

# Correlated Equilibria in Wireless Power Control Games

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## Abstract

In this paper, we consider the problem of wireless power control in an interference channel where transmitters aim to maximize their own benefit. When the individual payoff or utility function is derived from the transmission efficiency and the spent power, previous works typically study the Nash equilibrium of the resulting power control game. We propose to introduce concepts of correlated and communication equilibria from game theory to find efficient solutions (compared to the Nash equilibrium) for this problem. Communication and correlated equilibria are analyzed for the power control game, and we provide algorithms that can achieve these equilibria. Simulation results demonstrate that the correlation is beneficial under some settings, and the players achieve better payoffs.

## 1 Introduction

In this work, the notion of correlated equilibrium, which is a generalization of the Nash equilibrium, is applied in the context of power control in wireless network to determine efficient cooperative strategies. Power control in wireless networks has been studied using game theory in literature [8, 18] by characterizing the Nash equilibrium. However, as the Nash equilibrium is often inefficient, introducing the concept of correlated equilibrium will improve the players utility.

Several works apply the concept of correlated equilibrium to the wireless communications paradigm, we will now present some of the relevant papers. The papers [21, 22] look at peer-to-peer (P2P) networks, where the behavior of greedy users can degrade the network performance. Here, the authors introduce correlated equilibrium to improve the player utilities. The paper [23] studied the energy efficiency in ad hoc networks, and proposed a cooperative behavior control scheme to determine cooperative strategies, and help non-cooperative players to coordinate their strategies using the correlated equilibrium. An efficient broadcasting strategy in wireless ad hoc networks is proposed in [12], modeling the interaction among nodes as a game,

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the action set comprises two actions, to forward or drop the received message from the source. To achieve the correlated equilibrium, linear programming, and a distributed learning algorithm based on the regret matching procedure [13] are used.

The main objective of this paper is to propose another equilibrium concept (i.e., correlated equilibrium) in the context of wireless power control games, which allows players to obtain a larger equilibrium set and more efficient points in the presence of a correlation device. Assuming that we can add a correlation device to the game, is it possible to create a mechanism such that the equilibrium payoff set of the obtained game includes payoffs that are not in the initial set (game without correlation mechanism)? We provide answers to this question in this paper.

The key contributions and novelty of our paper are as follows:

1. Introduce the concepts of correlated and communication equilibrium to power control in wireless networks.
2. Provide an algorithm to achieve a correlated equilibrium via regret matching.
3. Provide an algorithm to obtain the pareto-optimal correlated equilibrium via Linear programming.
4. An extensive numerical study comparing the efficiency of the proposed correlated equilibrium with the standard Nash equilibrium.

## 2 System model

We consider a system comprised  $K \geq 2$  pairs of interfering transmitters and receivers, where the transmitters want to communicate with their respective receivers. The channel gain of the link between Transmitter  $i \in \{1, \dots, K\}$  and Receiver  $j \in \{1, \dots, K\}$  is denoted by  $g_{ij} \in \mathcal{G}$  (here  $g_{ij}$  are the real valued channel gains), where  $\mathcal{G} = \{g^1, \dots, g^N\}$  represents the alphabet of the possible channel gains. The transmitter  $i$  transmits at discrete power level  $p_i \in \mathcal{P}_i = \{p_i^1, \dots, p_i^M\}$ , with  $p_i^1 = P_i^{\min}$  and  $p_i^M = P_i^{\max}$ . Note that  $\mathcal{G}, \mathcal{P}_i \subset \mathbb{R}_{\geq 0} \forall i$ .

We denote by  $\varphi$  a communication efficiency function which measures the packet success rate as a function of the signal to interference and noise ratio (SINR). It is an increasing function and lie in  $[0, 1]$ , and is identical for all the users. Let  $\mathcal{A}_i$  denote a finite discrete set of actions that can be taken by player  $i$ . In a power control game, this action corresponds to the wireless signal power used by the transmitter  $i$ . The SINR at receiver  $i \in \mathcal{K}$  writes as:

$$\text{SINR}_i = \frac{a_i g_{ii}}{\sigma^2 + \sum_{j \neq i} a_j g_{ji}}. \quad (1)$$

where  $a_i \in \mathcal{A}_i$  is the power of the transmitter  $i$  and  $\sigma^2$  is the noise power.

Using these notations, the power control game denoted by  $\mathcal{G}$ , is defined in its normal form as follows.

**Definition 2.1** A power control game is a triplet:

$$\mathcal{G} = \{\mathcal{K}, \{\mathcal{A}_i\}_{i \in \mathcal{K}}, \{u_i\}_{i \in \mathcal{K}}\}; \quad (2)$$

where:

1.  $\mathcal{K} = \{1, \dots, K\}$  is the set of players.
2.  $\mathcal{A}_i = \{a_i^1, \dots, a_i^M\}$ , is the corresponding power level set of the player  $i \in \{1, \dots, K\}$ ; with  $a^m$  sorted such that  $a^m < a^{m+1}$ ,  $a_i^1 = P_i^{\min}$  and  $a_i^M = P_i^{\max}$ , are respectively the minimum and maximum transmitting power of player  $i$ ,  $M \geq 1$ .

3.  $u_1, \dots, u_K$  are the function utilities of the  $K$  players for a combination of choices  $a = (a_1, \dots, a_K) = (a_i, a_{-i})$ , where  $a_{-i} = (a_1, \dots, a_{i-1}, a_{i+1}, \dots, a_K)$  denotes the power levels of all other players except player  $i$ . For each player  $i$ , the utility function  $u_i$  depends on the success of its transmission, which is a function of all players' actions through  $a$ , and on the energy spent in transmission  $a_i$ . Mathematically, the players' utilities are defined by the following formula (3):

$$u_i(a_1, \dots, a_K) = \varphi(\text{SINR}_i) - \alpha a_i, \quad (3)$$

The parameter  $\alpha > 0$ , is introduced to weigh the energy cost.

Note that this kind of payoff, different from the traditional energy efficiency (the ratio of the data rate to the power) has been studied in literature [1], and is relevant when the payoff corresponds to the profit (in terms of money) for each step. In the following section, we introduce the problem of correlated equilibrium from the power control game, where an observer is added to help the players to correlate their actions.

### 3 Problem formulation

In the proposed game (2), the users are modeled as rational players, which means they are expected to choose actions from the possible choices to maximize their utilities. An important concept to characterize the outcome of the game is the Nash equilibrium, which states that every player will select an action which maximizes its utility given the actions of every other player. It corresponds to an action profile from which no player has interest in changing unilaterally its action. However, it is well known that the Nash equilibrium does not always lead to the best performance for players [8, 18].

Therefore, other concepts to reach such a more efficient equilibrium needs to be investigated. In this paper, we will study the concepts of correlated equilibrium and communication equilibrium, introduced by Aumann [5], and Forges [9], respectively. These concepts allow players to use an external mediator which provides each of them information about the action to be played in the game. Such a coordination scheme between players may sustain some equilibrium payoffs that are not achievable by an equilibrium without it (Nash equilibrium). The same conclusions hold for the sub-game perfect correlated equilibrium in repeated games, [16]. Moreover, the correlated equilibrium is simpler to compute than the Nash equilibrium [7]. In the following sub-section, we define the extended game, including an outside observer, and the correlated equilibrium concept.

#### 3.1 Power control games using a correlated device

The concept of correlated equilibrium is developed by considering an extended game that includes an outside observer (mediator), which provides each user with a private recommendation regarding which action to perform. The recommendations are chosen according to a probability distribution over the set of action profiles. This probability distribution is called a correlated equilibrium, if the action profile in which all players follow the observer's recommendations is a Nash equilibrium of the extended game.

**Definition 3.1** Define  $p$  as a joint probability distribution on the action profile set  $\mathcal{A} = \prod_{i \in \mathcal{K}} \mathcal{A}_i$ . The distribution  $p$  is a correlated equilibrium if and only if for every player  $i \in \mathcal{K}$ :

$$\sum_{a_{-i} \in \mathcal{A}_{-i}} p(a_i, a_{-i}) u_i(a_i, a_{-i}) \geq \sum_{a_{-i} \in \mathcal{A}_{-i}} p(a_i, a_{-i}) u_i(a'_i, a_{-i}), \forall a_i, a'_i \in \mathcal{A}_i. \quad (4)$$

Inequality (4) means that for each user  $i$ , choosing power level  $a'_i$  while it received recommendation to choose the power  $a_i$ , does not provide a higher expected utility. Thus, it is in the best interest for the users to follow the recommended action. The set of correlated equilibria is nonempty, closed and convex in every finite game [13], and it can include distributions that are not in the convex hull of the Nash equilibria distributions. Indeed, Nash equilibrium is a special case of correlated equilibria, where  $p(a_i, a_{-i})$  corresponds to the product of each individual probability. Thus, the set of Nash equilibrium points are a subset of the set of the correlated equilibrium points.

The correlated equilibrium considers the ability of users to coordinate actions, and computes the optimality by the joint distribution, so it provides a better solution compared with the non-cooperative Nash equilibrium, where each user acts in isolation. Further, the correlation can provide important insights, when we face the problem of equilibrium selection in games admitting multiple equilibria, which could be the case of the proposed game in some setups.

Now, if the problem is to add a mediator to the game and enable players to coordinate their actions, but also assume that the mediator receives information from the players before gives them recommendations, we could construct another kind of mechanism, that makes the information coming from players as inputs, and uses them to find the suitable outputs that correspond to the recommendations. In this scenario, the mechanism is also created such that the players have no interest to deviate from the recommendations, which is the communication equilibrium concept. This information exchange could bring performance improvement with respect to the case where players coordinate their actions without reporting any information to the mediator. In the following Section 3.2, we present how could we apply this concept to the power control game (2).

### 3.2 Communication equilibrium in power control games

Here, we assume that the mediator collects information from the players before making them recommendations. In the studied power control game, we assume the players have type sets represented by  $\mathcal{T}_i = \{(g_{ii}^1, \dots, g_{Ki}^1), \dots, (g_{ii}^N, \dots, g_{Ki}^N)\}$ . In the case of a wireless channel, the channel gains are randomly chosen following a certain (known) probability distribution. Therefore, the 'type' for each player is chosen randomly according to the given probability distribution over each player's type set. Each player  $i$  sends information about his type, i.e.,  $t_i \in \mathcal{T}_i$  to the mediator (the player might lie if it brings some gain). Thus, a communication device consists of a system  $p$  of probability distributions  $p = p(\cdot | t)_{t \in \mathcal{T} = \prod_{i \in \mathcal{K}} \mathcal{T}_i}$  over  $\mathcal{A} = \prod_{i \in \mathcal{K}} \mathcal{A}_i$ . The interpretation is that every player  $i \in \mathcal{K}$  reports its type  $t_i = (g_{ii}, g_{ji})_{\forall j \neq i}$  to the mediator, which privately recommend  $a_i$  according to  $p = p(\cdot | t)$ . The system  $p$  defines a communication equilibrium if none of the players can gain by unilaterally lying on its type or by deviating from the recommended action.

**Definition 3.2** *The system  $p$  defines a communication equilibrium if:*

$$\sum_{t_{-i} \in \mathcal{T}_{-i}} q(t_{-i} | t_i) \sum_{a \in \mathcal{A}} p(a | t) u_i(t, a) \geq \sum_{t_{-i} \in \mathcal{T}_{-i}} q(t_{-i} | t_i) \sum_{a \in \mathcal{A}} p(a | t'_i, t_{-i}) u_i(t, a'_i, a_{-i}) \forall i \in \mathcal{K}, \forall t_i, t'_i \in \mathcal{T}_i, \forall a'_i \in \mathcal{A}_i. \quad (5)$$

where  $q(t_{-i}|t_i) = \frac{q(t)}{\sum_{t_i \in T_i} q(t_i, t_{-i})}$ , is the subjective probability assigned to the event  $t_{-i}$ , that is the actual profile of the other players' types, if  $t_i$  is the type of  $i$ . The definition 3.2 implies that player  $i$  does not get a higher expected utility if it lies about its true type  $t_i$  and reports  $t'_i$ , or if it plays another action  $a'_i$  instead the recommended action  $a_i$ . In the following section, we propose some techniques to achieve correlated and communication equilibria.

## 4 Implementation of communication and correlated equilibria

The sets of correlated equilibria and communication equilibria are the subsets defined by the intersection of the half-spaces given by the inequalities (4) and (5), respectively. In this section, we investigate methods to obtain correlated and communication equilibria.

### 4.1 Linear programming method

In this paper, among the multiple correlated equilibria, we consider the one that provides the highest social welfare. Thus, the problem reduces to computing a correlated equilibrium that maximizes the sum of the players' expected utilities. In order to characterize that optimal equilibrium, we propose a linear programming method in which the optimization problem of the power control game can be formulated as follows:

$$\begin{aligned} & \max c'x \\ & A_i x > 0 \quad \forall i \in \mathcal{K} \\ & \sum_{j=1}^{M^K} x_j = 1; \\ & 0 \leq x_j \leq 1 \quad \forall j = \{1, \dots, M^K\} \end{aligned} \quad (6)$$

Where  $x' = (p(a_1^1, \dots, a_K^1), \dots, p(a_1^M, \dots, a_K^M))$ ;  $c' = (\sum_{i \in \mathcal{K}} u_i(a_1^1, \dots, a_K^1), \dots, \sum_{i \in \mathcal{K}} u_i(a_1^M, \dots, a_K^M))$ .

$$A_i = \begin{pmatrix} (u_i(a_i^1, a_{-i}^1) - u_i(a_i^2, a_{-i}^1)) & \dots & (u_i(a_i^1, a_{-i}^M) - u_i(a_i^2, a_{-i}^M)) & 0 & \dots & 0 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (u_i(a_i^1, a_{-i}^1) - u_i(a_i^M, a_{-i}^1)) & \dots & (u_i(a_i^1, a_{-i}^M) - u_i(a_i^M, a_{-i}^M)) & 0 & \dots & 0 & \dots & 0 & \dots & 0 \\ 0 & \dots & 0 & (u_i(a_i^2, a_{-i}^1) - u_i(a_i^1, a_{-i}^1)) & \dots & (u_i(a_i^2, a_{-i}^M) - u_i(a_i^1, a_{-i}^M)) & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \dots & 0 & (u_i(a_i^2, a_{-i}^1) - u_i(a_i^M, a_{-i}^1)) & \dots & (u_i(a_i^2, a_{-i}^M) - u_i(a_i^M, a_{-i}^M)) & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \dots & 0 & 0 & \dots & 0 & (u_i(a_i^M, a_{-i}^1) - u_i(a_i^{M-1}, a_{-i}^1)) & \dots & (u_i(a_i^M, a_{-i}^M) - u_i(a_i^{M-1}, a_{-i}^M)) & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \dots & 0 & 0 & \dots & 0 & (u_i(a_i^M, a_{-i}^1) - u_i(a_i^{M-1}, a_{-i}^1)) & \dots & (u_i(a_i^M, a_{-i}^M) - u_i(a_i^{M-1}, a_{-i}^M)) & \dots \end{pmatrix} \quad (7)$$

$p(a_i, a_{-i})$  is the probability that the action profile  $(a_i, a_{-i})$  is chosen. Thus, a distribution  $x^*$  is said to be correlated optimal if it is solution of the linear program (6).

In the same manner, we can characterize the optimal communication equilibrium. The solution could be obtained by solving the following optimization problem:

**Algorithm 1** Algorithm leading to the optimal correlated equilibrium in power control game

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- 1: In the beginning, the mediator chooses a power profile  $(a_i, a_{-i}) \in A$  according to  $p^*$ , that is obtained solving the described linear program, using an appropriate method.
  - 2: The mediator informs each user  $i$  of the power to choose  $a_i$ .
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$$\max_{a \in \mathcal{A}} \sum_{t \in \mathcal{T}} q(t) p(a|t) \sum_{i \in \mathcal{N}} u_i(t, a). \quad (8)$$

subject to constraint (5)

$$\sum_{t_{-i} \in \mathcal{T}_{-i}} q(t_{-i}|t_i) \sum_{a \in \mathcal{A}} p(a|t) u_i(t, a) \geq \sum_{t_{-i} \in \mathcal{T}_{-i}} q(t_{-i}|t_i) \sum_{a \in \mathcal{A}} p(a|t'_i, t_{-i}) u_i(t, a'_i, a_{-i}) \forall i \in \mathcal{N}, \forall t_i, t'_i \in \mathcal{T}_i, \forall a'_i \in \mathcal{A}_i. \quad (9)$$

and for all  $t \in \mathcal{T}$ .

$$\sum_{a \in \mathcal{A}} p(a|t) = 1. \quad (10)$$

$$p(a|t) \geq 0. \quad (11)$$

In the following we summarize the different steps to reach the optimal communication equilibrium.

**Algorithm 2** Algorithm leading to the optimal communication equilibrium in power control game

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- 1: The mediator simulates the sequence of reports that could receive from the users, that correspond to channel gain profiles, and the power profiles that could be received by the users given a channel gain profile.
  - 2: Using a method to solve the linear program constituted by the objective function (8) and the constraints (9)-(11), to find the optimal probability distributions  $p(\cdot|t)$  for all type profile  $t$ .
  - 3: For each player  $i$ , the Nature randomly chooses type, that corresponds to the channel gain profile  $(g_{i1}, \dots, g_{iK_i})$ , according to a given probability distribution over the type set  $T_i$ .
  - 4: Each player  $i$  reports its type,  $t_i$ , to the mediator.
  - 5: The mediator performs lotteries according to the received type profile, and sends private recommendations to the players, that corresponds to the transmitting power.
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However, with the linear programming method, the computation complexity grows exponentially with the number of users and actions since an increase in the number of users and actions, results an increase in the number of constraints. There exists a distributed learning approach, i.e., regret matching [13] to achieve a correlated equilibrium. However, regret matching does not ensure the pareto optimality of the given correlated equilibrium as it converges to an arbitrary correlated equilibrium, whereas the linear program as defined in (6) gives a correlated equilibrium maximizes the social welfare. In the following, we present the distributed learning approach.

## 4.2 Regret matching procedure

A game procedure is proposed in [13], called 'regret-matching'. In which the players measure the regret for not choosing other actions in the past, and change their current action with probabilities that are proportional

to these measures. Thus, the game is played with probability distribution over the action set. The details of the regret-matching algorithm [13] is shown in 3.

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**Algorithm 3** Regret matching algorithm for power control game
 

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1: For any two distinct power levels  $a'_i \neq a_i \in A_i$  calculate the average regret of user  $i$  at time  $t$  for not choosing  $a'_i$  as:

$$R_i^t(a_i, a'_i) = \max\left\{\frac{1}{t} \sum_{\tau \leq t} [u_i(a'_i, a_{-i}^\tau) - u_i(a_i^\tau)], 0\right\}. \quad (12)$$

2: Let  $a_i \in A_i$  the last power chosen by user  $i$ ,  $a_i^\tau = a_i$ . Then the probability distribution over the power levels for the next period, is defined as

$$\begin{cases} p_i^{t+1}(a'_i) = \frac{1}{\mu} R_i^t(a_i, a'_i), & \forall a'_i \neq a_i; \\ p_i^{t+1}(a_i) = 1 - \sum_{a'_i \in A_i, a'_i \neq a_i} p_i^{t+1}(a'_i), \end{cases}$$

where  $\mu$  is an enough large constant.

3: Let For every  $t$ , the empirical distribution of the power profile  $a$  is:

$$p^t(a) = \frac{1}{t} |\{\tau \leq t : a^\tau = a\}|. \quad (13)$$

where  $|\{\tau \leq t : a^\tau = a\}|$  is the number of times the power profile  $a$  has been chosen in the periods before  $t$ .

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It is shown in [13] that if the players follow the proposed algorithm 3, the empirical distribution (13) converges to an arbitrary correlated equilibrium of the game if it is not unique. The obtained correlated equilibrium by applying this procedure is not always Pareto-optimal (but the procedure can achieve the PO equilibrium). However, the one provided by the linear programming method is Pareto-optimal.

## 5 Numerical Results and Analysis

In this section, we present numerical results. The simulation setup is as follows. The number of Transmitter and Receiver pairs is equal to 2,  $\mathcal{K} = \{1, 2\}$ . Set of possible powers, that is the action set  $\mathcal{A}_i$ ,  $\forall i \in \mathcal{K}$ :  $M = 25$ ,  $P_i^{\min}(\text{dB}) = -20$ ,  $P_i^{\max}(\text{dB}) = +20$ . The presented results correspond to the expected values over different values of  $(g_{11}, g_{12}, g_{22}, g_{21})$  that lie in a discrete set  $\mathcal{G}_i = \{g_i^1, \dots, g_i^N\}$ , with  $g_i^1 = g_i^{\min}$ ,  $g_i^N = g_i^{\max}$ ,  $\forall i \in \mathcal{K}$ :  $N = 10$ ,  $g_i^{\min} = 0.01$ ,  $g_i^{\max} = 3$ , the channel gain increment equals  $\frac{3-0.01}{10}$ . The means of the channel gains are given by:  $(\bar{g}_{11}, \bar{g}_{12}, \bar{g}_{22}, \bar{g}_{21}) = (1, 1, 1, 1)$ . The communication efficiency function is:  $\varphi(x) = (1 - e^{-x})^L$ ,  $L$  being the number of symbols per packet (see e.g., [8][18][15]). In most of the simulations provided we take  $L = 100$ . The aforementioned parameters are assumed, otherwise they are explicitly mentioned in figures.

Fig 1 compares the payoffs attained by the regular Nash equilibrium and the correlated equilibrium with the region of all possible payoffs (in a centralized setting). We observe that the correlated equilibrium can improve the utility of both the players when compared to the Nash. We are limited to the two action case, but this is a very relevant case as seen from literature [24]. Fig 2a plots the utility of the correlated equilibrium and the communication equilibrium for higher action sets, but we plot to a maximum of four actions due to complexity issues in evaluating the communication equilibrium. Fig 2b compares the solution of regret matching with that of correlated equilibrium when the action sets are of size 25. Fig 2b demonstrates that although the regret matching algorithm is computationally fast, the solutions are not pareto-optimal.

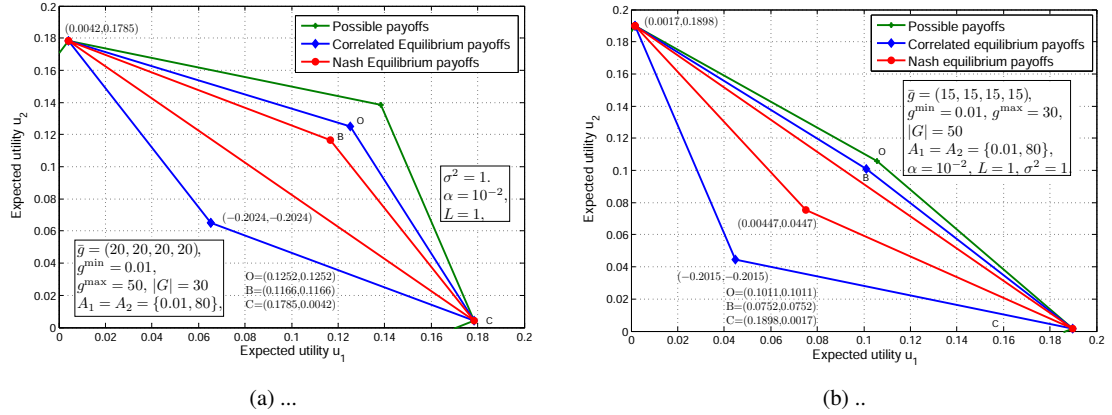


Fig. 1: Sets of: possible payoffs, correlated equilibrium payoffs and Nash equilibrium payoffs for two settings of parameters.

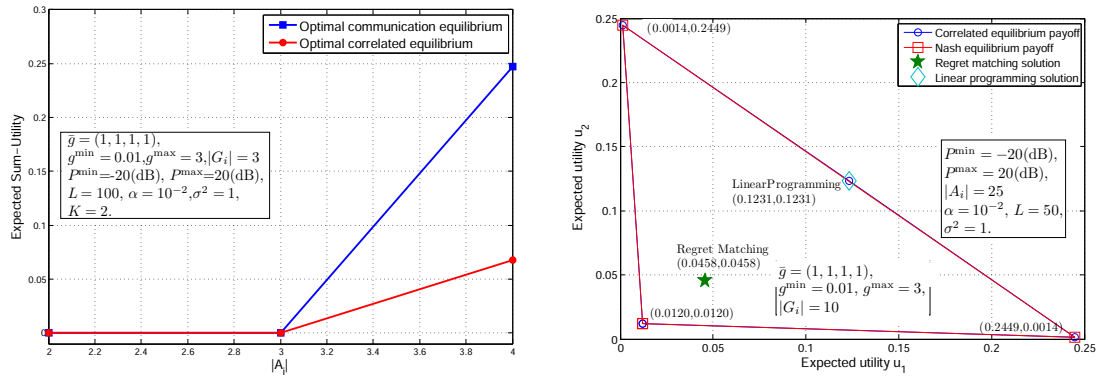


Fig. 2: Equilibrium payoffs for larger action sets.

## 6 Conclusion

We have introduced the concepts of correlated and communication equilibria to the paradigm of wireless power control games and provided algorithms based on linear programming and regret matching to achieve these equilibria. Our numerical results indicate that the resulting equilibria can be pareto-optimal and outperform the classical Nash equilibrium. While using linear programming to get the communication equilibrium results in a pareto-efficient solution, it has a computational complexity that is exponential in the action set size and number of players. Regret matching is computationally less demanding but results in solutions that are not necessarily pareto-optimal.



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