MAXIMIZING NETWORK THROUGHPUT

Power Control Using Game Theory in a Shared Open Spectrum

Emmanouil A. Panaousis, Christos Politis, and George C. Polyzos

Wireless local area networks (WLANs) based on the IEEE 802.11 standard [1] have turned out to be a very successful technology with widespread adoption, which has generated a whole communication sector. They can be found in public hotspots to home networks, are at the core of business models of many companies, even large ones, and are interoperating with other key communication technologies.

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The main problem of today's WLANs is interference from other WLANs in dense urban environments. To maximize network throughput while providing fairness is one of the key challenges. The main problem is the small number of available channels. Specifically, an IEEE 802.11b/g WLAN is available in general to choose from 14 (consecutive, but partially overlapping) channels. Two channels

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are not overlapping if four channels separate them. With three access points (APs) in the same area, the only assignment that satisfies the requirements for a maximum number of nonoverlapping channels is the combination of channels 1, 6, and 11 [2]. In this topology, if we add one more AP, we will have the problem of overlapping channels.

Therefore, interference management is a critical issue that should be investigated to enhance IEEE 802.11 WLAN performance in practical settings. Research works such as [3]–[5] propose to apply power control to provide a solution to this problem.

We focus on how to control the transmission power of the APs' pilot signals using game theory. First, we consider a noncooperative power control game (NPG) between competitive operators. In this case, we compute the power transmission level of each AP as a Nash equilibrium (NE) of the NPG. Second, we assume that the operators are cooperative, and also, we examine the case of a cooperative power control game (CPG). In this game, we assume the existence of a central authority called *game regulator*. In such a game, there exists an unique and feasible Nash bargaining solution (NBS). We apply the bisection method to derive the NBS. Finally, we present a punishment strategy enforced by the game regulator to punish selfish APs. In this article, we avoid proofs and minimize the display of equations.

The remainder of this article is organized as follows. In the "Related Work" section, the works done by different authors have been discussed. In the "Proposed Methodology" section, we describe the methodologies proposed, while in the "Performance Evaluation" section, we present the simulation results. We present our conclusions and plans for future work in the last section.

Related Work

Many researchers have argued in favor of a more flexible and more efficient management of the wireless spectrum, leading to a possible coexistence of various network operators in a shared spectrum area.

In [3], the authors suppose that mobile nodes can freely roam among various operators, and they model the behavior of the different network operators in a game-theoretic setting. The decision of connection to a base station is taken, considering the strength of the pilot signal of each base station. Every mobile node attaches to the station with the strongest pilot signal. According to this methodology, each operator decides on the transmission power of the pilot signal of its base stations. First, the authors compute the possible NE in a theoretical setting when all base stations are located on the vertices of a two-dimensional lattice. Afterward, they show that, in a more general case, computing the NE is NP complete. In addition, they prove that a socially, optimal NE exists and could be enforced by applying punishment tactics.

In [4], the authors argue that a cross-layer approach is required to perform starvation-free power control in IEEE 802.11 WLANs. Specifically, they state that transmitting power levels and carrier sensing parameters of the medium access control (MAC) layer should be jointly tuned. In addition, they present a framework that identifies optimum settings for the carrier-sensing parameters aiming to maximize the network throughput for elastic traffic. In fact, they apply a distributed power control algorithm that uses a Gibbs sampler.

In [5], the authors highlight that interference in coexisting WLANs can be viewed as a layered space-time (LST) structure, in which the number of APs is equal to the number of transmitting antennas. Thus, interference that is caused by the APs of different operators is equivalent to the interference between transmitting antennas in the LST architecture. This analogy can be further extended to IEEE 802.11 WLAN receiver strategies so that receiver structures derived from LST architectures can be directly applied to mitigate interference between operators. To improve the bit error rate (BER) further, a cross-layer design at both the physical (PHY) and MAC layers is proposed. It is shown that the proposed receivers demonstrate superior performance when compared with standard receivers for IEEE 802.11 WLANs systems.

Proposed Methodology

We suppose that two network operators have deployed their APs in a given area, similar to the scenario described in [3]. Their APs operate within the same unlicensed frequency band, and they can adjust the power level of their pilot signals to increase their utility functions. Thus, a two-player game is emerging. Obviously, cochannel interference is caused when clients associated with these APs are within the overlapping area of transmissions. Figures 1 and 2 depict two different kinds of networks in the NPG and CPG, respectively. Specifically, our proposed methodology in the case of NPG is based on the following steps:

- definition of the utility function for each AP
- definition of an NPG
- derivation of an NE.

For CPG, we follow the steps that are listed later using the same utility function we defined in the NPG:

- definition of the CPG
- implementation of an algorithm to determine the NBS
- derivation of the NBS
- implementation of a method to enforce the NBS.

Each AP runs the carrier sense multiple access with collision avoidance (CSMA/CA) algorithm. Because the APs suffer from the hidden node problem in both the NPG and CPG, each of them cannot sense the transmission of the competitor, as shown in Figures 1 and 2. As a result, two transmissions to the associated mobile clients are taking place concurrently causing a collision.

Assuming no request to send/clear to send (RTS/CTS) mechanism, each AP can never be informed about the concurrent transmission of the other. This situation results due to the degradation of the signal-to-interference ratio (SIR), because it actually increases the interference seen by each client. As a result, every AP has to adjust its transmission power level in a way that maximizes its mean utility and the mean SIR.

MANY RESEARCHERS HAVE ARGUED IN FAVOR OF A MORE FLEXIBLE AND MORE EFFICIENT MANAGEMENT OF THE WIRELESS SPECTRUM, LEADING TO A POSSIBLE COEXISTENCE OF VARIOUS NETWORK OPERATORS IN A SHARED SPECTRUM AREA.

Noncooperative Power Control Game

Let $G = [N, \{P_k\}, \{u_k(\cdot)\}]$ denote the two-player NPG, where $N = \{A_i, A_{-i}\}$ is the index set of APs in a given area, P_k is the strategy set, and $u_k(\cdot)$ is the utility function of an AP k.

Each AP selects a power level p_k. Let $i, -i$ be the set of APs that share the downlink bandwidth of the IEEE 802.11 cell. We assume that AP i controls its transmitted power p_i. This power is chosen from a set of strategies $P_i = (0, +\infty)$. We assume that the preferences of an AP are expressed through the utility function, which highlights the level of satisfaction for each AP and determines access to the wireless resources. According to [7], we express the utility function as the number of bits that are successfully received per unit of consumed energy as

$$u_i(p_i, \gamma_j) = (R/p_i)(1 - 2\mathrm{BER}(\gamma_j))^L \text{ b/J}. \tag{1}$$

The following terminologies need to be considered:

- R: rate of AP's transmitted information in b/s
- p_i: AP's i power of transmission
- γ_j: SIR seen by client j that receives data from i
- L: the number of bits per packet
- BER: it is the ratio between the number of incorrect bits transmitted to the total number of bits.

The level of utility that each AP gets depends on its own power level and on the strategy chosen by the competitive AP. In the two-player NPG, each AP maximizes its own utility in a distributed fashion. We assume two clients j, h that are associated with the APs i, $-i$, respectively. In our implementation, we reduce the power level of each AP from the initial value $P_{\max}$ until the achievement of an NE. Therefore, every time the power level is reduced, we check if the current power strategies of the APs comprise an NE. If this happens, we stop the power levels' reduction.

It is necessary to characterize a set of powers when an AP is satisfied with the utility it receives, given the power selection of the other AP. Such an operating point is called an NE. At the NE, given the power level of the AP $-i$, the AP i could not improve its utility level by making individual changes in its power level. The same holds true for AP i. Especially, at the NE, the power level chosen by a rational self-optimizing AP constitutes a best response to the choice of the competitive AP.

In the problem we are examining, we proved that there is one and only one NE. The aim of each AP is to maximize its utility function. At the point of maximization, the first derivative of the utility with respect to p_i should be zero. We have shown that the derived equilibrium is fair, as

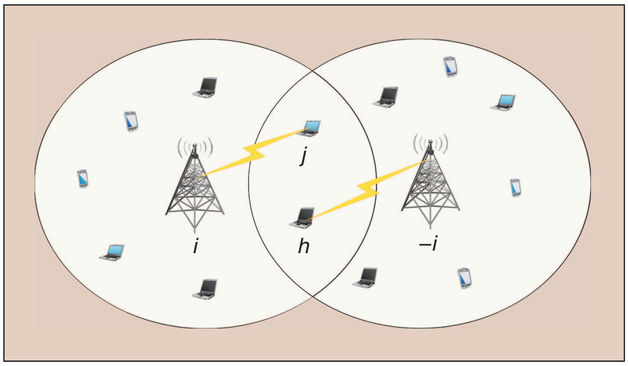

FIGURE 1 An example of the wireless environment in the case of NPG.

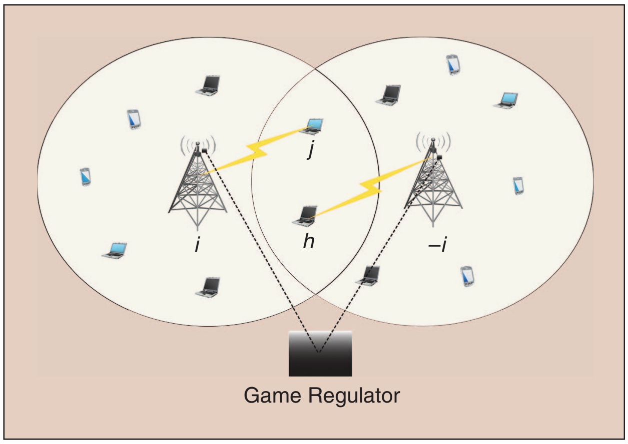

FIGURE 2 An example of the wireless environment in the case of CPG.

COCHANNEL INTERFERENCE IS CAUSED WHEN CLIENTS ASSOCIATED WITH THESE APS ARE WITHIN THE OVERLAPPING AREA OF TRANSMISSIONS.

both clients achieve the same SIR and throughput. However, according to [6], this NE is not Pareto optimal.

Cooperative Power Control Game

In this section, we examine the case of CPG. We provide a fair and efficient solution to the power control game similar to the one proposed in [8] for code division multiple access (CDMA) wireless data networks. We will show that if a regulator exists that acts appropriately then it is possible for the APs to achieve a Pareto optimal solution.

In this scenario, a central authority exists, as depicted in Figure 2, that plays the role of game regulator between the APs. To be specific, the game regulator enforces cooperation, resulting in derivation of a more efficient point than NE. This point is called an NBS [9]. The latter is a Pareto optimal point and, as a result, it maximizes the social welfare.

Another concept generally different from the NE is the Pareto efficiency or Pareto optimality. A strategy profile is Pareto optimal or Pareto efficient if there is no way to improve the performance of one player without harming the performance of the other. Thus, a Pareto optimal point is a cooperative dominating solution. According to [6], a strategy profile that constitutes an NE may not be Pareto efficient.

Algorithm 1:
Algorithm for the derivation of the NBS.

set $q_{\inf} = 0$, $q_{\sup} = \sigma^2(L+1)$
while $|q_{\sup} - q_{\inf}| > 2 * \varepsilon$ **do**
<> termination criterion $2 * \varepsilon$ is a positive small scalar
set $q_{\text{midpoint}} = (q_{\inf} + q_{\sup})/2$
if $r(q_{\text{midpoint}}) = 0$ then
  set $q_{\text{nbs}} = q_{\text{midpoint}}$
  return q_{nbs}
  exit running
else
  if $r(q_{\inf})r(q_{\text{midpoint}}) > 0$ **then**
    $q_{\inf} = q_{\text{midpoint}}$
  else
    $q_{\sup} = q_{\text{midpoint}}$
  end if
end if
end while
set $q_{\text{nbs}} = q_{\text{midpoint}}$
return q_{nbs}
exit running

In cooperative games, users are able to make enforceable outcomes through centralized authorities. Thus, for cooperative games, the interests lie in how good the game outcome could be, namely how to define and choose the optimality criteria in cooperative scenarios. Further, it is worth mentioning that the NBS plays an important role in cooperative games. The NBS is a unique Pareto optimal solution to the game-modeling bargaining interactions, and it is based on six intuitive axioms that have been given by Nash. To be specific, in a transaction when the seller and the buyer value a product differently, a surplus is created. A bargaining solution is then a way in which buyers and sellers agree to divide the surplus.

To examine the CPG, we defined the utility function of each AP as follows. Consider a linear function $\varphi : R^n \to R^n$, where $\varphi(u) = v$ and $v(q_i) = (1/g_i)u_i$. The transformed function v_i can be expressed as

$$v_i(q_{ij}) = (R/q_{ij})(1-e^{-\gamma})^L \text{ b/j}, \qquad (2)$$

with $q_{ij} = g_{ij}p_i$.

We proved that the utility of two APs at the NBS are symmetric. In addition, we proved that the NBS is a Pareto efficient point because the clients receive the same power q_{nbs}. We also proved that the NBS is unique and feasible.

To determine NBS, the game regulator runs an iterative algorithm. After the completion of the algorithm, the game regulator announces to the APs the value of the power q_{nbs}. Each of them has to adjust its transmission power level p_{nbs} according to the equation $p_{\text{nbs}} = q_{\text{nbs}}/g_{ij}$; namely, they have to adjust the power levels of their pilot signal to achieve the announced value q_{nbs}. We proved that the NBS in CPG coincides with $q_{\text{nbs}} \in [\delta, \sigma^2(L+1)]$, where δ is a sufficiently small positive scalar, σ is the noise at a client of the signal transmitted by the competitive AP, and L is the length of the packets (in bits). As we have located the interval where the root belongs, we have to apply a root-finding algorithm in this interval for the determination of NBS. We can use the bisection method to find NBS. Actually, the bisection method iteratively divides in half an interval and then it selects the subinterval in which a root exists. Therefore, we set the limits $q_{\inf}$, $q_{\sup}$ toward the derivation of NBS, and we implement Algorithm 1. The algorithm uses the function $r(q)$, which is the global maximum of the utility function $v(q)$.

The NBS is a point where the utilities of the two cooperative APs are maximized and is announced by the game regulator to the APs. This point is the threshold value of the received power by any client in the overlapping area. In addition, the NBS is a point where the social welfare is maximized, even though there is a possibility for it to not be adopted by one or more players. For example, a noncompliant player may desire to change its transmission power to achieve higher utility, violating the maximization of the social welfare. This violation, in most cases, causes significant degradation to the competitor's performance. Thus, it is essential to propose a mechanism to enforce the NBS and make the selfish APs conform. To be more specific, as we have discussed, at the NBS, two clients associated with competitive APs receive the same power. As a result, a selfish AP is an AP whose associated client receives a more powerful signal than the one suggested by the game regulator. On the other hand, this deviation may not be intentional. For example, an AP may underestimate the path link gain and increase the threshold of its transmit power.

As we have discussed, one role of the game regulator is to derive and announce the NBS to the APs. Another role is to punish the selfish players. A mechanism for the latter purpose is proposed in [7]. To punish an AP for improving its BER to the harm of other users, the game regulator should increase the nonconformant AP client BER (e.g., by introducing additional noise). Supposing that BER_{nbs} is the bit error rate at the NBS, the aim of the punishment is to give the client a BER equal to BER_{nbs}. As a result, the utility of the AP would be lower than the utility obtained at the NBS, because the consumption of energy would be larger in the case of this selfish behavior: i.e., although transmitted power increases, the BER remains the same because of the punishment procedure. The procedure implemented by the game regulator is summarized as follows:

- the game regulator calculates the NBS considering the system parameters, namely, the link gains between the APs and their associated clients
- the game regulator announces the NBS to the APs, namely, the required level of received power at their associated clients
- the game regulator monitors for selfish, nonconformant users and punishes them by reducing their clients BER to BER_{nbs}.

For the purpose of the NBS enforcement, the type of game where the game regulator can apply the punishment procedure are the repeated games. Actually, a repeated game has an extensive form, and it consists of some number of repetitions of a one-stage game. Thus, the set of players compete against each other on multiple occasions. In a single-stage game, the game regulator does not have the chance to apply the punishment. Thus, to achieve cooperation in the power control game, we need to consider repeated games.

Performance Evaluation

In this section, we present the results of simulations regarding our proposed methodologies. We used the MATLAB platform to simulate the described scenarios for both the NPG and CPG cases. Specifically,

- we simulate an AP-driven mechanism

A SELFISH AP IS AN AP WHOSE ASSOCIATED CLIENT RECEIVES A MORE POWERFUL SIGNAL THAN THE ONE SUGGESTED BY THE GAME REGULATOR.

- we assume the existence of two APs that belong to competitive operators and operate in the same frequency, time, and location
- the APs are impacted by the hidden node problem
- they adopt the binary phase shift keying (BPSK) modulation scheme
- they use the IEEE 802.11b protocol
- they set their transmission power at the maximum value, serving all the clients they can at the beginning. Specifically, the maximum power is equal to +30 dBm. This is the maximum permissible value according to the U.S. Federal Communications Commission (FCC) standards that set upper bounds on the transmitted power for IEEE 802.11 WLANs operating in the United States.

Furthermore, we did not simulate the RTS/CTS mechanism to avoid increased delivery delays and reduced throughput (e.g., according to [5]). We carried out simulations considering 10, 20, 30, 50, and 100 clients that are distributed uniformly. In addition, the clients are static, in the sense that they do not move during the period of time we apply our methodologies in the wireless network. We assume an IEEE 802.11b standard implementation with BPSK modulation, achieving 1 Mb/s data rate.

Let the two competitive APs be AP 1 and AP 2. The strategy of each AP is described in the following. Each AP reduces its transmission power level gradually until the achievement of an NE. At every step of the simulation, each AP decreases its power level by 50 mW (considering a small enough decrement toward the achievement of NE). Thus, the process of power reduction continues until the NE is achieved. The obtained NE is considered pure (see [10]), because each AP chooses to take one action with probability 1. According to the theoretical results, at the NE, the SIR of the nearest to AP 2 client j associated with AP 1 is equal to the SIR of the corresponding client h associated with AP 2.

Figure 3 depicts the improvement, as a percentage, of the mean utility of the APs at the NE. We observe that, for different numbers of clients, the improvement (percentage) function fluctuates in the interval [11%, 18%]. Figure 4 depicts the improvement of the mean SIR observed by the clients of the network at the NE. We observe that, for different numbers of clients, the improvement (percentage) function fluctuates in the interval [3%, 6.5%].

Figures 5 and 6 show two diagrams to indicate the effectiveness, in terms of utility and mean SIR, in the case of a CPG. Especially, Figure 5 depicts the improvement of the

IN COOPERATIVE GAMES, USERS ARE ABLE TO MAKE ENFORCEABLE OUTCOMES THROUGH CENTRALIZED AUTHORITIES.

utilities of the APs, which fluctuate in the interval [13%, 40%]. Moreover, Figure 6 depicts the improvement of the mean SIR observed by the clients at the NBS. We observe that for different numbers of clients the improvement (percentage) function fluctuates in the interval [2.5%, 8.5%].

It is worth mentioning that, in the CPG, a single reduction step is needed to achieve the NBS, assuming that all the entities are not cheaters, and they reduce their power to the value announced by the game regulator. On the other hand, in the NPG, the number of power reduction steps until the achievement of an NE is higher than the corresponding CPG. In addition, the simulation concludes that the final mean utility in the CPG is higher than the mean utility in the NPG.

The same trends are observed for the mean SIR of the clients associated with both APs. Because of space limitations, we included only the diagrams of the improvement

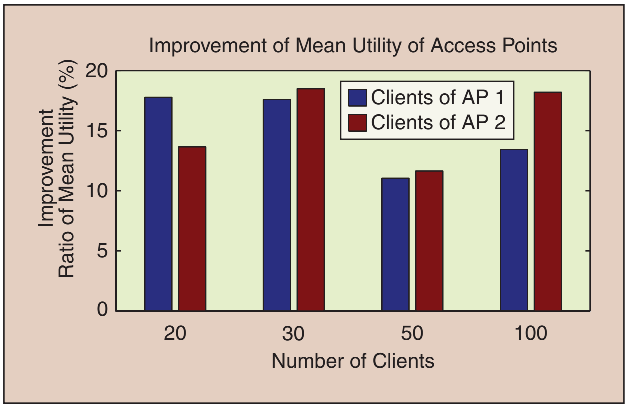

FIGURE 3 The improvement of the mean utility of the APs, at the pure NE, as a function of the number of clients (20, 30, 50, and 100).

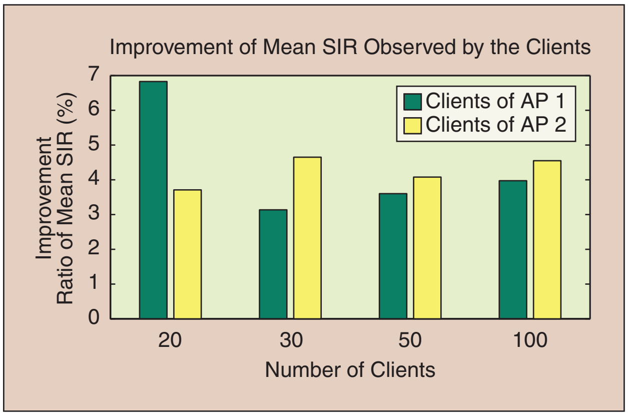

FIGURE 4 The improvement of the mean SIR, at the pure NE, observed by the clients associated with APs as a function of the number of clients (20, 30, 50, and 100).

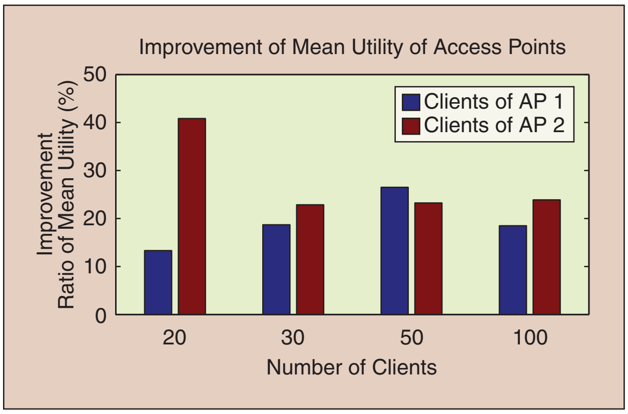

FIGURE 5 The improvement of the mean utility of the APs, at the NBS, as a function of the number of clients (20, 30, 50, and 100).

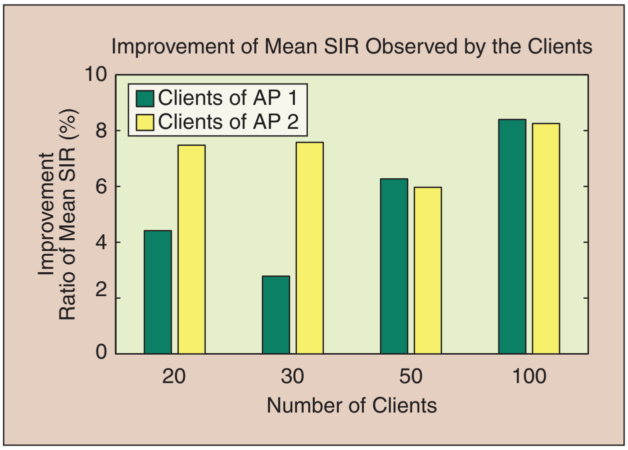

FIGURE 6 The improvement of the mean SIR, at the NBS, observed by the clients associated with the APs, as a function of the number of clients (20, 30, 50, and 100).

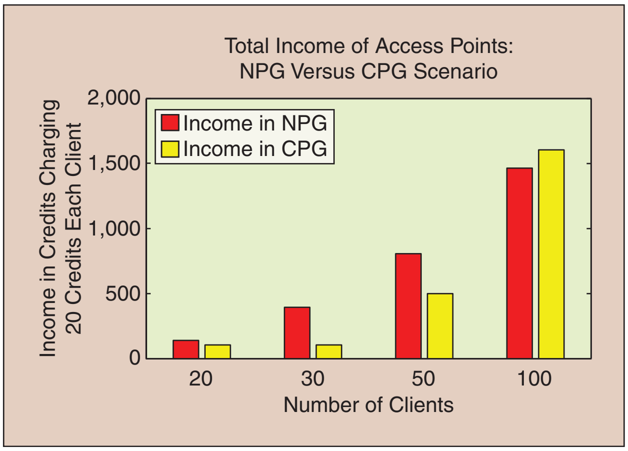

FIGURE 7 The total income of the operators in credits, assuming that each client is charged with 20 credits to be associated with the AP of an operator.

INTERFERENCE THAT IS CAUSED BY THE APs OF DIFFERENT OPERATORS IS EQUIVALENT TO THE INTERFERENCE BETWEEN TRANSMITTING ANTENNAS IN THE LST ARCHITECTURE.

of the mean utility of the APs and the mean SIR observed by the clients.

Last but not least, Figure 7 depicts the total income of an AP as a function of the number of associated clients in both cases of NPG and CPG. We assume that each client has to pay 20 credits when it is connected to an AP. We observed that, in the case of the NPG and for 20, 30, and 50 clients, operators make more profit due to the fact that more clients are connected with them.

However, as we proved, the mean SIR and APs' utility are worst in the case of an NPG. To put it simply, when the operators have more income due to the fact that they are transmitting with high power, the quality of service is lower because of the higher interference. This is the tradeoff between the two types of games. Nevertheless, when the number of clients is 100, the income of the operators is higher in the case of CPG, because in the NPG case, the APs have to reduce their power level significantly to reach the NE.

Conclusions

In this article, we investigated, using game theory, the competition in a shared open spectrum between two operators. We proposed a new way of maximization of the network throughput, and we provided new ways toward the provision of fairness. We computed an NE and NBS of an NPG and CPG, respectively.

Regarding strategies and the best game to be played, there is no single answer. The best solution depends on the perspective. However, the CPG is more effective in terms of clients' experienced quality of service.

Our future work involves experimenting with more than two APs in the shared area and evaluating various quality of service metrics.

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