Game Theoretic Model for Radio Resource Management in HIPERLAN Type 2 Networks

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Abstract: The radio resource management in wireless data networks is different from that of voice networks, mostly due to the different perception of the quality of service users get for different signal to interference ratios. The reference system is HIPERLAN type 2 which has a link adaptation mechanism, i.e. the possibility to adapt data rates to the channel quality, and a power control mechanism. These two mechanisms depend on each other. This paper defines a utility function and uses game theory to combine link adaptation and power control with the goal to increase energy efficiency. The existence of a solution is shown analytically for a similar virtual game and by means of simulation of the actual game. Simulation results are presented and compared to the case of optimal throughput for high load cases. Results for partial load are compared with outcomes from a previously published scheme. It turns out that the game theoretic approach is superior in highly loaded networks and shows good performance in networks with small radio cells.

I. Introduction

It is commonly known that frequency is a scarce physical resource requiring efficient use. Transmit power control (TPC) is an important means to avoid interference. Another method in modern systems is link adaptation (LA), i.e. the ability to adpat the data rate to the channel quality. Both, TPC and LA, operate with the signal-to-interference ratio (SIR) value at the receiver and depend on each other.

We will use HIPERLAN type 2 (H2) as a reference system. The system itself and the effect of LA and TPC are described in [1]. TPC works such that the access point (AP) announces its own transmission power $P_{t,\mathrm{AP}}$ and the expected receive power $P_{e,\mathrm{AP}}$. The mobile terminals (MT), then, can calculate the path loss and adjust their transmit power $P_{t,\mathrm{MT}}$ accordingly.

A number of publications is available dealing with combined LA and TPC in H2, [2], [3], [4]. This problem has proven to be difficult to treat and, therefore, all cited publications propose heuristic methods with the goal to optimise network throughput. An analysis of the optimum network throughput with fixed TPC parameters but with LA is described in [5]. An important result is that the maximum is generally achieved at power levels below the maximum.

Another important point is energy efficiency, i.e. the number of bits that can be transmitted per unit of energy. This is because many devices, especially MTs, are battery driven and battery lifetime is an important sales argument. This article deals with the optimisation of energy efficiency in H2 systems by using methods from game theory, [6], [7]. Game theoretic solutions always require a utility function which should reflect a realistic model of the utility received by participants in the game. The goal is always to find an equilibrium. In our case, the energy efficiency is certainly a very important point, but we need to keep in mind that the network throughput, too, contributes significantly to the well-being of a user. This means that the resulting utility is a mixture between maximum throughput and maximum energy efficiency and the ideal case would be to have both at their optimum in the point of operation.

Game theory has only lately been applied to TPC in wireless code division multiple access (CDMA) networks, [8], dealing with uplink (UL) TPC, i.e. considering the co-channel interference at the base station, caused by non-orthogonal signals of transmitting terminals. The scheme assumes a stationary scenario. The authors use a utility function which approximates the throughput divided by the required transmit power, having the unit [Bit/Joule], i.e. it is a quantification of the energy efficiency. It is possible to find a unique equilibrium for this kind of game. The authors also show that the equilibrium is inefficient and propose a scheme with pricing, where the use of higher transmit powers is getting more expensive.

In the case of H2, we have a strict separation of MTs inside a single radio cell by using time division multiple access (TDMA), so we are interested in interference originating from other radio cells. Morever, we deal not only with TPC but also with LA, or more precise, with their combination.

This paper is the continuation of the series of [3] and [5] by extending the work to a more theory-based modelling approach for joint LA and TPC. It relies on the same scenarios as described in [3], [5] and, consequently, the scenario description is kept to a minimum in this paper. The basic principles of the game and some analyses have been published in [9]; the achievement of this paper are a somewhat more detailed treatment of the theoretical analysis of the game and different results.

We will define a virtual game in section II which is similar but not equal to the actual game and which has been inspired by [8]. We will proof that, under certain conditions, an equilibrium exists. An algorithm for the actual game in real systems is described in sectionIII. Simulation results will be presented in section IV, followed by conclusions in section V.

II. Virtual game

The utilty function is based on an approximation function for the throughput, divided by the required transmit power. We consider the throughput after the ARQ (Automatic Repeat Request) protocol in the receiver and use the specific curves versus SIR from [1] without loss of generality. Due to LA, it is a piecewise function. As a consequence, the utility function is not continuously differentiable which makes it difficult, if not impossible, to proof the existence of an equilibrium. This leads to the definition of the virtual game with a continuously differentiable approximation of the throughput function's envelope which allows some investigations on the existence of an equilibrium. The envelope is the curve with the Phy mode where, for each SIR value, the maximum throughput is achieved. We will call SIR also γ in the sequel.

We denote with $\mathcal{R}_{\max}$ the maximally achievable data rate of 54 Mbit/s. Then we get the approximated virtual throughput function

$$\mathcal{T}^{\mathrm{virt}}(\gamma) = \mathcal{R}_{\max} \cdot (1 - e^{a \cdot \gamma^b})^d \tag{1}$$

where $a = -0.17$, $b = 0.5$ und $d = 1.6$. It is shown in fig. 1 together with the throughput curves from [1]. The graphs are versus linear γ but the representation is over a logarithmic scale.

Note that the virtual throughput function $\mathcal{T}^{\mathrm{virt}}(\gamma)$ cannot be achieved in reality, since it would require continuously adjustable transmission rates and full knowledge by the transmitter about the instantaneous SIR at the receiver. But even so, $\mathcal{T}^{\mathrm{virt}}(\gamma)$ is useful, since it contains all basic properties of the real throughput function.

We denote the transmitter as i and its transmit power as p_i to define a degenerate virtual utility function $n_i^{\mathrm{deg,virt}}(p_i,\gamma_i)$ for terminal i, similar to the utility function in [8]:

$$n_i^{\mathrm{deg,virt}}(p_i,\gamma_i) = \frac{\mathcal{T}_i^{\mathrm{virt}}(\gamma_i)}{p_i} \tag{2}$$

The unit of the utility function is bit/Joule. Note that γ_i is a function of p_i and of the interference power at the receiver. We have $\gamma_i = 0$ for $p_i = 0$. The utility is degenerate, because $\mathcal{T}^{\mathrm{virt}}(\gamma_i)$ approaches zero only slowly for $\gamma_i \to 0$, i.e. the utility function $n_i^{\mathrm{deg,virt}}(p_i,\gamma_i)$ goes to ∞ for $\gamma_i \to 0$. In order to avoid the degenerate solution, we introduce the virtual utility function $n_i^{\mathrm{virt}}(p_i,\gamma_i)$:

$$n_i^{\mathrm{virt}}(p_i,\gamma_i) = \frac{\mathcal{T}_i^{\mathrm{virt}}(\gamma_i)}{k_p \cdot p_i + \Delta p} \tag{3}$$

The parameter Δp makes sure that the nominator is always positive and, thus, avoids the degenerate solution. The parameter k_p allows to trade off throughput and energy efficiency, see [10]. Some examples for utility functions according to (3) are shown in fig. 2.

We define now the virtual game. Let $\Gamma^{\mathrm{virt}} = \left[\mathcal{N}, \{\mathbf{P}_{\mathrm{DL}}, \mathbf{P}_{\mathrm{UL}}\}, \mathbf{u}^{\mathrm{virt}}\right]$ the virtual non-cooperative LA and TPC game (V-NLTG), where $\mathcal{N}$ is the set of radio cells operating on the observed frequency channel. The strategy space $\{\mathbf{P}_{\mathrm{DL}}, \mathbf{P}_{\mathrm{UL}}\}$ describes the set of possible DL transmit powers, $P_{t,\mathrm{AP}}$, and the expected UL receive powers at the AP, $P_{e,\mathrm{AP}}$, cf. [11]. We assume for the virtual game that $P_{t,\mathrm{AP}} \in \mathbb{R}^+$, $P_{e,\mathrm{AP}} \in \mathbb{R}^+$ and for the MT's transmit powers, $P_{t,\mathrm{MT}} \in \mathbb{R}^+$.

The players are complete radio cells. The utility vector $\mathbf{u}^{\mathrm{virt}} = (u_1^{\mathrm{virt}}, u_2^{\mathrm{virt}}, ..., u_{\mathcal{N}}^{\mathrm{virt}})$ has the utility functions $u_i^{\mathrm{virt}}(\mathbf{p})$ of the radio cells i, $i = 1, ..., \mathcal{N}$ as its components, the vector $\mathbf{p} = (\mathbf{p}_1, \mathbf{p}_2, ..., \mathbf{p}_{\mathcal{N}})$ consists of $\mathbf{p}_i = \{P_{t,\mathrm{AP}}^{(i)}, P_{e,\mathrm{AP}}^{(i)}\}$. In other words, the components of the power vector are the values for the chosen DL transmit power and the expected UL receive power in each radio cell $i = 1...\mathcal{N}$.

Finally, we define the virtual utility function of a radio cell:

$$u_i^{\mathrm{virt}}(\mathbf{p}_i) = \sum_{k=0}^{N_i} \left[n_k^{\mathrm{virt}}(p_k^{\mathrm{DL}}, \gamma_k^{\mathrm{DL}}) \, + \, n_k^{\mathrm{virt}}(p_k^{\mathrm{UL}}, \gamma_k^{\mathrm{UL}})\right] \tag{4}$$

The utility function of the game is a measure for the energy efficiency. It consists of the sum of the single utility functions n_k^{virt} in UL and DL of the N_i terminals that are allocated to radio cell i. The p_k^{DL} depend on $P_{t,\mathrm{AP}}^{(i)}$ and the p_k^{UL} on $P_{e,\mathrm{AP}}^{(i)}$ and the present path loss between AP i

and MT k. The interference values γ_k^{DL} and γ_k^{UL} are determined by the transmit powers p_k^{DL} and p_k^{UL} on the one hand, on the other hand by the interference power at the receiver at the very instant of reception. The interference power will be assumed to be constant for our virtual game.

A Nash equilibrium (NE) can be shown to exist, if the utility function of the game is quasi-concave, [6][1]. The utility function of the virtual game in (4) is the sum of several utility functions from (3) and, thus, is not quasi-concave. In particular, the resulting utility function can have more than one maximum in its domain. Note, however, that quasi-concavity is not a necessary but only a sufficient condition for the existence of an NE , i.e. even if it is not given, a NE can exist.

A suitable method from game theory are supermodular games. They have far more relaxed requirements to prove the existence of an NE, called NDD (Non-Decreasing Differences), [6], [12]. NDD means that an increase in the strategies of at least one rival of player i raises the desirability of playing a higher strategy for player i. A criterion for NDD is as follows: If the utility function $u(\mathrm{x})$ with $\mathrm{x} = \{x_1, ..., x_N\}$ is twice differentiable, NDD is given if and only if $\partial^2 f(\mathrm{x})/\partial x_i \partial x_j \geq 0$ for all $i, j, i \neq j$, [12, p.42].

It can be proven that this is the case in the virtual game Γ^{virt} for a pair of transmitters for transmit powers above a certain but very small threshold. We give here only the outline of the proof. The full proof can be found in [10].

The scenario we envisage for the proof, consists of two nodes transmitting simultaneously, and a receiver. Node 1 is the observed transmitter and has transmit power p_1, node 2 is the interferer with transmit power p_2. The pathloss between node 1 and the receiver is h_1 and between node 2 and the receiver, we have h_2. Then, the SIR γ at the receiver with respect to node 1 is:

$$\gamma = \frac{h_1 \cdot p_1}{h_2 \cdot p_2 + N_0} \tag{5}$$

Replacing γ in (1), we obtain for the throughput depending on p_1 and p_2:

$$\mathcal{T}^{\mathrm{virt}}(p_1, p_2) = \mathcal{R}_{\max} \cdot (1 - e^{-a \cdot \left(\frac{h_1 \cdot p_1}{h_2 \cdot p_2 + N_0}\right)^b})^d \tag{6}$$

Replacing the throughput function in (3) with the one in the previous equation yields:

$$n_1^{\mathrm{virt}}(p_1, p_2) = \frac{\mathcal{T}_1^{\mathrm{virt}}(p_1, p_2)}{k_p \cdot p_1 + \Delta p} = \frac{\mathcal{R}_{\max} \cdot (1 - e^{-a \cdot \left(\frac{h_1 \cdot p_1}{h_2 \cdot p_2 + N_0}\right)^b})^d}{k_p \cdot p_1 + \Delta p} \tag{7}$$

[1]Quasi-concavity means, in simple terms, that not more than one maximum exists in the domain of the function

Now we compute the second derivative $(\partial^2 n_1^{\text{virt}}(p_1, p_2)/(\partial p_1 \partial p_2)$. The next step would be to find the zero crossing of the second derivative with respect to p_1 for constant p_2. Unfortunately, this is not easily possible due to the fact that γ appears both, as a factor and in the exponent. An estimation of the behaviour of the second derivative for very small p_1 shows that $(\partial^2 n_1^{\text{virt}}(p_1, p_2)/(\partial p_1 \partial p_2) > 0$ for big p_1 and $(\partial^2 n_1^{\text{virt}}(p_1, p_2)/(\partial p_1 \partial p_2) < 0$ for $p_1 \to 0$.

The approximate position of the zero crossing of $(\partial^2 n_1^{\text{virt}}(p_1, p_2)/(\partial p_1 \partial p_2)$ is found by developing it into a Taylor series. It turns out that $(\partial^2 n_1^{\text{virt}}(p_1, p_2)/(\partial p_1 \partial p_2) < 0$ only for small values of p_1, so NDD is given for most feasible, except very small, transmission powers.

To apply the result from the limited scenario to the entire utility function in (4), we use the fact that all second derivatives have the same structure and, concerning the derivative with respect to a second power choice, the remaining power choices have the same effect as N_0 in the calculations above, i.e. they remain constant. All derivatives of all addends $n_1^{\text{virt}}(\mathbf{p})$ are calculated seperately and summed up again. They all have the properties explained above, so the sum, too, has these properties. This completes the proof.

III. Proposed game for real systems

A. Utility function

Now we apply the results from the virtual game Γ^{virt} to H2. We have the following restrictions in H2:

- $P_{t,\text{AP}}$ is not continuous and unlimited but can be adjusted between -15 dBm and 30 dBm in 3 dB steps. $P_{e,\text{AP}}$ can be adjusted in 4 dB steps between -71 dBm and -43 dBm.
- The Phy mode can be modified in discrete steps with raw data rates of 6, 9, 12, 18, 27, 36, 54 Mbit/s[2]

Analogously to the virtual utility function in (3), we define now the utility function for a Phy mode. Each Phy mode PM is represented by its raw data rate on the physical layer denoted as $\mathcal{R}_{PM}$. The packet error rate (PER) is taken from [1] and approximated versus linear γ:

$$PER_{PM}(\gamma) = 1 - (1 - e^{a_{PM} \cdot \gamma^{b_{PM}}})^{d_{PM}} \tag{8}$$

[2]The Phy mode with 9 Mbit/s is not considered in this paper, since it has worse performance than the one with 12 Mbit/s, [1]

The parameters a_{PM}, b_{PM} and d_{PM} are listed in table I.

TABLE I: Approximation pararameters a_{PM}, b_{PM} and d_{PM}

R_{PM}	a_{PM}	b_{PM}	d_{PM}
6 Mbit/s	-6.00	0.22	432
12 Mbit/s	-2.85	0.32	30
18 Mbit/s	-3.40	0.24	100
27 Mbit/s	-2.25	0.28	50
36 Mbit/s	-1.85	0.27	50
54 Mbit/s	-1.50	0.25	50

If we interpret $(1-PER)$ as the packet success rate and consider the automatic repeat request (ARQ) protocol of H2, [13], the useful throughput of the Phy-modes PM is approximated as:

$$\mathcal{T}^{PM}(\gamma) = R_{PM} \cdot (1 - PER_{PM}(\gamma)) \tag{9}$$

The resulting throughput curves are shown in fig. 1. The utility function $n_i^{PM}(p_i, \gamma_i)$ for Phy-mode PM is:

$$n_i^{PM}(p_i, \gamma_i) = \frac{\mathcal{T}_i^{PM}(\gamma_i)}{k_p \cdot p_i + \Delta p} \tag{10}$$

If we assume that the interference power and the path losses between all simultaneous transmitters and the receiver are constant, we can define $\gamma_i = k_{\gamma,i} \cdot p_i$ with

$$k_{\gamma,i} = \frac{h_{i,r}}{\sum\limits_{j;\, j \neq i} p_j \cdot h_{j,r} + N_0} \tag{11}$$

Example utility functions for different values of $k_{\gamma,i}$ are shown in fig. 3. We define now the utility of a single transmitter as a function of p_i. It is the envelope of the graph in fig. 3. Let $\max_{p_i}(PM)$ the Phy-mode with the maximum utility for a certain p_i. Then, we get the utility function $n_i(p_i)$:

$$n_i(p_i) = n_i^{\max_{p_i}(PM)}(p_i) \tag{12}$$

The utility function has more than one maximum, see fig. 3. Moreover, we have to consider that p_i can be adjusted in discrete steps only, which means that we may not hit the maximum exactly.

We define the utility function for a radio cell similar to (4) by replacing n_k^{virt} by n_k from (12):

$$u_i(\mathbf{p}_i) = \sum_{k=0}^{N_i} \left[n_k(p_k^{\mathrm{DL}}, \gamma_k^{\mathrm{DL}}) \, + \, n_k(p_k^{\mathrm{UL}}, \gamma_k^{\mathrm{UL}}) \right] \tag{13}$$

We call the game $\Gamma = [\mathcal{N}, \{\mathbf{P}_{\mathrm{DL}}, \mathbf{P}_{\mathrm{UL}}\}, \mathbf{u}]$ non-cooperative LA and TPC game (NLTG).

B. Proposed algorithm

As pointed out above, the utility function is not continuously differentiable. This property, however, is a prerequisite to calculate the position of the NE analytically, as e.g. happened in [8]. Therefore, we need to find a different algorithm to approach the NE of the game. Such a mechanism is the Cournot adjustment process (CAP), see [6, section 1.2.5]. The idea behind is that players adjust their strategy choices by learning rather than by analytical deduction.

In the CAP, actors choose their strategies in the current round based on the strategy choices of all other players in the previous round, assuming that the power choices have changed only little compared to the previous round. This basic principle is translated into an algorithm to play the NLTG game. For a more detailled explanation of the algorithm, the reader is referred to [9], [10].

Note that, although the power choices of the other radio cells are not known, their effect is implicitely taken into account in the utility of the observed radio cell in the form of interference, summarised in the values $k_{\gamma,i}$ of all nodes in the observed radio cell k, cf. (11).

Unfortunately, we cannot conclude that an equilibrium exists in the game NLTG from having an equilibrium in the virtual game V-NLTG. The prerequisites for the existence in discrete games is discussed in [6, sec. 1.3.3]. An equilibrium exists, if its location depends only weakly on the granularity of the discrete values. In other words, if the continuous game has a stable equilibrium, in general the discrete pendant has an equilibrium, too.

The convergence properties of CAP are well known, see e.g. [14] and references therein. The CAP converges to a stable equilibrium, if certain properties of the utility function are given. If the process converges to the same point of operation from every starting point, the equilibrium is globally stable. In fact, if the game does converge to a globally stable equilibrium, this equilibrium is an NE, [6, section 1.2.5].

IV. Numerical results

The game NLTG was implemented and simulated with an event-driven simulation tool which contains models for the MAC and ethernet-based convergence layer of H2, [13], [15]. The reception power is calculated by a two-slope path loss model, [16]. A simplified model is used for the physical layer by using the PER curves from [1], calculation of the SIR at the receiver (considering all ongoing transmissions and a basic noise floor of -95 dBm) and, finally, computing the PER with eq. (8). All simulation results presented have a standard deviation below 1 %. More details can be found in [10].

First, we can say that the simulation of NLTG converges to a stable equilibrium in all investigated scenarios, regardless of the start values for $P_{t,\mathrm{AP}}$ and $P_{e,\mathrm{AP}}$. After only a few moves, the game switches to stable combinations of $P_{t,\mathrm{AP}}$ and $P_{e,\mathrm{AP}}$. There are sporadic changes in $P_{t,\mathrm{AP}}$ and $P_{e,\mathrm{AP}}$ due to the stochastic nature of the SIR at the receiver and the mobility of the MTs. However, a frequency analysis of the changes in UL and DL power shows no periodicities. This is a strong evidence for the existence of a NE in the considered game NLTG (see the statement about convergence of the CAP in the previous section).

In order to compare the results from the virtual and the real game, we have investigated a scenario which can be treated analytically due to its simplicity. We assume two APs with a distance of $D = 100\,\mathrm{m}$, located in east-west direction of each other. A static MT is located south of each AP with distance ρ to its AP. We have simulated with NLTG and computed with V-NLTG all equilibria for all combinations of the parameters $k_p \in \{0.1, 1.0, 2.0\}$, $\Delta p \in \{0.001\,\mathrm{W}, 0.005\,\mathrm{W}, 0.01\,\mathrm{W}, 0.05\,\mathrm{W}\}$ and $\rho \in \{10\,\mathrm{m}, 20\,\mathrm{m}, 40\,\mathrm{m}\}$, see figure 4. The small saw-teeth have constant k_p and ρ but variable Δp. A change of ρ happens in the middle of the larger sawteeth. The results show that both models arrive at stable points of operation and that the values of $P_{t,\mathrm{AP}}$ are quite close to each other in all cases.

The remaining results have been obtained with the simulation model of the real game only, since mathematical solution of the virtual game with more complicated scenarios is not possible. We always consider a constellation of five APs with circular cells of radius R, arranged in a regular fashion with distance D between APs. MTs move equally distributed in each cell. In order to avoid edge effects, only the results of the radio cell in the middle of the constellation are considered. We have evaluated the total throughput and the average measured energy efficiency

$\mathcal{E}$ for UL and DL seperately. Note that $\mathcal{E}$ is not equal to the utility in eq. (13)! The difference is mostly due to Δp and k_p in eq. (10).

We compare all results with the results of a scheme called 'ideal' which optimises optimum network throughput for static choice of the , see [5], [10]. We denote the ideal throughput as $\mathcal{T}_{\text{ideal}}$ and the one for the game NLTG as $\mathcal{T}_{\text{NLTG}}$. Similarly, we use $\mathcal{E}_{\text{ideal}}$ and $\mathcal{E}_{\text{NLTG}}$. Additional "UL" or "DL" in the index distinguishes results in the UL and DL, respectively.

The results presented here are for constant ratio of the distance D between APs and the cell radius R. We will consider first a high load scenario, i.e. the traffic sources are adjusted such that all devices have to transmit at least one packet at all times. In a second step, we compare NLTG with the slightly modified scheme from [3] for partial load situations.

The scenarios are (1) $D = 150\,\text{m}$ and $R = 50\,\text{m}$ and (2) $D = 75\,\text{m}$ and $R = 25\,\text{m}$, i.e. $D/R = 3$. The simulated values for throughput and energy efficiency for the optimum throughput case are shown in table II, [10].

TABLE II: Throughput and energy efficiency with throughput optimisation

Scenario	$\mathcal{T}_{\text{ideal}}$	$\mathcal{E}_{\text{ideal,DL}}$	$\mathcal{E}_{\text{ideal,UL}}$
$D = 150\,\text{m},\ R = 50\,\text{m}$	18.57 Mbit/s	89.34 Mbit/J	115.28 Mbit/J
$D = 75\,\text{m},\ R = 25\,\text{m}$	18.89 Mbit/s	91.33 Mbit/J	117.31 Mbit/J

We can see that the relative throughput with NLTG is between approximately 80 % and 95 % for $D = 75\,\text{m}$ for all values of k_p, whereas we have around 60 % to 70 % for $D = 150\,\text{m}$. Considering the energy efficiency relative to the one in the optimum throughput case in fig. 6, we obtain an increase in $\mathcal{E}$ of 4.5 to 12 in the UL, compared to around 2 for $D = 150\,\text{m}$, so we have a significantly higher $\mathcal{E}$ level for $D = 75\,\text{m}$. Even though the DL is not as relevant as the UL case, the increase by a factor of 80 to 200 is approximately two orders of magnitude higher than for $D = 150\,\text{m}$.

The second set of results is a comparison of $\mathcal{E}$ achieved with NLTG and the JLAP scheme in [3]. The scheme there uses the empty space per MAC frame as a measure for available capacity. Since the throughput increases monotonically with γ, see fig. 1, a power decrease means decreasing and power increase increasing achievable throughput. This means that, if the empty space in the MAC frames is large, there is excess capacity on the air interface, so we can decrease capacity by decreasing transmission power. The other way round, lack of capacity can be recognised by small empty spaces and be combated by an increase of transmit power, until the transmission power finally reaches its maximum possible value. Note, however, that the dependendy of capacity and transmission power assumed in JLAP neglects the effect of mutual interference between radio cells.

We modify JLAP such that $P_{t,\mathrm{AP}}$ and $P_{e,\mathrm{AP}}$ cannot exceed the values, where $\mathcal{T}_{\mathrm{ideal}}$ is achieved according to [5]. The modified scheme is called M-JLAP. The experiment has been conducted for $k_p = 1.0$ and $\Delta p = 0.01$.

Throughputs increase both, for NLTG and JLAP, with increasing load, until they reach saturation when the offered load reaches the capacity limit. The saturation throughputs for M-JLAP are equal to those listed in table II and for NLTG as depicted in fig. 5. The energy efficiency versus offered load is shown in fig. 7 for $D = 75\,\mathrm{m}$. The curves for $D = 150\,\mathrm{m}$ are similar with lower absolute $\mathcal{E}$ levels.

We see that for both, UL and DL, the energy efficiency achieved with M-JLAP is bigger for low load conditions and that NLTG is superior with respect to $\mathcal{E}$ only for rather high load situations. The course of $\mathcal{E}$, however, is different for UL and DL with both schemes. We have an increase in $\mathcal{E}$ versus offered load in the UL for low load conditions for both, M-JLAP and NLTG. Whereas $\mathcal{E}$ continues to increase monotonically for all offered loads with NLTG, it starts to decrease with M-JLAP for higher loads. The course of the DL energy efficiency for both, M-JLAP and NLTG, decreases almost monotonically over the offered load, until it finally remains constant, as the throughput reaches saturation. The $\mathcal{E}$ curve of M-JLAP, however, is much steeper than the one of NLTG.

V. Conclusions

We have explained a game theoretic scheme to combine link adaptation and transmit power control for HIPERLAN type 2 radio networks. The existence of an equilibrium has been proven analytically for a similar virtual game. The numerical analysis shows that the game leads to a stable equilibrium.

The simulation results suggest that the game theoretic scheme is well suited for scenarios with small radio cells and for high load conditions. If the expected load in the network is low, the simple M-JLAP scheme, which relies on the empty space in a MAC frame as an indicator for capacity use, is superior with respect to maximum achievable throughput and energy efficiency.

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Figures

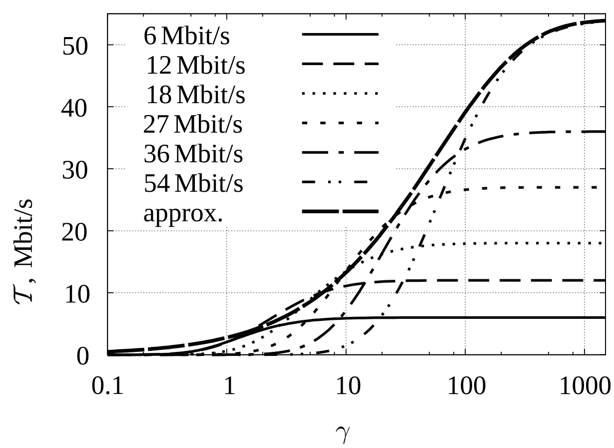


Fig. 1: Approximation function for $\mathcal{T}^{\mathrm{virt}}$ and the piecewise functions

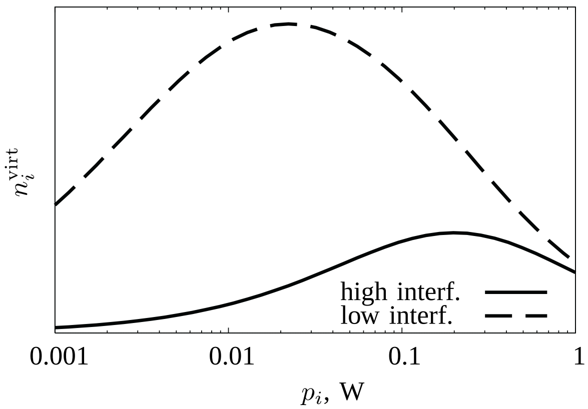


Fig. 2: n_i^{virt} versus p_i for high and low interference

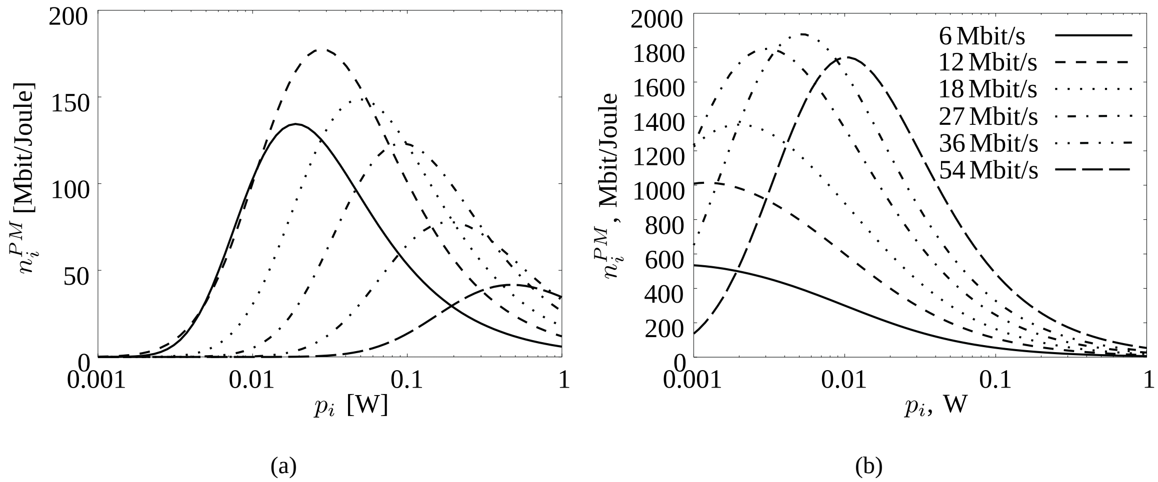


Fig. 3: Utility functions n_i^{PM}; (a) $k_{\gamma,i} = 10^2 \frac{1}{\mathrm{W}}$, (b) $k_{\gamma,i} = 10^4 \frac{1}{\mathrm{W}}$

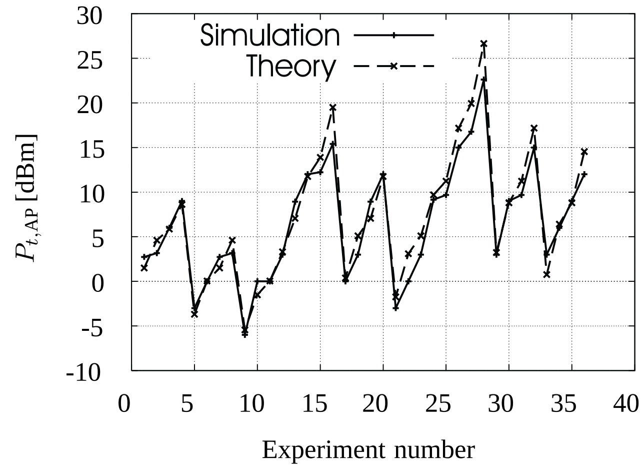


Fig. 4: Values of $P_{t,\mathrm{AP}}$ in equilibrium

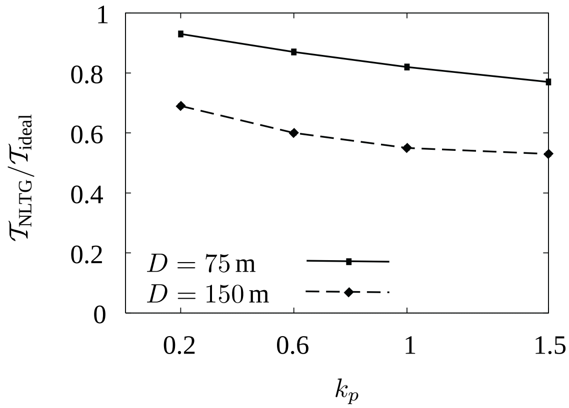


Fig. 5: Relative throughput $\mathcal{T}_{\mathrm{NLTG}}/\mathcal{T}_{\mathrm{ideal}}$ for $D = 75\,\mathrm{m}$ and $D = 150\,\mathrm{m}$

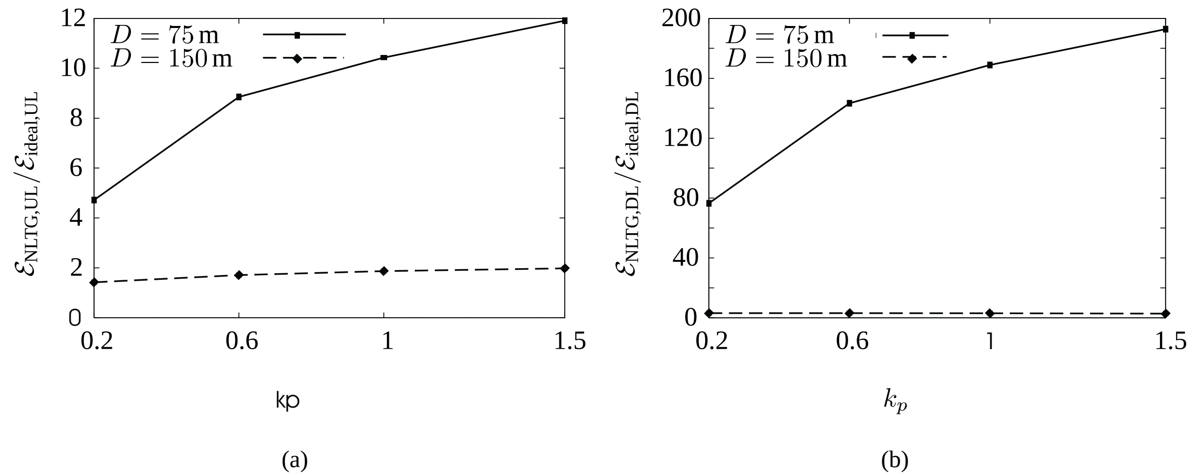
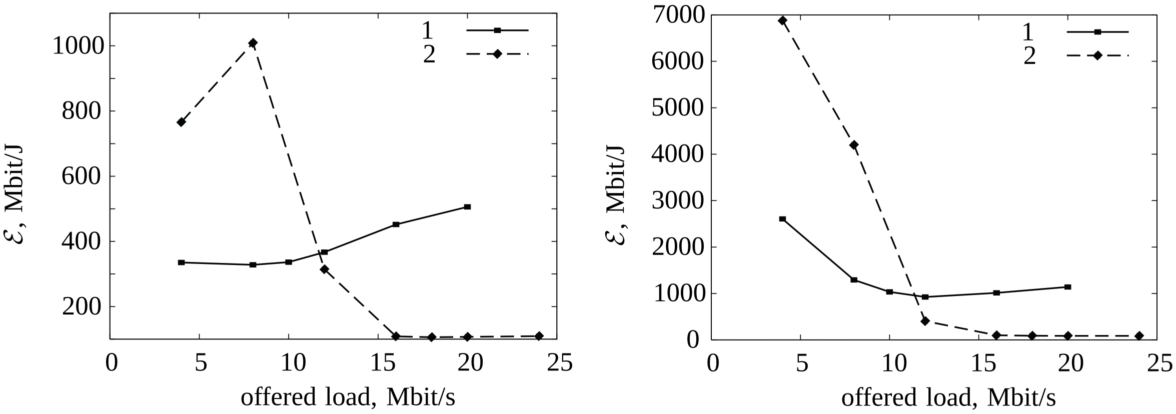


Fig. 6: $\mathcal{E}_{\mathrm{NLTG}}/\mathcal{E}_{\mathrm{ideal}}$ for $D = 75\,\mathrm{m}$ and $D = 150\,\mathrm{m}$; (a) UL case, (b) DL case



(a)

(b)

Fig. 7: $\mathcal{E}$ for $D = 75\,\mathrm{m}$; 1: NLTG, 2: M-JLAP; (a) UL; (b) DL