary, to the right of this point it is better to adopt. This is further supported by the changing relation between $\pi_{(D,A)}$ and $\pi_{(A,D)}$. Note how this point moves to the left with a higher β value.

Thesis 2.4 (Numerical solution of the Stackelberg game). *I have formulated the parameter setting decision of the mediator as a classic optimization problem. I have derived numerical results for different parameter settings, and shown how different objective functions (greedy vs. social welfare maximizing) results in different payoffs for the mediator.*

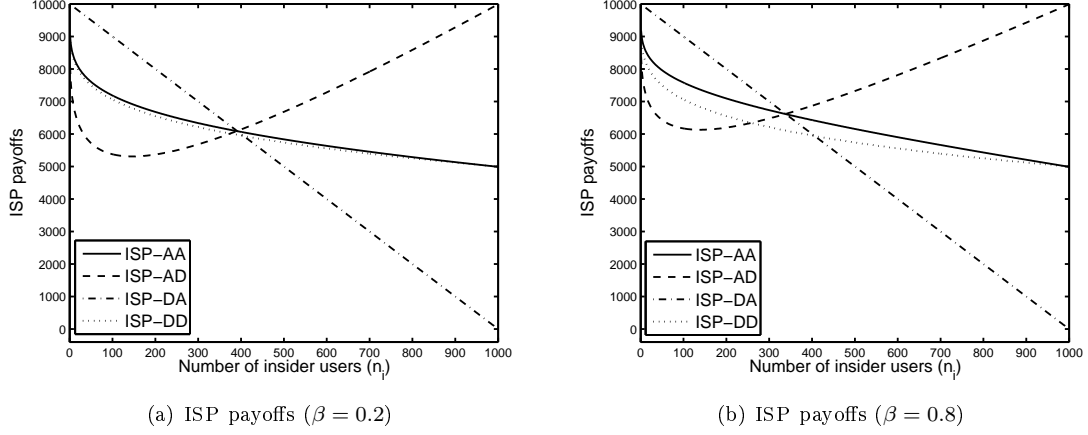


Figure 5: Expected revenue for ISPs: low and high revenue shares (β)

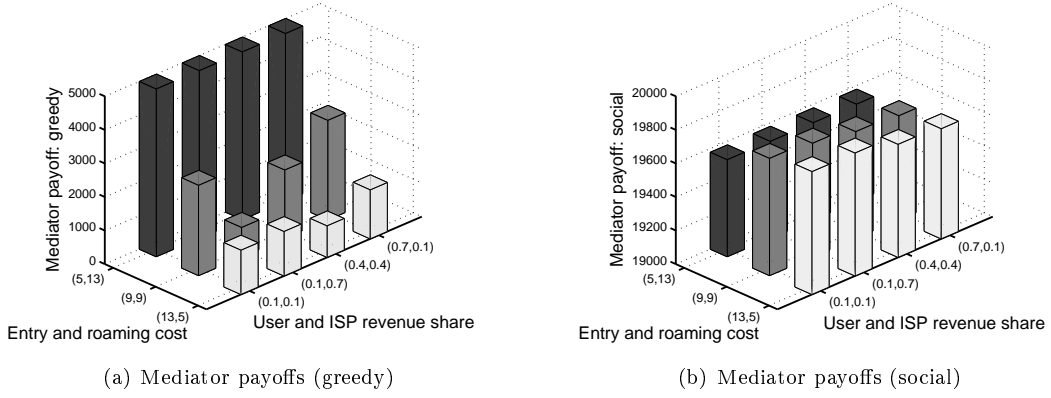


Figure 6: Mediator payoffs: greedy vs. social welfare (x axis: revenue shares (α, β) , y axis: cost parameters (c_i, c_o))

By consciously implementing a given parameter set, the mediator can achieve different goals, e.g., she can maximize her own profit, aim for the maximum utility of insiders, side with the ISPs or target social welfare. In the greedy scenario the objective function to be maximized is:

$$\pi_m^g = GTn_o^*(\alpha, \beta, c_o, c_i)c_o(1 - \alpha - \beta T_a^*(\alpha, \beta, c_o, c_i)) - c_m + n_i^*(\alpha, \beta, c_o, c_i)c_i. \quad (12)$$

On the other hand, when the mediator wants to maximize social welfare, she has to consider all parties: insider and outsider users, adopter and defector ISPs, and herself. Formally:

$$\pi_m^s = \pi_m^g + \sum_{j=1}^{n_i^*} \pi_u^j(s_i) + n_o^* \pi_u(s_o) + n_a^* \pi_a + n_d^* \pi_d \quad (13)$$

where n_a^* is the number of adopter and n_d^* is the number of defector ISPs in equilibrium. In either case, the optimization problem (which is essentially a one-player game, hence the notation s_m)

becomes:

$$s_m = \operatorname{argmax}_{c_o, c_i, \alpha, \beta} \pi_m(c_o, c_i, \alpha, \beta). \quad (14)$$

The solution method for Stackelberg games is *backward induction*. In this case, backward induction is not analytically tractable, therefore a numerical approach is used. Results can be seen in Figure 6. In the greedy case, the mediator achieves the highest profit when $c_i < c_oG$; then every user is an insider. In the social case, community welfare is the highest when user income share α is low and roaming cost c_o is equal or greater than entry cost c_i . Note, how the all-insider scenario (where $(c_i, c_o) = (5, 13)$) is inefficient in this case.

Note, that we used the evolutionarily stable strategy setting for the user game.

Thesis 2.5 (Data-driven simulations: temporal evolution of user participation). *I have proposed a data-driven, evolutionary simulation model (based on statistics from an existing wireless community and population density data) and evaluated the evolution of the user population. Specifically:*

- (i) *I have proposed a novel mobility model for wireless community networks.*
- (ii) *I have shown that the diversity of users' geographic relevances enables technology adoption, independently from the number of initial insiders in the system.*
- (iii) *I have shown that adequately selected cost and revenue share parameters can ensure successful technology diffusion. A steady growth in technology penetration is expected even at relatively high entry costs.*

In Figure 7 the temporal evolution of the insider population can be seen. Note, how diverse geographic relevances bootstrap the system, even in the zero and low initial penetration scenarios. If relevances are homogeneous, then there are no high-relevance users (hubs, in a sense) who can facilitate technology diffusion. Simulation results also indicate that with a good combination of revenue share α , entry cost c_i and roaming cost c_o , technology adoption progresses steadily.

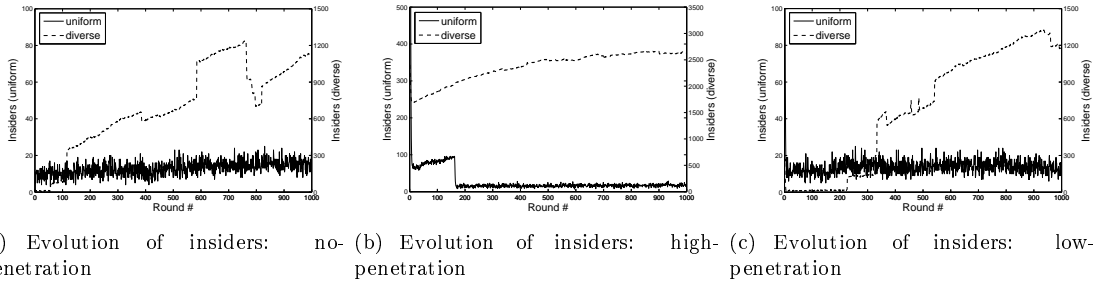


Figure 7: Temporal evolution of the user population under different initial conditions ($u = 4, c_o = 3, c_i = 3, \alpha = 0.5, \mu = 0.001$)

Theses 3: Congestion Control in Dynamic Mobile Environments [C4] [C7] [S1] [S2] [T3]

There are a number of proposed high-speed TCP variants designed for large bandwidth delay product (BDP) networks. While all of these show significant advantages over TCP Reno, they reach full utilization slowly at drastic, sudden capacity increases (referred to as up-switches).

In these theses I have investigated the performance of existing, high-speed TCP variants in dynamic mobile environments through testbed measurements. I have found that none of the TCP variants performed adequately during both sudden capacity increase and decrease. Thus, I have proposed SpeedDetect, a novel TCP extension built on top of any loss-based TCP protocol, which effectively handles sudden capacity increase. Moreover, through both measurements and simulations, I have shown that SD handles capacity fluctuations of different magnitude in an efficient manner without suppressing standard TCP background traffic.

Definition 3.1 (Handover model). The data path consists of the TCP sender, the emulation node, and the receiver, with a single bottleneck queue at the emulation node. At handover time, capacity of the link following the emulation node is changed to zero for some period (interruption time) to account for physical link outage. During this period no transmissions are made by the emulation node, but end hosts are not notified of the event. In particular, the TCP sender is continuing to fill up the bottleneck queue with more data packets (as long as it keeps receiving upstream ACKs already on their way from the emulation node). After the interruption time has passed, link capacity is reset, thus resuming transmission along the whole path. In the case when link characteristics are different before and after the handover—inter-system handovers—all other link characteristics (delay, delay variation, packet loss ratio, buffer sizes etc.) are also changed at this point.

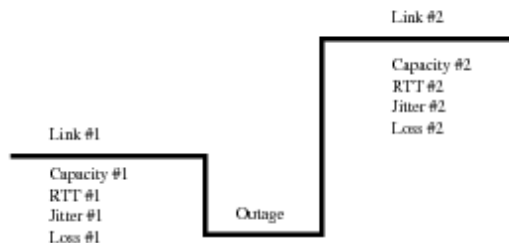


Figure 8: Handover model

The handover model is illustrated in Figure 8. Certainly, this model does not capture every aspect of a handover, but I believe, from the capacity point of view, it models reality adequately.

Note that serious capacity changes can occur even when no handovers are involved. Technologies that implement the shared channel concept (WLAN, HSPA, 3GPP-LTE, WiMax etc.) are primary candidates for such events. Capacity changes are mainly caused by population changes in a cell because of mobility, and radio link quality change due to interference and fading effects. One could imagine an extreme situation of a user with an active TCP session moving from an empty cell into a densely populated one. In this case this user's TCP session can experience a serious capacity drop. Results presented below stand in the case of sudden capacity changes caused by any event (handover, user mobility, flow dynamics).

Thesis 3.1 (Limitations of current TCP versions in case of sudden capacity change). *Under the assumptions of Definition 3.1*

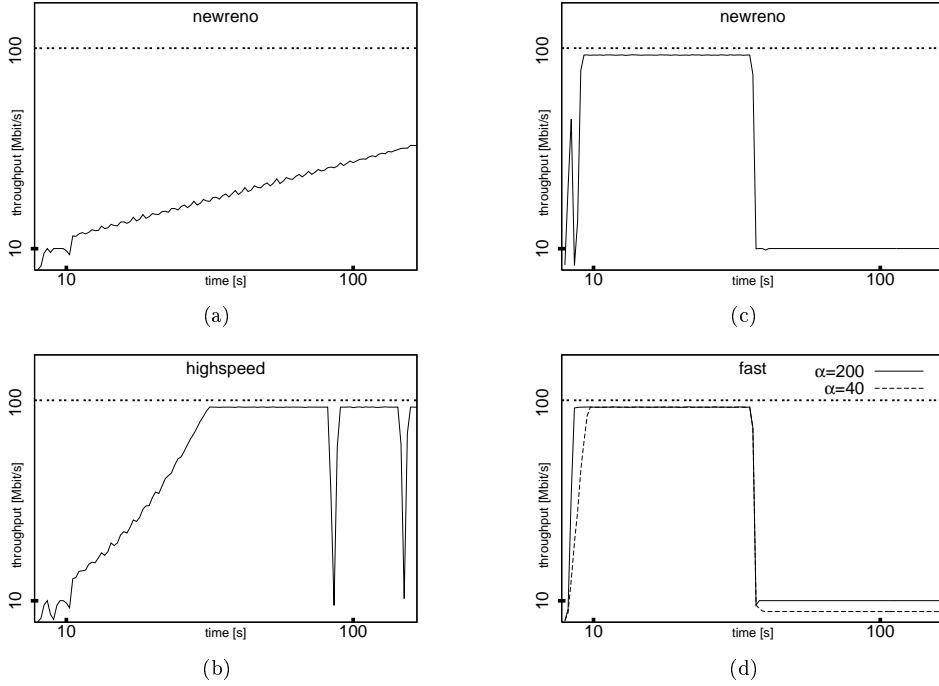


Figure 9: Throughput of various TCP variants during inter-system handovers

- (i) I have shown by testbed measurements that major loss-based TCP versions in use namely NewReno, BIC, HighSpeed and Scalable perform poorly after a sudden capacity increase;
- (ii) I have derived a lower bound for the parameter α of FAST TCP that has to be met to utilize the link fully after a handover.

$$\alpha \geq (T'_0 - T_0)\mu' \quad (15)$$

where T_0 is the minimum RTT measured before the handover, T'_0 is the minimum RTT measured after the handover and μ' is the bandwidth of the link after the handover. I have also shown by testbed measurements that FAST severely underutilizes the link after a sudden capacity decrease if the above lower bound is not met.

Figure 9(a) and 9(b) show the evolution of throughput after an inter-system up-switch for TCP NewReno and HighSpeed TCP respectively. Note, that the elapsed time from the handover event until TCP fully utilizes the new link is in the 40 second range even for the more aggressive HighSpeed TCP.

In Figure 9(c) and 9(d) it can be seen that while TCP NewReno has no problem utilizing the new, scarcer bandwidth of the link after the inter-system down-switch, FAST can struggle depending on its parameter settings. Note, that Thesis 3.1 gives a lower bound for α which is only dependent on link characteristics.

Thesis 3.2 (The SpeedDetect algorithm). *I have proposed SpeedDetect, a novel non-congestion detection algorithm, which can be built on any TCP version (which measures round-trip times) enabling swift adaption to increased capacity.*

Furthermore, I have proposed a method to calculate the effective setting of the trigger-on parameter p_1 depending on the network environment for SpeedDetect implemented on top of standard (NewReno) TCP.

Algorithm 1: SpeedDetect – detection

Input:
Output:
while there is data to send **do**
 if $srtt = 0$ **then**
 └ longtermsmooth $\leftarrow mrtt \cdot 2^{1024}$;
 else
 └ longtermsmooth $\leftarrow \frac{1023}{1024} \cdot \text{longtermsmooth} + \frac{1}{1024} \cdot mrtt$;
 if trigger is off and $\frac{srtt}{\text{longtermsmooth}} \leq p_1$ **then**
 └ trigger \leftarrow on;
 └ minsrtt \leftarrow srtt;
 if trigger is on **then**
 if $srtt < \text{minsrtt}$ **then**
 └ minsrtt \leftarrow srtt;
 if $\frac{srtt}{\text{minsrtt}} \geq p_2$ **then**
 └ trigger \leftarrow off;
 └ longtermsmooth \leftarrow srtt;

Algorithm 2: SpeedDetect – reaction

Input: trigger is on
Output:
if AIMD TCP **then**
 └ **if** cwnd was increased by 1 **then**
 └ cwnd \leftarrow cwnd + MAXINCREMENT - 1;
else if BIC TCP **then**
 └ enter regime “max_increment”;

The basic concept of the SpeedDetect algorithm is to detect the sudden decrease of RTT, and trigger the congestion control to probe for increased capacity at the next sending event. Detection is done by comparing the actual RTT estimate to a long term average: a trigger is raised if the estimate is significantly less than the average RTT. On trigger, congestion control is switched to its most aggressive phase to increase the rate of the offered load, until the RTT estimate starts to grow again. The growth of the estimate signals that the bottleneck buffer is building up, at which point the trigger is turned off.

The algorithm is an extension applicable to already existing TCP variants (called base version in the following), and consists of two parts, *detection* and *reaction*, both of which are executed during existing procedures of the TCP protocol stack. *Detection* is aimed at identifying time-intervals when the short-term RTT estimate is significantly lower than a long-term estimate, therefore its methods are appended to the base TCP’s RTT updating phase. *Reaction* is a conditional modification of the base TCP’s congestion window updating process, and it is executed only if the trigger set by

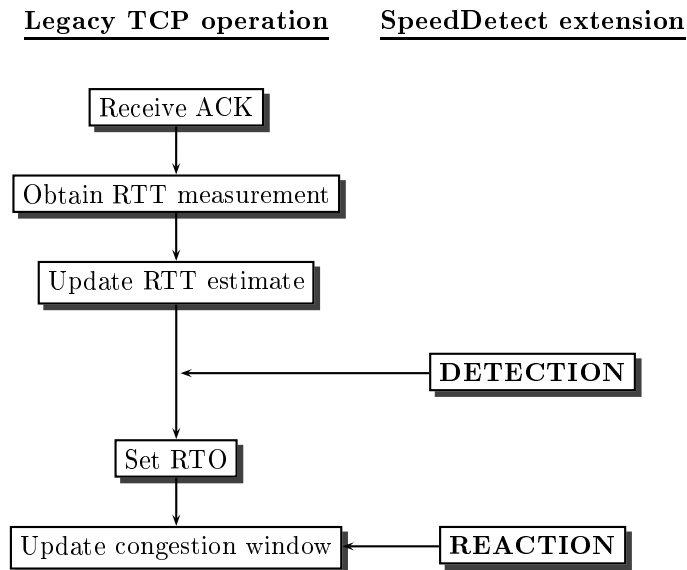


Figure 10: Block diagram of the proposed extension

detection is on. Note, that the actual implementation of *reaction* depends on the underlying base TCP version (AIMD vs. BIC, see Algorithmalg:sdr).

The sensitivity of the free capacity detection algorithm is controlled by the trigger-on parameter p_1 : the higher the value of the parameter, the smaller shift in RTT can be detected. (The mechanism triggers if the original srtt (s_n) and the newly introduced long-term average RTT (l_n) diverge significantly, i.e., $\frac{s_n}{l_n} \leq p_1$). Naturally, an oversensitive detection method would result in unnecessary positive triggers. On the other hand though, if we choose p_1 to be close to zero, SpeedDetect would miss significant capacity increases and even if it detects them the reaction time will be unsatisfactory. The proposed method builds on the measured RTT time series and the periodical sawtooth pattern of NewReno TCP.

Note, that for the testbed experiments presented in Thesis 3.1 and 3.3 link characteristics were set as follows: propagation RTT $T_p = 70\text{ms}$ and capacity before handover $C = 10\text{Mbit/s}$, which corresponds to $p_1 \approx 0.75$. Note that while this estimation is based on Reno’s behavior, we used the resulting parameter for BIC TCP in practice with success, as well.

It is important to mention that several parameters can affect the optimal setting of p_1 . These include the application of delayed ACKs resulting in a reduced number of RTT samples measured; the expected number of flows in the bottleneck router that influences the buffer size [34]; and of course link capacity. As for p_2 , the parameter responsible for deactivating the trigger, we found after exploring the parameter space that $p_2 = 1.125$ is sufficient for a wide range of scenarios.

Thesis 3.3 (Performance of SpeedDetect in the case of sudden capacity increase: testbed measurements). *Using the algorithm proposed in Thesis 3.2 as an extension for current TCP versions Reno and BIC in the case of a sudden capacity increase due to handovers, traffic volume changes or flow dynamics, I have shown by testbed measurements that*

- (i) *the extended versions RenoSD and BICSD outperform the base versions in terms of reaction*

time;

- (ii) the SD algorithm reacts faster than PNCD (Persistent Non-Congestion Detection, proposed as a part of TCP Westwood) and is more consistent in the detection of increased capacity.

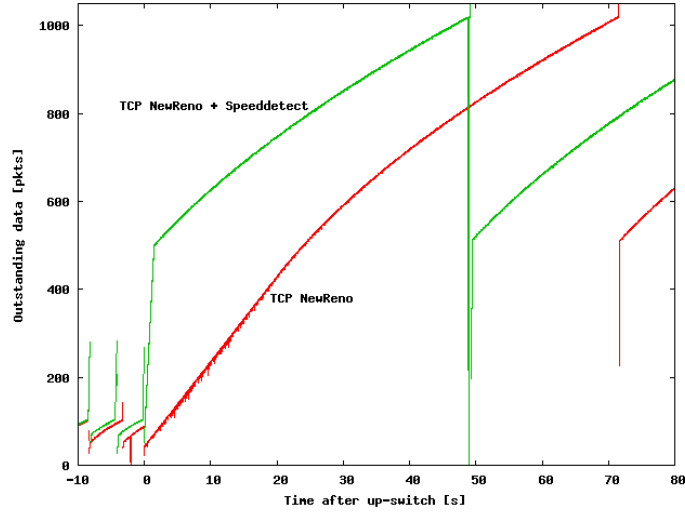


Figure 11: RenoSD reaction time after up-switch

The difference in reaction times for Reno and RenoSD (defined as the elapsed time between the handover event and reaching full utilization on the changed link) is illustrated in Figure 11. Distribution of detection times regarding increased capacity can be seen in Figure 12.

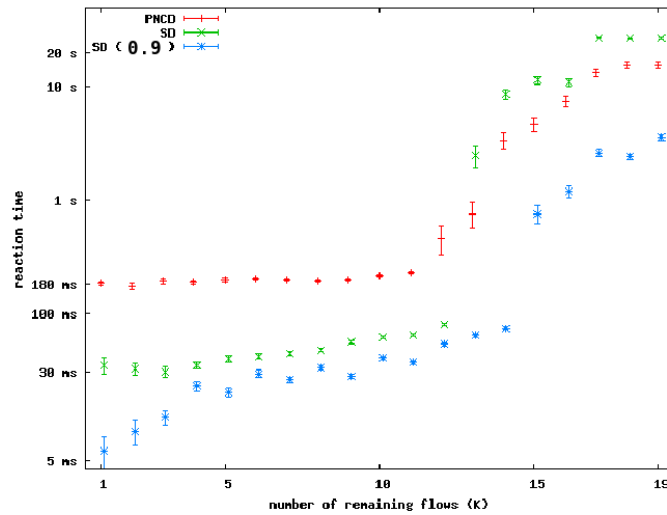


Figure 12: SD vs. PNCD: distribution of detection time

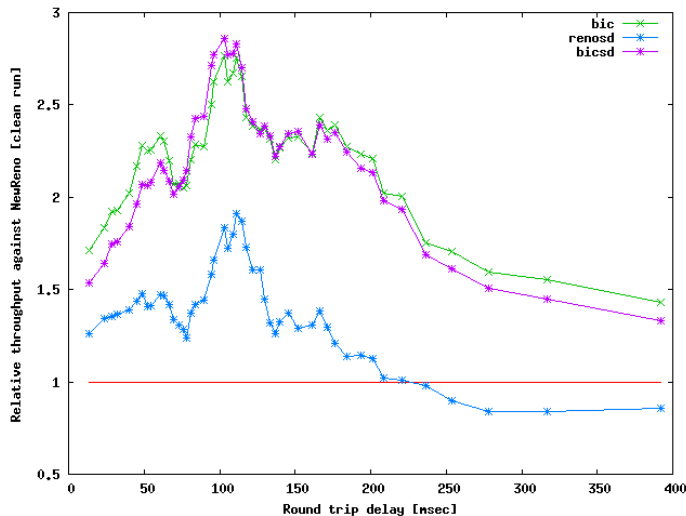


Figure 13: Average throughput relative to NewReno

Thesis 3.4 (Performance of SpeedDetect in the case of minor capacity fluctuations: simulations). *Using the algorithm proposed in Thesis 3.2 as an extension for current TCP versions Reno and BIC in the case of minor capacity fluctuations created by flow dynamics only, I have shown by ns-2 simulations that*

- (i) *RenoSD outperforms Reno in terms of average throughput in a wide range of scenarios, while BICSD conserves the performance of BIC.*
- (ii) *the intra-protocol fairness of the base TCP versions are conserved by the extended versions;*
- (iii) *RenoSD performs best in terms of inter-protocol fairness to Reno across all investigated TCP versions.*

Note, that no handovers occurred during simulations; the goal of these simulations were to check if SpeedDetect does not interfere with normal TCP operations, when capacity changes are minor and caused by flow dynamics only. Results show that both throughput (Figure 13) and intra-protocol fairness properties (Figure 14) of SpeedDetect-enabled TCP versions are better than or similar to the base versions. Furthermore, by using the exact same code, topology, traffic and fairness metric as in [35], it is shown that RenoSD is the most fair to standard TCP across all high-speed, modified versions, making it a viable candidate for real deployment.

5 Application of novel results

Results presented in Theses 1 prove that user loyalty is an important factor when pricing Internet access. This should open up the eyes of service providers and make them reward loyal customers with premium service instead of getting into price wars for new customers. The accompanying simulation study presented in [J2] can provide an input to the pricing strategy of Internet Service Providers. On the other hand, the user-influenced pricing scheme (see Thesis 1.3) is designed for actual use by ISPs. There are a number of practical questions concerning the implementation of the mechanism; please refer to [C5] for a detailed discussion.

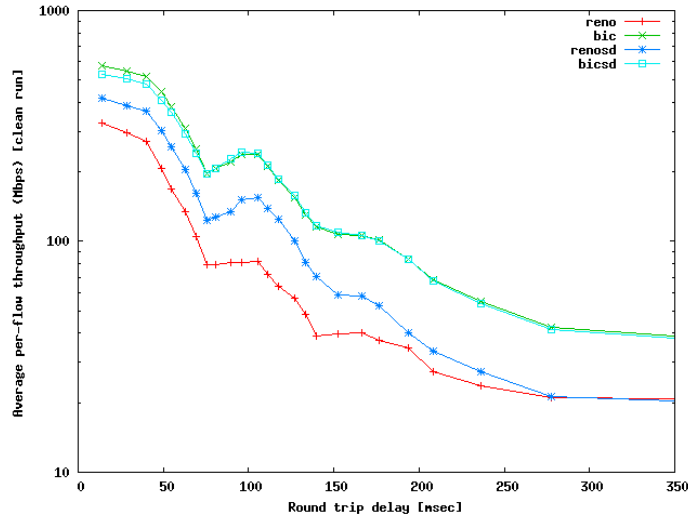


Figure 14: RTT fairness (as per-flow average throughput for flows with diff. RTTs)

The incentive framework proposed in Theses 2 can serve as a practical guideline for wireless community providers. It shows that indeed, there is a way to spread out the wireless community to a global level, while maintaining profitability for both users, ISPs and community providers. Furthermore, the data-driven simulations show steady technology diffusion in realistic scenarios. The most significant impact of this work could be convincing ISPs to allow connection sharing for their users; this is clearly not the case today. On a different note, these results can possibly spark further research dealing with the more technological problems of user-provided networking, such as trust, mobility management and opportunistic relaying.

The work presented in Theses 3 was carried out with applicability as a first order concern in mind. The design goals (simplicity, end-to-end operation, only server-side modification, implementability with integer arithmetic) were set to facilitate the creation of a life-proof, deployable SpeedDetect mechanism. A working (Linux) kernel-level implementation of the proposed TCP extension has resulted from the work. Furthermore, two international patent applications were filed as an outcome of this work (now published in the EU, and under revision in the US) [S1] [S2].

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Invited Talks

- [T1] **G. Biczók**. Monitoring Network Bias. Invited Talk, *FuturICT 2009: Hungarian-Japanese Joint Conference on Future Information and Communication Technologies*, Budapest, Hungary, June 2009.
- [T2] **G. Biczók**. FIND – a következő generációs Internet. Invited Talk, *IPv6 Workshop 2007*, in Hungarian, Magyar Telekom, Budapestm Hungary, May 2007.
- [T3] ***G. Biczók**. High-Speed Mobile Characteristics and TCP Performance. Invited Talk, *Evergrow Traffic Observatory Measurement InfrastruCture (ETOMIC) Workshop 2006*, Collegium Budapest, Budapest, Hungary, February 2006.

* Publications connected to theses.