Signaling Game-based Approach to Power Control Management in Wireless Networks
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ABSTRACT

In this paper, we revisit the power control problem in wireless networks by introducing a signaling game approach. This game is known in the literature as “Cheap Talk”. Under the considered scenario, we consider two players named player I and player II. We assume that player I only knows his channel state without any information about the channel state of player II and vice-versa. Player I moves first and sends a signal to player II which can be accurate or distorted. Player II picks up his power control strategy based on this information and his belief about the nature of the informed player’s information. In order to analyze such a model, the proposed scheme game is transformed into 4 x 4 matrix game. We establish the existence of Nash equilibria and show by numerical results the equilibria and the performance of the proposed signaling game.

Categories and Subject Descriptors
H.4 [Information Systems Applications]: Miscellaneous; D.2.8 [Software Engineering]: Metrics—complexity measures, performance measures

General Terms
Theory, Performance

Keywords
Wireless networks; Power control; Partial information; Signaling game; Belief.

1. INTRODUCTION

A signal is a special sort of physical interaction between two agents which represents the product of a strategic dynamic between sender and receiver, each of whom is pursuing distinct but interrelated objectives. Moreover, a signal is a specific type of strategic interaction in which the content of the interaction is determined by the sender, and it changes the receiver’s behavior by altering the way the receiver evaluates alternative actions. This situation type is known in the literature as a signaling game theory [2, 3]. A recent work is proposed in [5] to study two competition problems between service providers with asymmetric information by applying the signaling game approach.

Power control management is an important problem in wireless networks [14, 6]. This problem is well studied in the literature with different approaches [9, 4]. The power control game is one of these approaches in wireless networks and is a typical non-cooperative game where each mobile decides about his transmit power in order to optimize his performance [13, 10]. The authors in [7] study the power control problem by applying the evolutionary game theory for pairwise interaction networks. In [1], the authors study a competition between wireless devices with incomplete information about their opponents. They model such interactions as Bayesian interference games. Each wireless device selects a power profile over the entire available bandwidth to maximize his data rate, which requires mitigating the effect of interference caused by other devices. Such competitive models represent situations in which several wireless devices share spectrum without any central authority or coordinated protocol.

The main difference in this work is to use of signaling game theory for studying the power control game in the wireless networks context. To the best of our knowledge, this direction has not been done in this context. Specifically, we consider a situation where players compete to maximize their individual throughput by optimizing their transmit power. We assume that the power takes two values: high or low. We will restrict our study to the case of two players namely, player I and player II. We further assume that player I only knows his channel gain without any information about the channel gain of player II and vice-versa. Finally, the signal sent by player I to player II may be accurate or distorted which allows us to extend the original signaling model to situations where player II could receive a misleading information from player I. Although its simplicity, this scheme allows us to study the problem of distributively allocating transmit power in wireless systems using a signalling game and address some interesting features that allows us to gain insight on problems with partial and asymmetric information among players.

This is a natural setting for hierarchical wireless networks, where users have access to the medium in a hierarchical manner. For example, in cognitive radio networks [11] where primary (licensed) users have priority to access the medium and
then secondary (unlicensed) users access the medium after sensing the environment. At the core lies the idea that in signaling games, the informed player (player I) moves first and sends a signal about his decision with which the uninformed player (player II) may update his beliefs [12] about the nature of the informed player’s information [12, 8]. We thus have a situation with partial and asymmetric information among players. Under this setting, the following questions may naturally arise. Do player I has a strategic advantage to cheat by sending misleading information to player II? In particular, how should be player II’s reaction to the information sent by player I?

The remainder of the paper is organized as follows: Section 2 presents the signaling game model description. The game theoretic analysis is given in Section 3. Numerical results are provided in Section 4 and Section 5 concludes the paper.

2. GAME MODEL DESCRIPTION

Under the proposed scenario, player I only knows his channel gain (H1) without any information about the channel gain (H2) of player II and vice-versa whereas player I – moving first – is considered more informed than the other one (player II). Users leverage the reciprocity principle to estimate the reverse link channel from the BS. The channel state is referred to as “good” (G) if the channel gain is high with probability πG and “bad” (B) if the channel gain is low with the distribution πB such that πG + πB = 1. This is particularly suitable setting when mobile users are either “aggressive” (transmitting with high power level) or “peaceful” (transmitting with low power level) like in [13, 7]. It is further known that when the channel state is good the mobile user uses a low power otherwise he uses high power level. At a first stage, based on the received information from the BS, player I observes his channel state. If the channel state is good (corresponding to the higher channel gain H2), he decides to use the lower power level (P1L) otherwise if the channel state is bad (corresponding to the lower channel gain H2) he uses the higher power level (P1H). At a second stage, player I sends a signal to player II who, based on the received signal from player I, decides to use the higher power level (P2H) or the lower power level (P2L) depending on his belief in the received signal.

Formally, this can be written as following

- Player I has four pure signaling strategies: qiqj for i, j = 1, 2 where qi stands for the signal sent if he observes H2. Let S1 be the set of these strategies, i.e., S1 = {q1q1, q1q2, q2q1, q2q2}.

- Player II has also four pure response strategies: pkpk for l, k = 1, 2. The strategy pkpk means that player II chooses pk when he observes signal ql from player I and pl otherwise. Similarly, let S2 be the set of player II strategies defined as S2 = {p1p1, p1p2, p2p1, p2p2}.

3. SIGNALING GAME MODEL ANALYSIS

3.1 The matrix game

To ease the understanding of the aforementioned problem formulation, we transform this game in a 4 x 4 matrix game. The matrix contains all possible actions of the both players. We thus have qi = P1L if i = 1 and qi = P1H if i = 2 for player I and pl = P2L if l = 1 and pl = P2H if l = 2 for player II. For example, the element q1q1 means that the good and bad states are selected by player I with the same lower power level P1L. Similarly, plpk means that the good and bad states are chosen by player II with the same power level P2L.

Formally, a signal is designed as follows:

\[ s(H1, i, j) = \begin{cases} s_i, & \text{if } H1 = H2; \\ s_j, & \text{if } H1 = H2. \end{cases} \]

s and sj are computed as function of player I’s belief, namely

\[ s_i = \begin{cases} 1, & \text{if } b1 \in [0, th1] \text{ and } H1 = H2; \\ 2, & \text{if } b1 \in [th1, 1] \text{ and } H1 = H2. \end{cases} \]

\[ s_j = \begin{cases} 1, & \text{if } b1 \in [0, th1] \text{ and } H1 = H2; \\ 2, & \text{if } b1 \in [th1, 1] \text{ and } H1 = H2. \end{cases} \]

where b1, respectively and th1, is the belief, respectively the threshold belief of player I. The threshold belief is defined as the level under which the signal is considered as accurate. Otherwise, the signal is considered as biased. Accordingly, player I decides to send a signal to player II as follows

- If the channel state of player I is good (i.e., H1 = H2) and his belief is lower than th1 (i.e., b1 ∈ [0, th1]), then he will send an accurate signal. This means that \( \epsilon(H1, i, j) = 1 \) which corresponds to the low power level. Otherwise, if his belief is higher than th1 (i.e., b1 ∈ [th1, 1], player I will send a biased signal. In this case \( \epsilon(H1, i, j) = 2 \) which corresponds to the high power level.

- If the channel state of player I is bad (i.e., H1 = H2) and its belief is lower than th1 (i.e., b1 ∈ [0, th1]), then he will send an accurate signal, i.e., \( \epsilon(H1, i, j) = 2 \) which corresponds to the high power level. Otherwise, when player I’s belief is higher than th1, he will send an accurate information. In this case \( \epsilon(H1, i, j) = 1 \) which corresponds to the low power level.

We can now define player II’s belief about the received signal as

\[ s(b2) = \begin{cases} 1, & \text{if } b2 \in [0, th2], \text{ player II does not believe; } \\ 2, & \text{if } b2 \in [th2, 1], \text{ player II believes.} \end{cases} \]

where b2, respectively th2, is the belief, respectively the threshold belief of player II. Then, player II’s response based on the received signal and his belief is given by

\[ \phi(H1, H2, i, j, l, k) = \begin{cases} r_k, & \text{if } H2 = H2; \\ r_l, & \text{if } H2 = H2. \end{cases} \]

where \( r_l \) and \( r_k \) are computed as function of player II’s belief:

\[ r_k = \begin{cases} 2, & \text{if } \epsilon(H1, i, j) = 1, \text{ } s(b2) = 1 \text{ and } H2 = H2; \\ 1, & \text{if } \epsilon(H1, i, j) = 2 \text{ and } s(b2) = 2, \text{ and } H2 = H2; \\ 1, & \text{if } \epsilon(H1, i, j) = 1 \text{ and } s(b2) = 2 \text{ and } H2 = H2; \\ 2, & \text{if } \epsilon(H1, i, j) = 2 \text{ and } s(b2) = 2 \text{ and } H2 = H2. \end{cases} \]

\[ r_l = \begin{cases} 2, & \text{if } \epsilon(H1, i, j) = 1, \text{ } s(b2) = 1 \text{ and } H2 = H2; \\ 2, & \text{if } \epsilon(H1, i, j) = 2 \text{ and } s(b2) = 2, \text{ and } H2 = H2; \\ 1, & \text{if } \epsilon(H1, i, j) = 1 \text{ and } s(b2) = 2 \text{ and } H2 = H2; \\ 1, & \text{if } \epsilon(H1, i, j) = 2 \text{ and } s(b2) = 2 \text{ and } H2 = H2. \end{cases} \]

Based on the received signal and his belief in that signal, player II decides to use the strategy plpk.
The utility of player I depends on his decision (strategy \(q_i, q_j\)) and the amount of interferences caused by player II. This is given by

\[
U^1(q_i, q_j, p_i p_j) = E_{h_1}^1(q_i, q_j, p_i p_j) - C_1(q_i, q_j),
\]

where \(C_1(q_i, q_j) = \mu (\pi_{CG} + \pi_{BG})\) is the energy cost for strategy \((q_i, q_j)\). The expected throughput of player I is given by

\[
E_{h_1}^1(q_i, q_j, p_i p_j) = \pi_G \log \left(1 + \frac{q_i |H_G|^2}{\sigma^2 + p_i |H_{G, H_{B}, i, j, k, l}| |H_B|^2}\right) + \pi_B \log \left(1 + \frac{q_j |H_B|^2}{\sigma^2 + p_j |H_{B, H_{G}, i, j, k, l}| |H_B|^2}\right).
\]

The utility of player II depending on his decision (strategy \((q_i, q_j)\)) and the received signal is given by

\[
U^2(q_i, q_j, p_i p_j) = E_{h_2}^2(q_i, q_j, p_i p_j) - C_2(p_i p_j),
\]

where \(C_2(p_i p_j) = \mu (\pi_{CG} p_i + \pi_{BG} p_j)\) is the energy cost of player II. The expected throughput of player II is

\[
E_{h_2}^2(q_i, q_j, p_i p_j) = \pi_G \log \left(1 + \frac{p_i |H_{G, H_{B}, i, j, k, l}| |H_B|^2}{\sigma^2 + q_i |H_{G, H_{B}, i, j, k, l}| |H_B|^2}\right) + \pi_B \log \left(1 + \frac{p_j |H_B|^2}{\sigma^2 + q_j |H_{B, H_{G}, i, j, k, l}| |H_B|^2}\right).
\]

### 3.2 Equilibrium Strategies

We recall that player I sends a signal (strategy \((q_i, q_j) \in S_1\)) to player II who uses this signal to choose his strategy in \(S_2\). At equilibrium, player II responds by a strategy \((p_i, p_j) \in S_2\) that maximizes his expected utility. The Nash equilibrium for such a game is a pair of strategies \((q^*_i, q^*_j, p^*_i, p^*_j)\) such that each player uses the best response in a non-cooperative way, given the probability distribution of the quality of their respective channel.

**Lemma 1.** At an equilibrium point \((q^*_i, q^*_j, p^*_i, p^*_j)\) in the game, player I’s strategy \((q_i, q_j) \in S_1\) are function of the best response of player II, namely

\[
\text{argmax}_{p_i, p_j \in S_2} U^2(q_i, q_j, p_i p_j).
\]

The equilibrium point \((q^*_i, q^*_j, p^*_i, p^*_j)\) \((i, j, k, l = 1, 2)\) are computed as follows

1. **Player I’s best response** is given by

\[
\text{argmax}_{q_i, q_j \in S_1} \sum_{p_i, p_j \in S_2} U^1(q_i, q_j, p_i p_j) = \sum_{p_i, p_j \in S_2} U^1(q^*_i, q^*_j, p_i p_j).
\]

2. **Player II’s best response** is given by

\[
\text{argmax}_{p_i, p_j \in S_2} \sum_{q_i, q_j \in S_1} U^2(q_i, q_j, p_i p_j) = \sum_{q_i, q_j \in S_1} U^2(q^*_i, q^*_j, p^*_i, p^*_j).
\]
Figure 2: Expected utility at the equilibrium as function of the probability to have a good channel state $\pi_G$ when player I sends an accurate signal and player II believes in the received signal.

Figure 3: Mixed equilibria as function of $\pi_G$ when player II does not believe in the received signal.

Figure 4: Mixed equilibria as function of $\pi_G$ when player II believes in the received signal.

Figure 5: Expected utility at the equilibrium as function of the probability to have a good channel state $\pi_G$ when player I sends a biased signal and player II does not believe in the received signal.

4.2 Impact of a biased signal

We present in Figure 5 the expected utilities for player I and player II in function of the probability to have a good channel state when the signal sent is biased and player II does not believe in the signal. For $\pi_G < 0.35$, player II's utility is higher than player I's utility at the equilibrium while for $\pi_G > 0.35$, player I's utility at the equilibrium becomes higher than player II's utility. From Figure 6 we observe that player I always outperforms player II at the equilibrium. Here, one can conclude that, when player I sends a misleading signal, in order to obtain a better expected utility than player I at the equilibrium, player II should not believe in the received signal and the probability to have a good channel must be less than 0.35.

5. CONCLUSION

In this paper, we have introduced a signaling game approach for power control in wireless networks in which the signal sent by player I to player II may be accurate or misleading. In particular, we have showed that, at the equilibrium, player I always performs better than player II except in situations where player II does not believe in the received signal either the received signal is accurate or misleading.
Figure 6: Expected utility at the equilibrium as function of the probability to have a good channel state $\pi_G$ when player I sends a biased signal and player II believes in the received signal.

6. REFERENCES


