NON-COOPERATIVE BEHAVIOR IN WIRELESS NETWORKS

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PAR

MÁRK FÉLEGYHÁZI

Ingenieur Electricien Diplomé (M.Sc.),
Budapest University of Technology and Economics, Budapest, Hongrie

de nationalité hongroise

acceptée sur proposition du jury:

Prof. Jean-Pierre Hubaux, directeur de thèse
Prof. Emre Telatar, president de jury
Prof. Karl Aberer, rapporteur
Prof. Peter Marbach, rapporteur
Prof. Jean Walrand, rapporteur

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Chapter 1

Border Games in Cellular Networks

1.1 Introduction

Today's cellular networks operate on separate frequency bands to avoid interference between them. The operators of these networks obtain an exclusive right to use a given frequency band in their respective country. However, the division based on frequency bands does not apply across national borders. The operators have to resolve their conflicts across the borders themselves. One of the issues is when mobile users of one operator attach to the network of the operator of the other country while still being in their own country. This problem is referred to as *accidental roaming* [INT06, Lee06]. Often, the operators make make mutual agreements to resolve these conflicts, but these agreements are difficult to enforce, because they require the mutual cooperation of the operators. The proper understanding of this special case is important for the future studies of the coexistence of cellular networks, because there exist many examples where cities reside close to a national border. One can find examples for the border scenario on each of the continents such as Geneva, Basel or Aachen in Europe; San Diego and Detroit in the USA; or Hongkong and Singapore in Asia.

In this chapter, we consider the problem of strategic behavior of operators on the border of their cellular networks. We consider the operators of 3G cellular networks, such as the *Universal Mobile Telecommunication System (UMTS)* for example, that are based on the *Code Division Multiple Access (CDMA)* technology [HT02, Rap02, Sch05]. Note however, that the problem we highlight in this chapter applies to any CDMA network. In these networks, the base stations emit pilot signals to help users to assess the available channel quality and to attach to the base station with the best offered quality. According to the current definition in the UMTS standard, the pilot power for the base stations is determined at the network dimensioning phase and remains fixed afterward. However, as the number of users changes, the operators may adjust the network parameters. This *slow adaptation* of the pilot signal power is part of the network re-dimensioning process and hence it exists on a large time scale. On the other hand, the technology enables the base stations to quickly adapt their pilot signals to the actual usage. This *fast adaptation* technique is commonly referred to as *cell breathing* [HT02, Rap02, Sch05].

In this work, we assume that the operators control the power of the pilot signal of their base stations to attract more users over time. Several methods (e.g., cell-breathing [Rap02, Sch05]) have been proposed to implement fast adaptation in CDMA networks. We survey them in Section 1.6. In our work, however, we focus on the slow adaptation problem. We study how the network operators can fine-tune their pilot power in the presence of other operators given a certain user distribution. We investigate whether this situation leads to a game and we study the properties of the equilibria of power control strategies.

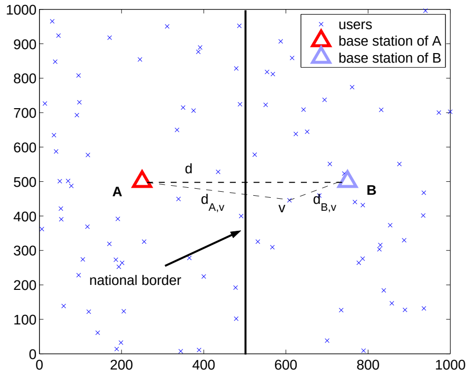

Figure 1.1: Network scenario with two base stations.

1.2 Model

1.2.1 System Model

We consider a scenario with two cellular network operators A and B. We assume that their networks are separated by a national *border*. The operators operate their network based on the principles of the CDMA method. We assume that the two operators acquired the same frequency band for their networks in their respective country. This means that their networks interfere along the border. We assume that each operator controls a set of *base stations (BS)* $\mathcal{B}_i$, where $i \in \{A, B\}$. We refer to the set of all base stations as $\mathcal{B} = \bigcup_i \mathcal{B}_i$. We also assume a set of *users* $\mathcal{M}$ equipped with *wireless devices* who access the communication network. For the sake of convenience, we assimilate the operators with their base stations and the users with their devices. In order to get an insight, we study the case in which each operator has one BS and we refer to the BSs by the letters of their operators (i.e., base station A and B). This single-cell model is often considered in the literature [Jak94, LZJH04]. The network scenario is shown in Figure 1.1.

We assume that the radios of the base stations and the mobile devices are compatible, meaning that any user is able to access the network via any of the base stations. We further assume that the antennas of the BSs and wireless devices are omnidirectional. Note that the results derived in this chapter are still valid if the operators use sectorized antennas that point towards the national border. Sectorized antennas have more impact in the general scenario, where the operators have several base stations each. The study of this general scenario is the main focus of our ongoing work.

Throughout this chapter, we assume that the users are not associated with any of the operators (i.e., they are roaming users) and thus they attach to the base station with the best signal quality.

In CDMA networks, power control is used to mitigate the near-far effect [Rap02], to optimize the transmission power of the devices and to reduce interference. In this chapter, we focus on the *downlink (or forward link) power control of the pilot signals* emitted by the base stations. The pilot signal helps the wireless devices to perform the following tasks:

- detection of the available base stations,
- synchronization with them and

- estimation of the channel quality and handover decision based on this estimation.

In particular, we focus on the problem of how the network operators can determine the pilot signal power that will potentially attract the highest number of users. We leave the study of the competitive fast adaptation problem as a future work.

In the remainder of this chapter, we present the physical model of CDMA. As mentioned earlier, the pilot signal is used to attract users. If several users attach to a given base station, their transmissions are performed on different *channels*. In CDMA-based cellular networks, unlike GSM networks, channels are not separated in different frequencies, but use different codes. Hence each transmission uses the same frequency band. In theory, the codes from one base station are orthogonal, meaning that the transmissions to different receivers do not interfere with each other. In practice, there exists some interference between concurrent transmissions from a given base station because of multipath propagation. This interference is called the *own-cell interference*. In addition, there is an interference caused by the transmissions of other base stations, called the *other-cell interference*.

Let us consider the scenario shown in Figure 1.1. According to the *physical model* of signal propagation in a CDMA system [TV05], we can write the *signal-to-interference-plus-noise ratio (SINR)* of the pilot signal of base station $i \in \mathcal{B}$ to user $v \in \mathcal{M}$ as:

$$\mathit{SINR}_{iv}^{pilot} = \frac{G_p^{pilot} \cdot P_i \cdot d_{iv}^{-\alpha}}{N_0 \cdot \mathbb{W} + I_{own}^{pilot} + I_{other}^{pilot}} \tag{1.1}$$

where $G_p^{pilot} = \frac{\mathbb{W}}{\mathbb{R}^{pilot}}$ is the *processing gain* for the pilot signal, $\mathbb{W}$ is the available bandwidth, $\mathbb{R}^{pilot}$ is the data rate of the pilot signal, P_i is the power of the transmitted pilot signal of BS i, d_{iv} is the distance between BS i and user v, α is the path loss exponent, N_0 is the noise spectral density, and I_{own}^{pilot} as well as I_{other}^{pilot} are the own-cell and the other-cell interferences that affect the pilot signal of BS i.

Let us first express the own-cell interference I_{own}^{pilot}:

$$I_{own}^{pilot} = \zeta \cdot d_{iv}^{-\alpha} \Big(\sum_{w \in \mathcal{M}_i} T_{iw} \Big) \tag{1.2}$$

where ζ is the *orthogonality factor* (also called the *own-cell interference factor*) that expresses the non-orthogonality between the different transmissions from BS i. Furthermore, $\mathcal{M}_i$ is the set of users at BS i and T_{iw} is the traffic power assigned to user $w \in \mathcal{M}_i$ by BS i.

Similarly, we can write the interference I_{other}^{pilot}:

$$I_{other}^{pilot} = \eta \cdot \sum_{j \neq i} d_{jv}^{-\alpha} \Big(P_j + \sum_{w \in \mathcal{M}_j} T_{jw} \Big) \tag{1.3}$$

where η is the *other-to-own-cell interference factor*, d_{jv} is the distance between BS j and user v. Furthermore P_j is the pilot signal power of BS j, whereas $\mathcal{M}_j$ is the set of users at BS j and T_{jw} is the traffic power assigned to user $w \in \mathcal{M}_j$ by BS j.

Similarly to (1.1), we can express the SINR for the traffic signal T_{iv}:

$$\mathit{SINR}_{iv}^{tr} = \frac{G_p^{tr} \cdot T_{iv} \cdot d_{iv}^{-\alpha}}{N_0 \cdot \mathbb{W} + I_{own}^{tr} + I_{other}^{tr}} \tag{1.4}$$

where $G_p^{tr} = \frac{\mathbb{W}}{\mathbb{R}^{tr}}$ is the *processing gain* for the traffic signal, $\mathbb{W}$ is the available bandwidth, $\mathbb{R}^{tr}$ is the data rate of the specific traffic signal, and I_{own}^{tr} as well as I_{other}^{tr} are the own-cell and the other-cell interferences that affect the traffic signal of BS i to user v.

Let us write the own-cell interference I^{tr}_{own} for the traffic signal as:

$$I^{tr}_{own} = \zeta \cdot d^{-\alpha}_{iv}(P_i + \sum_{w \neq v, w \in \mathcal{M}_i} T_{iw}) \tag{1.5}$$

and the interference from other BSs j as:

$$I^{tr}_{other} = I^{pilot}_{other} = \eta \cdot \sum_{j \neq i} d^{-\alpha}_{jv}(P_j + \sum_{w \in \mathcal{M}_j} T_{jw}) \tag{1.6}$$

Furthermore, we can express the *carrier-to-interference ratio (CIR)* as a function of SINR:

$$CIR^{pilot}_{iu} = \frac{SINR^{pilot}_{iv}}{G^{pilot}_{p}} \tag{1.7}$$

Similarly, we can write the CIR of the traffic signal:

$$CIR^{tr}_{iv} = \frac{SINR^{tr}_{iv}}{G^{tr}_{p}} \tag{1.8}$$

where G^{tr}_p is the processing gain for the traffic signal from BS i to user v.

In UMTS systems [HT02], the processing gain for the pilot signal is $G^{pilot}_p = 256 \approx 14.3$ dB and the available bandwidth (for the spread signal) is $\mathbb{W} = 3.84$ MHz. The processing gain of the traffic signal G^{tr}_p depends on the bitrate of the application running on the user device. In this work, we refer to different types of communication as the *traffic type*, namely audio ($\mathbb{R}^{tr} = 12.2$ kbps), video ($\mathbb{R}^{tr} = 144$ kbps) and data ($\mathbb{R}^{tr} = 384$ kbps) flows.[1] Accordingly, we distinguish different requirements for different traffic types as presented in [HT02]. We summarize these parameters in Table 1.1.

traffic type	required SINR	processing gain	required CIR
pilot	$\approx$ -6 dB	14.3 dB	-20 dB
audio, $\mathbb{R}^{tr} = 12.2$ kbps	5 dB	25 dB	-20 dB
video, $\mathbb{R}^{tr} = 144$ kbps	1.5 dB	14.3 dB	-12.8 dB
data, $\mathbb{R}^{tr} = 384$ kbps	1 dB	10 dB	-9 dB

Table 1.1: UMTS parameters [HT02].

In wireless networks, the authorities impose a transmission power limit to the devices. In UMTS networks, the base stations must emit their signal below 43 dBm = 20 W [HT02]. This limit is called the *downlink power budget*. In addition, this power budget must be split between the control channel signals, such as the pilot signal, and the traffic channel transmissions. The actual utilization of the power budget is called the *load* of the base station. As the load increases, the *bit-error-rate (BER)* at the user devices increases exponentially [HT02]. Hence, the BS load is typically kept such that the BER does not exceed a certain threshold, for example 10^{-3}. Here, we assume that the BS load is kept below 10 W.

In order to determine the average usage of the two networks, we developed a numerical simulator in MATLAB. We summarize the parameters of our simulation in Table 1.2. In each simulation run, we distribute the users according to the uniform distribution[2] and calculate the number of users that attach to each of the BSs based on the physical model developed in this section (i.e., using Equations (1.1)–(1.8) and the requirements shown in Table 1.1). We repeat this experiment several times for each power setting and we obtain the average number of users at each BS.

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[1] For simplicity, we consider only constant bitrate traffic.

[2] Note that we use a random uniform user distribution in our study, but our qualitative results hold for any user distribution.

Parameter	*Value*
simulation area size	1 km^2
BS positions	(250 m, 500 m) and (750 m, 500 m)
default distance between BSs, d	500 m
user distribution	random uniform
number of simulations	500
default path loss exponent, α	4
BS max power	43 dBm $=$ 20 W
BS max load	40 dBm $=$ 10 W
BS standard power, P^s	33 dBm $=$ 2 W
BS min power	20 dBm $=$ 0.1 W
power control step size, P_{step}	0.1 W
orthogonality factor, ζ	0.4
other-to-own-cell interference factor, η	0.4
user traffic types:	audio, $\mathbb{R}^{tr}$ $=$ 12.2 kbps video, $\mathbb{R}^{tr}$ $=$ 144 kbps data, $\mathbb{R}^{tr}$ $=$ 384 kbps
required CIR (audio, video, data):	-20 dB, -12.8 dB, -9 dB
expected incomes (θ_{audio}, θ_{video}, θ_{data}):	10, 20, 50 CHF/month

Table 1.2: Simulation parameters (based on [HT02]).

1.2.2 Power Control Game

We model competitive power control using game theory [FH06a, FT91, Gib92, OR94]. We define a two-player non-cooperative *power control game* **G** with the operators as *players*. In this game, the *strategies* of the operators determine the pilot transmission power of their base stations. Formally, we can write the strategy of operator i as the pilot signal power value of his BS:

$$s_i = P_i \tag{1.9}$$

where 0 W $< P_i <$ 10 W is the pilot signal power of BS i. According to the UMTS standard, the BSs transmit their pilot signal with approximately 33 dBm $=$ 2 W. We denote this standard pilot power by P^s. We call the set of strategies of all players a *strategy profile* $s = \{s_1, s_2\}$.[3] In our game, the players have the same strategy set S.

The operators define their strategies in order to maximize their *expected payoff* u_i:

$$u_i = \sum_{v \in \mathcal{M}_i} \theta_v \tag{1.10}$$

where θ_v is the *expected income* obtained by serving user v of a certain traffic type. Suppose that each user has the same traffic type, for example audio. Then the expected payoff obtained at BS i is:

$$u_i = |\mathcal{M}_i| \cdot \theta_{audio} \tag{1.11}$$

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[3] Note that one can easily extend the definitions in the power control game to several BSs and operators.

We further assume that the income[4] per user increases according to the data rate of the given service, thus $\theta_{audio} < \theta_{video} < \theta_{data}$. We obtain the expected income by performing several simulation runs with various pilot power settings as described in the previous section. This results in an *expected payoff matrix* for the two players. We apply the classic game-theoretic concepts on this payoff matrix. We express the payoffs of the players in *Swiss francs (CHF)* to emphasize the monetary advantage.

In order to get an insight into the strategic behavior of the operators, we apply the game-theoretic concepts of best response, Nash equilibrium and Pareto-optimality introduced in Sections **??** and **??**.

We present our results using a symmetric scenario of the base stations and assuming that the users are uniformly distributed in the simulation area. Note that the result qualitatively hold for and base station placement and any user distribution. Naturally, in these cases, the Nash equilibrium strategies and payoffs are going to by asymmetric.

1.3 Is There a Power Control Game?

In this section, we study the behavior of the operators in a single-stage game. We first assume that one of the operators does not play and show that the other operator has an incentive to be strategic.[5] Second, we consider the case in which both operators have the possibility to adjust their pilot power and show that they are better off by doing so. We obtain our simulation results using the simulation environment described in Section 1.2.1.

1.3.1 Only Operator A is Strategic

First, we consider the case where only operator A is strategic and adjusts the pilot power of his BS to attract more users, whereas operator B operates his BS according to the standard pilot power of $P^s = 2$ W. To quantify the advantage of the strategic player, we define the concept of *normalized payoff difference* Δ_i.

Definition 1.1. *The* normalized payoff difference Δ_i *is the normalized difference between the maximum payoff of player* i *and his payoff using the standard power* P^s *assuming that the other player* j *uses* P^s.

$$\Delta_i = \frac{\max_{s_i}(u_i(s_i, P^s)) - u_i(P^s, P^s)}{u_i(P^s, P^s)} \tag{1.12}$$

Suppose that there are on average 10 users of the data traffic type in the simulation area. We show the payoffs of players A and B as a function of the pilot signal power P_A as well as the sum of their payoffs in Figure 1.2. Figure 1.2a shows these payoffs for $\alpha = 2$, whereas Figure 1.2b presents the same results for $\alpha = 4$. We observe that in both cases the operators are able to serve all users in the area using certain power values. If all users are served, then the game is a zero-sum game. In the zero-sum game, if player A adjusts his pilot power and obtains the increase of Δ_A, he causes the decrease of Δ_A in the payoff of the non-strategic player B. Furthermore, the payoff function of operator A has a unique maximum point. It is interesting to observe that the maximum payoff point requires a higher pilot power than $P^s =$ 2 W. Because the two operators serve all the users in this case, the normalized payoff difference Δ_A of player A means the decrease of Δ_B in the payoff of the non-strategic player B. Hence, we conclude that operator A should be strategic and adjust his pilot signal. Note that we get qualitatively the same result for different user traffic types.

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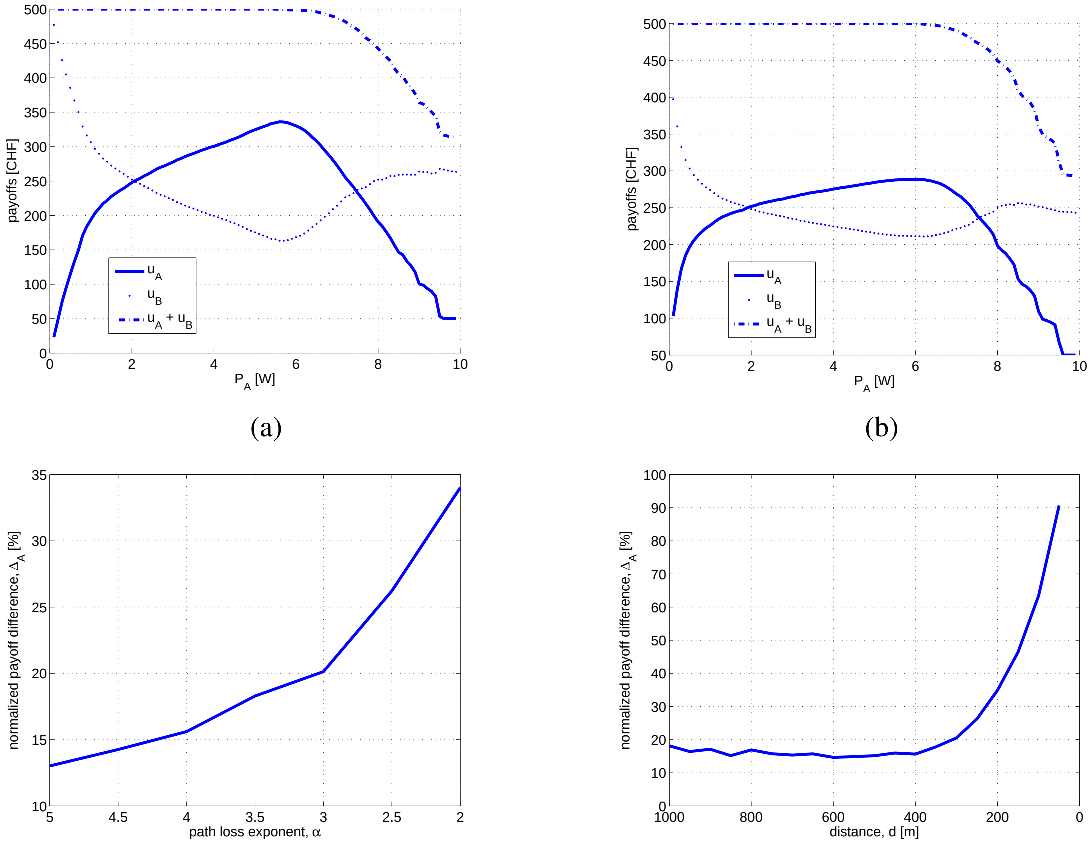
[4] Note that the income is defined by the total amount of downloaded data, which can vary according to the length of communication sessions. If we change these income values, our results only change quantitatively, but not qualitatively.

[5] Due to symmetry, we only show the results for player A.



(a) (b)

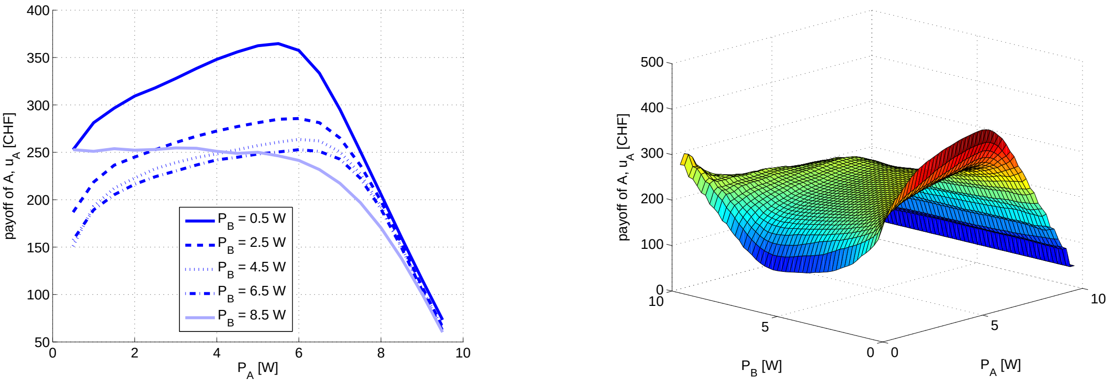
(c) (d)

Figure 1.2: Payoffs of the players as a function of the pilot power of player A for 10 data users: (a) for $\alpha = 2$ and (b) for $\alpha = 4$. We also show the normalized payoff difference Δ_A as a function of (c) the path loss exponent α and (d) the distance d between the two BSs.

Figures 1.2a and Figure 1.2b show that the value of the normalized payoff difference Δ_A depends on the parameter α. We show this dependency in Figure 1.2c. One can observe that Δ_A increase as α decreases. The reason is that by low α values the pilot signals propagate easier giving a higher benefit to A if he uses higher pilot power. The value of Δ_A also depends on the distance d between the two BSs as shown in Figure 1.2d. As the distance decreases, Δ_A increases exponentially. The reason for this increase is the same as discussed before. In the remainder of the chapter, we choose the conservative default values $\alpha = 4$ and $d = 500$ m for the simulations. We will show that even with these conservative values, the players have an incentive to fine-tune their pilot powers.

1.3.2 Both Operators are Strategic

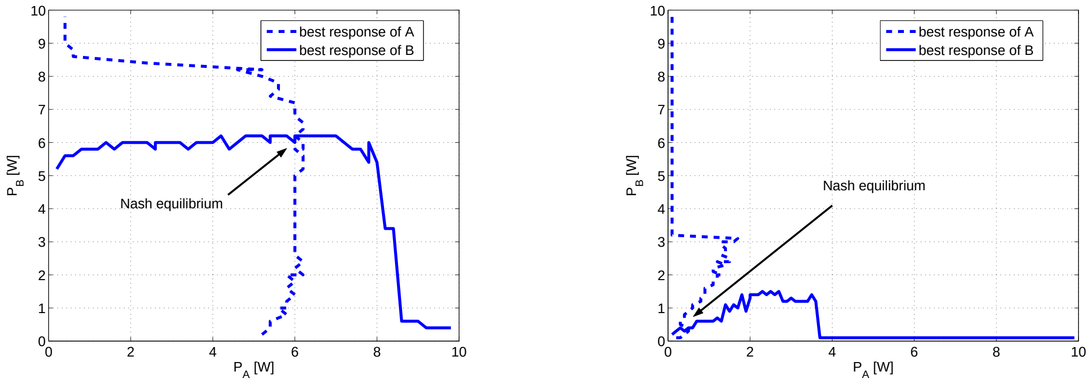
In the second set of simulations, we assume that both operators adjust their pilot power. We still consider 10 data users in the simulation area. We provide the payoff of player A as a function of his pilot power P_A in Figure 1.3a. We obtain different payoff curves as the pilot power of the other BS P_B increases.



(a) (b)

Figure 1.3: Payoff of player A as a function of his pilot power if there exist 10 data users. Both operators are strategic, hence we present this payoff for various values of P_B in (a). We show the complete payoff surface in (b).

We can observe that each of the payoff functions has a unique maximum point for P_A. Moreover, this maximum point depends on the pilot power of the other BS, P_B. For low values of P_B, the maximum payoff value decreases as P_B increases. In Figure 1.3b, we show the payoff surface for operator A as a function of the pilot power values of the two BSs.



(a) (b)

Figure 1.4: Best response functions for the two players with (a) 10 data users, (b) 100 data users.

Using the two payoff surfaces, we derive the best response functions (i.e., the set of maximum payoff points) for the operators as shown in Figure 1.4 for various user densities. Based on the concept of best responses introduced in Section 1.2.2, we can identify the Nash equilibria in the power control game as shown in Figures 1.4a for 10 data users and Figures 1.4b for 100 data users. We see that there exists a unique Nash equilibrium point defined as the crossing point of the two best response functions. Note that for 10 data users the Nash equilibrium strategy profile defines $P_A = P_B = 6$ W, which are higher than

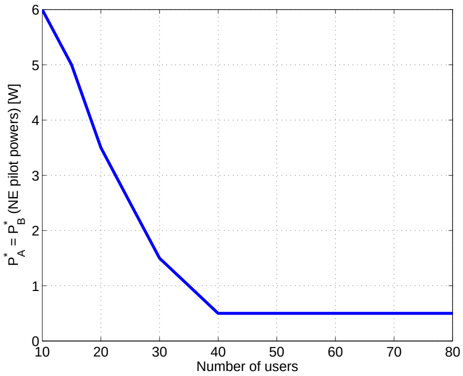


Figure 1.5: Nash equilibrium pilot power values as a function of the user density.

the standard pilot powers. For 100 data users the Nash equilibrium strategy profile defines $P_A = P_B =$ 0.5 W. The reason is that the capacities of BSs saturate by using a relatively small power and hence there is no reason for them to go above these pilot power values.

Next, we study the pilot power values in the Nash equilibrium as a function of the number of users. We show the results in Figure 1.5. Due to symmetry in the user distributions, the Nash equilibrium pilot power is the same for both players. We observe that the Nash equilibrium pilot powers decreases as the number of users increases. For high user densities, the Nash equilibrium pilot powers stabilize at the value of 0.5 W.

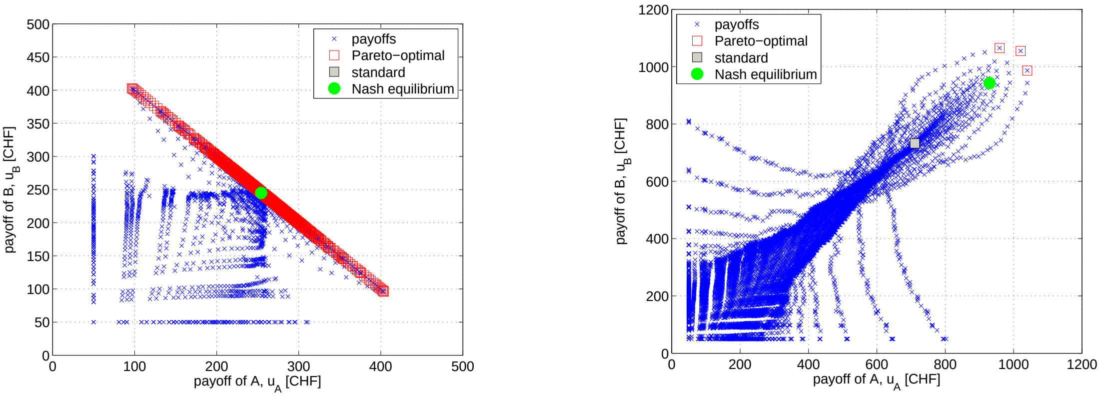
In the following set of experiments, we study the *efficiency* of the system in a Nash equilibrium with respect to the case in which the players both use the standard power P^s. To this end, we investigate the *payoff region*, i.e. the payoff values for various pilot power levels. We identify the payoffs corresponding to the Nash equilibrium, the standard pilot power setting using P^s and the payoffs that correspond to Pareto-optimal strategy profiles. In particular, we can define the *Pareto frontier* as the set of Pareto-optimal payoff points. In our case, the Pareto-optimal payoff points characterize the system-efficient solutions.

Figure 1.6a shows the achieved payoffs as a function of the pilot power values P_A and P_B for 10 data users. We observe that in this case the Pareto frontier defines a straight line, because in a Pareto-optimal strategy profile each user in the system is attached to one of the BSs. Furthermore, the standard pilot powers and the Nash equilibrium strategy profile result in the same payoffs for the players and in addition they both lie on the Pareto frontier. This means that the players achieve a desirable state from the system point of view. Recall, however, that in this case the Nash equilibrium strategy profile requires higher pilot powers than the standard setting.

We present the payoffs for 100 data users in Figure 1.6b. In this case the Pareto-optimal points do not form a straight line anymore, because some users cannot be served. Another observation is that the Nash equilibrium is still close to Pareto-optimality, but the standard solution becomes very inefficient.

Following the previous experiment, we formally express the efficiency of the standard and the Nash equilibrium solutions compared to the best Pareto-optimal point (i.e., the Pareto-optimal strategy profile in which the sum of the payoffs for the two players is maximized). To this end, let us define the following two concepts:

Definition 1.2. *The* price of anarchy *[KP99] is the ratio between the total payoff achieved by the two*



(a) (b)

Figure 1.6: The payoff region with all possible payoffs for (a) 10 data users and (b) 100 data users. We highlight the Nash equilibrium, the payoff of the standard powers and all Pareto-optimal points.

players in the best Pareto-optimal point and in the Nash equilibrium.

Definition 1.3. *The* price of conformance *is the ratio between the total payoff achieved by the two players in the best Pareto-optimal point and when using the standard pilot powers P^s (i.e., being non-strategic).*

We perform a set of experiments to measure these values for increasing user densities. Figure 1.7 presents the price of anarchy and the price of conformance as a function of the user density assuming they have data traffic. We see that both prices increase as the number of users increases. As we have seen in Figure 1.6a, both the standard payoff point and the Nash equilibrium achieves Pareto-optimality if there is a small number of users. Hence, the two prices are very close to one. As the user density increases, we observe that both prices increase and then stabilize around a constant value. Note, however, that the price of anarchy stabilizes close to one, whereas the price of conformance stabilizes around 1.4. This shows that for a high number of users, the players can achieve a higher payoff if both of them are strategic.

1.4 Convergence to a Nash Equilibrium

We have seen in the previous section that the expected payoff function for a certain player is continuous and has a unique maximum point. In this section, we propose a distributed algorithm to achieve the Nash equilibrium in a given scenario.

The algorithm is similar to the better-response dynamics [FM01], i.e., where each player tries to improve his payoff in each step. They continue to increase their pilot powers, until they pass over the maximum payoff point and then they change to pilot power decrease. The players stop the optimization if they reach their maximum payoff again. Since the two players might change their pilot powers in the same optimization step, they define the payoff curve for the other player (i.e., as presented in Figure 1.3a). Thus, the payoff of player i that stopped optimizing might change due to the strategic behavior of the other player j. If this is the case, player i continue the optimization procedure. Due to the above properties, the convergence algorithm might oscillate around the maximum payoff points. To resolve this potential instability, we include a probability with which the players update their pilot powers in

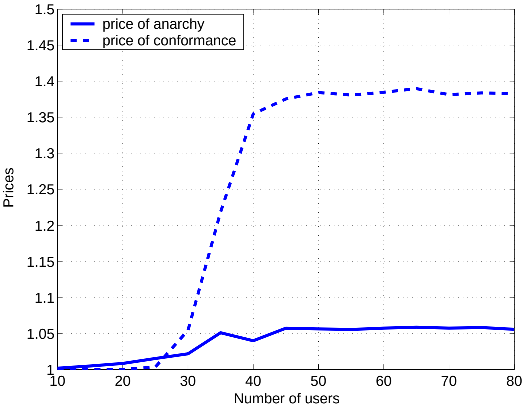


Figure 1.7: The price of anarchy and the price of conformance as a function of the user density.

each step and denote it by q. This probability ensures that sequential moves appear in the distributed optimization. We provide the pseudo-code for this procedure as shown in Algorithm 1.1.

Algorithm 1.1 Distributed convergence algorithm to achieve the NE

```
for all player $i$ do
    set pilot power $P_i = 0.1W$
    set the direction of optimization $dir_i = +1$
end for
set power control step size $P_{step} = 0.1W$
while $\exists$ BS that optimizes do
    for all player $i$ do
        if $u_i$ changed compared to previous step then
            CONTINUE the optimization for player $i$
        end if
        update $P_i$ with a probability $0 < q < 1$
        $P_i = P_i + dir_i \cdot P_{step}$
        if $u_i$ decreased then
            {the optimization passed the maximum payoff value}
            $dir_i = -dir_i$
        end if
        if reached the previously passed maximum payoff point again then
            STOP optimization
        end if
    end for
end while
```

Figure 1.8 shows the evolution of the pilot power values applying Algorithm 1.1. We observe that the pilot power values follow the linear increase defined in the algorithm. After reaching the Nash equilibrium pilot power values, the algorithm stabilizes after certain steps.

Figure 1.9 shows the evolution of the payoffs during the convergence process. We see that the algorithm deviates from the Nash equilibrium payoffs while the pilot powers increase. As soon as the pilot powers reach the Nash equilibrium strategies, the payoffs remain close to the Nash equilibrium payoffs as well.

Figure 1.10 shows the convergence path to reach a Nash equilibrium. Because the Nash equilibrium

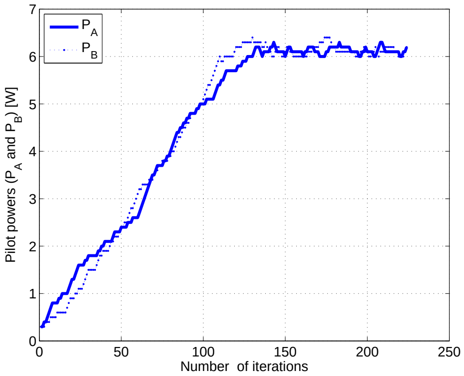


Figure 1.8: The evolution of the pilot power values using Algorithm 1.1.

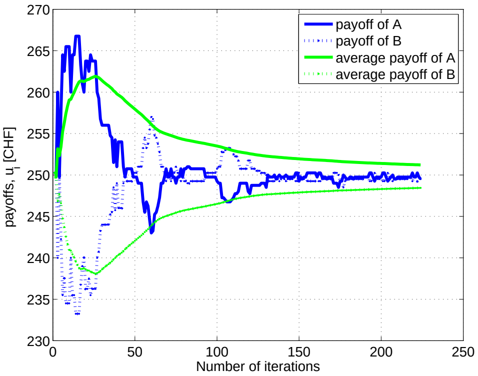


Figure 1.9: The evolution of the payoffs using Algorithm 1.1.

payoffs are almost equivalent to the starting payoffs, one might ask why the players start the optimization at all. We can observe from Figure 1.10, however, that the players reach higher payoffs during the optimization procedure. Since for low user densities, the game is a zero-sum game, the increase of u_i means the decrease of u_j. Player j adjusts his pilot powers as soon as he becomes aware of this loss. Hence, the payoffs equalize again.

1.5 Power Control Game with Power Cost

We have seen that the operators are able to serve all users in the area if the user density is low. We observe, however, that the Nash equilibrium pilot powers are higher than the standard value. Recall that the payoff function defined in (1.10) does not include the possible cost due to the operation with high pilot power. Let us now extend the expected payoff function defined in (1.10) to capture this important aspect of the power control game. We introduce two cost values for each player. The first cost denoted by C_i^{op} shows the *operating cost* of a BS i. This includes the aging of devices and hence the maintenance costs. The other cost, C_i^{subj}, expresses the *subjective cost* of player i. This covers every other aspect such

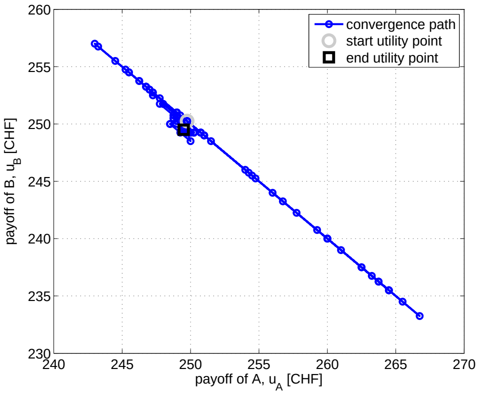


Figure 1.10: Convergence path of an example simulation run using Algorithm 1.1.

as the risk of lawsuits or potential bad reputation due to high emission power. Without loss of generality, we assume that these cost are an increasing function of the downlink transmission power of the base stations.

According to the above description, we can extend the notion of expected payoff as:

$$u_i = (\sum_{v \in \mathcal{M}_i} \theta_v) - C_i^{op} - C_i^{subj} \tag{1.13}$$

We define a non-cooperative power control game with the new expected payoff function introduced in (1.13) and denote it by $\hat{\mathbf{G}}$. We assume that the players are able to calculate the Nash equilibrium of the original game G with no power cost. Hence we define the strategy in the extended game $\hat{\mathbf{G}}$ as the choice between the standard and the Nash equilibrium strategies. Formally, we can write the strategies in $\hat{\mathbf{G}}$ as:

$$s_i = \{P_i^*, P^s\} \tag{1.14}$$

Let us call U the expected payoff that the players obtain by serving half of the total number of users. As we have seen in Section 1.3.2, if they play the Nash equilibrium strategy profile by low user densities, then it requires a higher pilot power from each operator. Without loss of generality, we denote by C^* the additional cost imposed by the Nash equilibrium compared to the standard pilot power setting P^s. The cost C^* includes both the operating and the subjective costs. Recall that we defined the normalized payoff difference Δ_A in Section 1.3.1. Due to symmetry $\Delta_A = \Delta_B$ and we denote it by Δ. In the extended game $\hat{\mathbf{G}}$, we assume that the normalized payoff difference is higher than the corresponding cost of using higher pilot power, thus $\Delta > C^*$.

We present the payoff matrix of the game $\hat{\mathbf{G}}$ in Table 1.3. In each payoff pair, the first payoff belongs to player A, whereas the second to player B.

To emphasize the structure of the payoff matrix, let us substitute the values $U = 3$, $\Delta = 2$ and $C^* = 1$. Substituting these values in Table 1.3, we obtain Table 1.4. From the payoff matrix, one can realize that the game $\hat{\mathbf{G}}$ is equivalent to the well-known Prisoner's Dilemma [FT91, Gib92, OR94]. Analogously, the strategy P^s corresponds to cooperation, whereas the strategy P_i^* corresponds to defection. This means that in the Nash equilibrium, each player uses high power and the resulting payoffs are lower than if both had complied.

		Player B	
		P^s	P_B^*
Player A	P^s	U,U	$U - \Delta$,$U + \Delta - C^*$
	P_A^*	$U + \Delta - C^*$,$U - \Delta$	$U - C^*$,$U - C^*$

Table 1.3: Payoff matrix of the game $\hat{\mathbf{G}}$.

		Player B	
		P^s	P_B^*
Player A	P^s	3,3	1,4
	P_A^*	4,1	2,2

Table 1.4: The extended power control game $\hat{\mathbf{G}}$ corresponds to the Prisoner's Dilemma.

1.6 Related Work

Power control has been extensively studied in the context of cellular networking. Baccelli *et al.* [BBT03] consider downlink power allocation and admission control in CDMA networks relying on stochastic geometry. Hanly and Tse [HT99] as well as Catrein *et al.* [CIM04] consider power control and capacity in CDMA networks. There is a very little literature about pilot power optimization, though [KCL99, VY03].

Game theory is used to study the power control of user devices in wireless networks, notably in cellular systems as studied in [ABSA02, AFB$^+$05, GM01, HBH06, JH98, MW01, MCPS05, LMS02, XSC03] and [ZZHJ04]. A general framework for resource allocation in wireless network is addressed in [DCS03].

Recently, the coexistence of multiple Internet Service Providers (ISPs) was studied by Shakkottai and Srikant in [SS05]. They consider both transit and customer prices for the ISPs. They show that if the number of ISPs competing for the same customers is large, then it can lead to price wars. In another paper [SAK06], Shakkottai *et al.* consider the problem of non-cooperative multi-homing in WLANs. Zemlianov and de Veciana study a scenario in [ZdV05], in which users are able to choose between a cellular network and a Wi-Fi network. They show that congestion sensitive strategies are better than proximity-based strategies. Félegyházi and Hubaux [FH06b] consider the competition between different operators in terms of pilot power control of their base stations. They show that in the pilot power control game a socially desirable Nash equilibrium exists and that it can be enforced by punishments.

1.7 Summary

In this chapter, we studied the problem of competitive pilot power control in two CDMA networks that reside on two sides of a national border. We were motivated by many real-life complaints from cellular network users. This problem is especially significant in cities such as Geneva, where the French network attracts users on the Swiss territory.

We investigated whether the operators of these networks have an incentive to adjust their pilot signal powers. To get an insight into the problem, we considered the single-cell case with two base stations. Initially, we assumed that only one operator can adjust the pilot signal power of his base station. We showed that he has an incentive to behave strategically and quantified the effect of various parameters on the increase of his payoff. We further showed that when the user density is low and if both operators behave strategically, then their payoffs are similar whether they adjust their pilot powers or not. We recognized that the two solutions require different pilot powers. If the user density is high, then the Nash equilibrium is more efficient than using the standard pilot powers, which suggests that the operators again have an incentive to be strategic. Finally, we extended the payoff function to include the cost of using high pilot powers. The game with power costs corresponds to the well-known Prisoner's Dilemma: The players still have an incentive to adjust their pilot powers, but their strategic behavior leads to a sub-optimal Nash equilibrium.

Border games represent an interesting and rarely advertised problem in cellular networks. Several real-life examples show that this problem is a real burden to users who live near national borders. From our private communication with cellular operators, our impression is that they do not pay enough attention to the problem, mostly for financial reasons or because they indeed benefit from the accidental roaming of the users. In this chapter, we uncovered the fundamental mechanisms that drive the operators towards this behavior. The goal of our work is twofold: we want to raise the awareness of the users and to help the operators to counter this problem by showing them the appropriate game-theoretic tools.

Publication: [FCDH07]

Conclusion

Wireless networks provide services that have become crucial to our everyday life. The recent evolution of wireless networks points towards decentralized wireless access: On the users' side, devices have become more sophisticated and programmable than before; on the operators' side, wireless infrastructure devices (such as access points) have become affordable and easily manageable. This ease of programming for both users and operators opens the door to selfish behavior: (i) the users can selfishly modify the original programs of their devices in order to exploit the available network services and (ii) prospective wireless operators can easily deploy their networks and compete with existing large operators.

In this thesis, our objective is to assess the effect of selfish behavior on the efficiency of wireless networks. We studied this effect in a wide range of wireless networks and for a set of important problems. In our study, we relied on the framework of non-cooperative game theory. Our analysis characterized the vulnerability of wireless networks to selfish behavior and enabled us to suggest game-theoretic techniques to counteract.

In the first part of the thesis, we introduced game theory with examples tailored to wireless network engineers. This comprehensive summary is important, because, at the time of this writing, virtually all of the available textbooks about game theory are written for the practitioners of other disciplines, e.g. for economists or political scientists. Our game theory tutorial enables wireless engineers to get a flavor of incentive design and hence educates them to take this important aspect into account at the design of wireless communication protocols.

In the second part of the thesis, we made several contributions studying the efficiency of wireless networks with selfish users. First, we formalized the channel allocation problem in competitive wireless networks using a non-cooperative, single-stage game. Based on this model, we showed that a Nash equilibrium channel allocation achieves load balancing over the set of available channels. Another contribution was the detailed study of the efficiency and fairness properties of the Nash equilibria relying on the widely-known concept of the price-of-anarchy and max-min fairness, respectively. We pursued our analysis to identify a subset of Nash equilibria that are also resistant against a coalition of selfish users. Finally, we designed two convergence algorithms to achieve the load-balancing Nash equilibria and proved their convergence theoretically or by simulations. The results show that efficient channel allocation can be reached even if the devices are selfish. This is particulary encouraging because the channel allocation model can be easily extended to model upcoming mesh and cognitive radio networks.

Second, we studied whether incentives in packet forwarding are needed to encourage participants in an ad hoc networks. Unlike existing work, we provided a formal model for static networks that takes the topology into account. We derived a cooperative solution from this model, but our results showed that the likelihood that spontaneous cooperation exists in general is very small. Thus, we concluded that external incentives are required to maintain cooperative packet forwarding in ad hoc networks. Extending our previous results, we studied the effect of mobility on cooperation. We concluded that mobility promotes cooperation, although some generosity of the participants is always required to bootstrap the network operation.

The recent evolution of social networks on the Internet are driven by the users. We believe that a similar evolution might happen in the wireless domain. In fact, social community networks based on WiFi are already extending to provide wireless access. Our results show that selfish users degrade the performance of such social wireless networks, but this undesired effect can be countered by appropriate behavior of the other users in repeated interactions. Our results apply to user operated networks such as community mesh networks or mobile personal area networks.

In the third part of the thesis, we contributed to ongoing research in wireless sensor networks and shared spectrum communication. In this part, we focused on wireless networks run by non-cooperative operators. First, we proposed a game-theoretic model to investigate the potential of cooperation in a joint packet forwarding and power control problem. Our results showed that the benefits of energy saving encourages the sensor network operators to cooperate. The advantage of cooperation is twofold: (a) the authorities can largely benefit by providing service of their sinks for other's sensor networks and (b) if sinks are common resources, then cooperative packet forwarding is beneficial for sparse networks or in hostile environments. These results show viable methods to improve the performance of sensor networks using cooperation.

Second, we envisioned a scenario where users can freely roam across cellular networks operated in a shared spectrum and considered the competitive power control of these networks. We provided a formal model of a single-stage game for this scenario and identified the Nash equilibria depending on the sensitivity of networks operators to interference. In a repeated game, we showed that a socially desirable Nash equilibrium (i.e., the one that produces the least interference) can be enforced and we presented a strategy to achieve it. Although we focus on cellular networks in our model, our results show guidelines for the coexistence of other wireless networks, such as WiFi networks.

Finally, we turned our attention to existing 3G cellular networks and highlighted an important shortcoming, namely the existence of cross-border interference. We were motivated by many real-life complaints of the cellular network users. We developed a game-theoretic model of pilot power control and showed that the operators have an incentive to behave strategically at their borders, i.e., to adjust the transmit power of their pilot signals. We studied the existence and properties of Nash equilibria in an empirical model and showed their efficiency for different user densities. We provided a distributed convergence algorithm to achieve the identified Nash equilibria and characterized its convergence properties. We also extended the payoff function to include the cost of using high pilot powers. The game with power costs corresponds to the well-known Prisoner's Dilemma: The players still have an incentive to adjust their pilot powers, but their strategic behavior leads to a sub-optimal Nash equilibrium. This implies that cellular operators should carefully agree about their pilot power control on national borders.

Competition between wireless operators increases with the emergence of new wireless networks. We studied the coexistence of wireless operators in existing and prospective wireless networks. Our results demonstrate that the strategic behavior of wireless operators can result in a in undesired operation of their networks (e.g., by using high transmission powers). But, we have shown appropriate coordination techniques that can mitigate the effect of selfish behavior. We have shown that by using distributed coordination relying on game theory, the wireless operators can avoid the undesired network operation. These results give guidelines on how to design incentive-aware protocols in future wireless networks with heterogeneous technologies and operators.

Future Research Directions

In this thesis, our main focus was to study incentives for cooperative behavior in wireless networks. In existing works, various incentive mechanisms were proposed to promote cooperation, for example in packet forwarding in ad hoc networks, but their need was never formally justified. Based on the second part of the thesis, in the future we will focus on designing incentives in prospective wireless networking technologies, notably in cognitive radio. We believe that incentives for cooperation in cognitive radio networks are essential, because cognitive radio devices are strategic by definition.

Pervasive wireless networking is a vision shared by many researchers. To achieve this goal, wireless networks have to coexist such that users can use their services regardless of time and location. Based on the third part of the thesis, we will further study the coexistence of wireless networks, notably in unlicensed spectrum. We will pay particular attention to the competition between unlicensed network operators providing best-effort services (e.g., WiFi networks) and licensed network operators with guaranteed quality-of-service (e.g., cellular networks). We believe that competition between various network operators will further increase as more and more networking services based on pervasive data access are available.

We are also interested in incentive problems in the area of security and privacy. Existing examples show that current security protocols to protect systems and the privacy of users do not work properly. Most of the time, the basic security protocols are correct, but there are inappropriate or there are not any incentives to apply them correctly. Hence, a promising research area is the design of incentive schemes that facilitate the appropriate deployment of security and privacy protocols.

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MÁRK FÉLEGYHÁZI

Research and teaching assistant
Laboratory for computer Communications and Applications (LCA)
School of Computer and Communication Sciences (IC)
EPFL (Ecole Polytechnique Fédérale de Lausanne), Switzerland
Station 14
CH-1015 Lausanne, Switzerland

e-mail: mark.felegyhazi@epfl.ch
url: http://people.epfl.ch/mark.felegyhazi
phone: +41 21 6936486

PERSONAL

Born in Budapest, Hungary on May 10, 1978. Citizen of Hungary.
Languages: Hungarian - native, English - fluent, German - fluent, French - intermediate

RESEARCH

My research focuses on selfish behavior in wireless networks. During my PhD work at EPFL, I have analyzed the incentives for cooperation in various wireless networks using game theory and have shown which of them require external incentives to enforce cooperative behavior. My previous work at Ericsson Research included Mobile IP protocol testbed implementation and the design of ad hoc network protocols for the Bluetooth short-range wireless technology.

EDUCATION

PhD. student in communication systems, *Sep. 2002 – present*
EPFL, SWITZERLAND
thesis title: *Non-cooperative Behavior in Wireless Networks*
advisor: Prof. Jean-Pierre Hubaux
expected graduation: April 2007

Doctoral school in communication systems, *Oct. 2001 – Jul. 2002*
EPFL, SWITZERLAND

Diploma (Dipl. Ing.) in electrical engineering, *Sep. 1996 – Jun. 2001*
BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS (BME), HUNGARY
thesis title: *Development and Evaluation of a Dynamic Bluetooth Scatternet Formation Procedure*
advisors: Dr. György Miklós and Dr. András Valkó (Ericsson Research, Hungary)
major in telecommunication, minor in mobile communication
Hungarian and German certificate (from UNIVERSITÄT KARLSRUHE (TH), GERMANY)

PROFESSIONAL EXPERIENCE

Associate member, *2006 – present*
LABORATORY OF CRYPTOGRAPHY AND SYSTEM SECURITY (CRYSYS LAB.)
BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS (BME), HUNGARY

Research and teaching assistant, *Sep. 2002 – present*
SCHOOL OF COMPUTER AND COMMUNICATION SCIENCES (IC)
EPFL, SWITZERLAND

Trainee, *1999 – 2001*
ERICSSON RESEARCH, HUNGARY

TEACHING

Teaching assistant

Mobile Networks, EPFL – 2005, 2007
Self-Organized Mobile Networks, EPFL – 2003, 2004, 2005, 2006
Informatics I-II - C++ programming, EPFL – 2004, 2005
Object Oriented Programming - JAVA, EPFL – 2002

Supervised projects

Julien Freudiger, *Anonimity in Vehicular Networks*, course, 2007
Christophe Waber, *Channel Assignment in Mesh Networks*, master, 2007
Diego Dufour, *Border Games in Cellular Networks*, semester, 2006
Sivan Altinakar, *Cellular Operators in a Shared Spectrum*, master, 2006
Shirin Saeedi, *Multi-radio Channel Allocation in Competitive Wireless Networks*, course, 2005
Megha Goel, *A Routing Architecture for Wireless Messaging Ad Hoc Networks*, internship, 2004
Martin Klauser, *Connection Establishment Models in Wireless Ad Hoc Networks*, semester, 2003

PROFESSIONAL ACTIVITIES

Reviewer for scientific journals

ACM/Kluwer Mobile Networks and Applications (MONET), IEEE Transactions on Wireless Communications (TWC), IEEE Transactions on Mobile Communications (TMC), Wiley Transactions on Communications, IEEE/ACM Transactions on Networking (ToN)

Reviewer for scientific conferences, workshops

ACM Mobicom, ACM Mobihoc, IEEE Infocom, IEEE WiOpt, ACM WiSe, IEEE DySPAN, ESAS

AWARDS

Selected poster at Mobicom 2005, in the Student Research Competition (best 7 posters)
EPFL doctoral school fellowship, Oct. 2001 – Jul. 2002
3rd price at the Students' Scientific Conference, Budapest, Oct. 2000
2nd price at the Students' Scientific Conference, Budapest, Oct. 1999
Fellowship of Universität Karlsruhe (TH), Sep. 1998 – Feb. 1999
Fellowship of the Budapest University of Technology and Economics (BME), 1996 – 2001

REFERENCES

Prof. Jean-Pierre Hubaux, Full Professor,
EPFL, Switzerland
Room BC 207, +41 21 6932627, jean-pierre.hubaux@epfl.ch

Prof. Levente Buttyán, Associate Professor,
BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS (BME), Hungary
Room IE 419, +36 1 4631803, buttyan@hit.bme.hu

Prof. Peter Marbach, Associate Professor,
UNIVERSITY OF TORONTO, Canada
Room BA 5232, +1 416 9781680, marbach@cs.toronto.edu

Prof. Srdjan Čapkun, Assistant Professor,
ETHZ, Switzerland
IFW C 41.2, +41 44 632 7190, capkuns@inf.ethz.ch

Dr. András Valkó, Manager,
TRAFFIC LAB, ERICSSON RESEARCH, Hungary
+36 1 437 71 00 (central number), andras.valko@ericsson.com

PUBLICATIONS

Book chapter

1. M. H. Manshaei, M. Félegyházi, J. Freudiger, J.-P. Hubaux, and P. Marbach, **Spectrum Sharing Games of Network Operators and Cognitive Radios**, in *Cognitive Wireless Networks: Concepts, Methodologies and Visions*, F. Fitzek and M. Katz, eds.

Journals

2. M. Félegyházi, J.-P. Hubaux and L. Buttyán, **Nash Equilibria of Packet Forwarding Strategies in Wireless Ad Hoc Networks**, IEEE Transactions on Mobile Computing (TMC), vol. 5 nr. 5, May 2006.

Conferences, workshops

3. L. Buttyán, L. Dóra, M. Félegyházi, and I. Vajda, **Barter-Based Cooperation in Delay-Tolerant Personal Wireless Networks**, in Proceedings of the IEEE Workshop on Autonomic and Opportunistic Communications (AOC 2007), Helsinki, Finland, Jun. 18, 2007.
4. M. Félegyházi, M. Čagalj, D. Dufour, and J.-P. Hubaux, **Border Games in Cellular Networks**, in Proceedings of Infocom 2007, Anchorage, USA, May 6-12, 2007.
5. M. Félegyházi, M. Čagalj, S. Saeedi, and J.-P. Hubaux, **Non-cooperative Multi-radio Channel Allocation in Wireless Networks**, in Proceedings of Infocom 2007, Anchorage, USA, May 6-12, 2007.
6. M. Félegyházi, M. Čagalj, and J.-P. Hubaux, **Multi-Radio Channel Allocation in Competitive Wireless Networks**, International Workshop on Incentive-Based Computing (IBC 2006), in conjuction with ICDCS'06, Lisboa, Portugal, Jul. 4, 2006.
7. M. Félegyházi and J.-P. Hubaux, **Wireless Operators in a Shared Spectrum**, in Proceedings of Infocom 2006, Barcelona, Spain, Apr. 23-29, 2006.
8. M. Félegyházi and L. Buttyán and J.-P. Hubaux, **Cooperative Packet Forwarding in Multi-Domain Sensor Networks**, in Proceedings of the First International Workshop on Sensor Networks and Systems for Pervasive Computing (PerSeNS 2005), in conjunction with PERCOM 2005, Kauai, Hawaii, USA, March 12, 2005.
9. M. Goel and M. Félegyházi, **Evaluation of a Routing Architecture for Wireless Messaging Ad-Hoc Networks**, Workshop on Performance Issues in Mobile Devices (PIMD 2004), Bangalore, India, Dec. 22, 2004.
10. M. Félegyházi, S. Čapkun and J.-P. Hubaux, **SOWER: Self-Organizing Wireless Network for Messaging**, in Proceedings of the ACM International Workshop on Wireless Mobile Applications and Services on WLAN Hotspots (WMash 2004), in conjunction with Mobicom 2004, Philadelphia, USA, Oct. 1, 2004.
11. M. Félegyházi and L. Buttyán and J.-P. Hubaux, **Equilibrium Analysis of Packet Forwarding Strategies in Wireless Ad Hoc Networks – the Static Case**, in Proceedings of Personal Wireless Communication (PWC 2003), Venice, Italy, Sep. 23-25, 2003.
12. M. Félegyházi and Gy. Miklós, **Development and Evaluation of a Dynamic Bluetooth Network Formation Procedure**, Telecommunications and Mobile Computing Conference (TCMC 2001), Graz, Austria, Oct. 15-16, 2001.
13. M. Félegyházi, E. Kail, Cs. Szabó, and Z. R. Turányi, **Handover Analysis in Wireless Mobile IP Networks**, 12. Távközlési es Informatikai Hálózatok Szeminárium es Kiállítás, Sopron, Hungary, Oct. 4-6, 2000. (in Hungarian)

Theses

14. M. Félegyházi, **Non-cooperative Behavior in Wireless Networks**, PhD. Thesis, EPFL, Lausanne, Switzerland, Apr. 2007.

15. M. Félegyházi, **Development and Evaluation of a Dynamic Bluetooth Scatternet Formation Procedure**, Master Thesis, Budapest University of Technology and Economics (BUTE), Budapest, Hungary, Jun. 2001.

Patents

16. Gy. Miklós and M. Félegyházi, **Traffic Dependent Bluetooth Scatternet Optimization Procedure**, US Patent Nr.: 09/666529, Jul. 2000.

Technical reports, posters

17. M. Félegyházi and J.-P. Hubaux, **Game Theory in Wireless Networks: A Tutorial**, EPFL Technical Report: LCA-REPORT-2006-002, accepted to ACM Computing Surveys and withdrawn for copyright reasons, Jun. 2006.
18. M. Félegyházi and J.-P. Hubaux, **Wireless Operators in a Shared Spectrum**, refereed poster at Mobicom 2005, Köln, Germany, Aug. 28 - Sep. 2, 2005.
19. M. Félegyházi, L. Buttyán and J.-P. Hubaux, **The Effect of Mobility on Cooperation in Ad Hoc Networks**, refereed poster at WiOpt 2004, Cambridge, UK, Mar. 24-26, 2004.
20. M. Félegyházi, J.-P. Hubaux and L. Buttyán, **Equilibrium Analysis of Packet Forwarding Strategies in Wireless Ad Hoc Networks – the Dynamic Case**, EPFL Technical Report IC/2003/68, Nov. 2003.
21. M. Félegyházi, **Design and Analysis of a Bluetooth Network Optimization Algorithm**, Students' Scientific Conference, Budapest, Oct. 2000, 3rd price. (in Hungarian)
22. M. Félegyházi, Cs. Szabó and V. Tímár, **An Experimental Analysis of Mobile IP in a Wireless Environment**, Students' Scientific Conference, Budapest, Oct. 1999, 2nd price. (in Hungarian)

Under submission

23. M. Félegyházi, M. Čagalj and J.-P. Hubaux, **Efficient MAC in Cognitive Radio Networks: A Game-Theoretic Approach**, submitted to IEEE Journal on Selected Areas in Communications, Special Issue on Cognitive Radio: Theory and Applications, Mar. 2007.