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Power Control Game for Spectrum Sharing in Public Safety Communications

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Abstract— **Wireless communications technologies play a critical role for the Public Protection and Disaster Relief (PPDR) operational needs in crisis situations. The role of spectrum sharing is recently gaining momentum to address the major limitations of emergency communications including the lack of network capacity and interoperability issues. Cognitive radio is a critical enabler for the realization of the spectrum sharing models. In this paper we address the problem of transmit power control in secondary spectrum sharing. We consider the model where the Primary User (PU) imposes the *interference temperature* restriction and that interference temperature cannot be exceeded by transmitting Secondary Users (SU). Power control of the SUs is designed and implemented using a game theoretic approach. In order to fulfill the game we propose a utility function that maximizes Signal to Interference-plus-Noise Ratio (SINR) and minimizes the transmit power of a SU. We then compare the performance obtained using our game theory based approach with that of a resource optimization approach. We observe that our approach is more sensitive to the transmission power levels and is cheaper in terms of computation costs.**

I. INTRODUCTION

Wireless technologies play a major role for provisioning reliable communication during emergencies and disasters. Current public safety communication facilities are facing major limitations on one side due to the lack of network capacity to serve the exceptionally high traffic load and demand during an emergency scenario, and on the other side due to the incompatibility of the first responder communication network raising interoperability issues [1]. Further, the unpredictable nature of communication requirements during an emergency put several limitations on the network planning for PPDR operations.

The role of spectrum sharing is recently gaining momentum as a means to address the lack of network capacity and interoperability issues [2]. Cognitive radio (CR) is a critical enabler for the realization of the spectrum sharing models. CR enables a radio device to monitor, sense, detect [15] and autonomously adapt its communications channel access to the dynamic Radio Frequency (RF) environment in which it exists [3]. Based on an assessment of their operating environment, that may also include an evaluation of location identification information and any particular operating rule sets. A cognitive capability that can make real-time autonomous decisions for radio operations can increase spectrum efficiency leading to higher bandwidth services as well as reduce the burdens of centralized spectrum management by public safety communications officials.

Two scenarios that exploit CR capabilities can be directly applied to improve PPDR operations. The first is the capability of a public safety CR to recognize the spectrum availability and reconfigure for efficient spectrum use and for other services. Secondly, CR is a prime application that may facilitate interoperability between communication systems. By adapting to the requirements and conditions of another network the CR could identify the operating conditions and rules of the new network and reconfigure itself.

Transmission power control is one of the most important issues in wireless communication systems [4], [5]. From one side, increased transmission power improves SINR and overall system performance, but from another side it may cause harmful interference in a network. Therefore, a trade-off between transmission power and SINR is required for balanced communication in the network. For obtaining this tradeoff, Game theory paradigm is typically used [6], [7].

A cognitive framework described in [8] is aimed at improving the coexistence of heterogeneous wireless networks. The main idea of this framework is to minimize interference between PUs and SUs whilst of maximizing one`s throughput. Plenty of works have been done on power control for CR network. For example, [9] considers the case when both the PUs and SUs acted as decision makers. The system rewards PU for allowing SUs to share their licensed spectrum, and penalizes it when the amount of interference becomes greater than interference cap. The transmit power control game algorithm [10] supports both the transmit power control and modulation adaptation. The aim of the protocol is to maximize spectral efficiency and the total throughput. These research works consider power control problem for the PUs and SUs in a network [5], [6].

However, the problem of spectrum sharing for secondary users was also tackled recently in [11], [7]. For instance, in [12] ‘intelligent’ power allocation strategies are developed for unlicensed users. Each user has ‘reputation’ which is based on previous actions. Using this strategy the players tend to achieve socially optimal operation of the network. A power allocation scheme for SUs based on cooperation of data transmission is presented in [13]. This scheme helps the SUs to achieve maximum Signal to Interference-plus-Noise Ratio (SINR) and improved sum-rate for PUs.

In this paper we address the power control problem in secondary spectrum sharing for public safety CR networks. We use the model where PUs imposes the interference temperature restriction which cannot be violated by SUs. This restriction is expressed by a Control Point (CP) [14]. CP monitors the power level of each SU's transmitter and requests to adjust the corresponding power in accordance with the restriction. Besides, we apply a game theory paradigm and propose the utility function which tends to

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maximize the SINR and minimize the transmit power. The centralized power control algorithm is focused on finding a trade-off between the minimal transmit power and the highest rate of each user.

The remaining part of the paper is organized as follows: Section II provides an overview of the network model. In Section III, we introduce the game model, present the designed utility function, perform the analysis of transmit power optimization, and describe the power control algorithm. Simulation results are presented in Section IV. We conclude the paper in Section V with findings on optimality.

II. PROBLEM FORMULATION

Let *User 1*, *User 2*, …., *User i* are SUs where $i=\{1,2, \ldots, N\}$. Each SU includes a transceiver (t_i) and receiver (r_i). The scenario we consider for spectrum access among SUs is shown in Figure 1. We assume the SUs transmit the data in the form of packets at a rate of R bits/sec over a frequency bandwidth of B (Hz). We also assume that:

- Primary Users (PU) are represented as a CP with interference temperature restriction;
- SUs may have different communication characteristics/parameters;
- SUs share one communication channel;
- SUs have the same rights for spectrum utilization;
- SUs are rational: each user' node knows the system state information of other SUs.

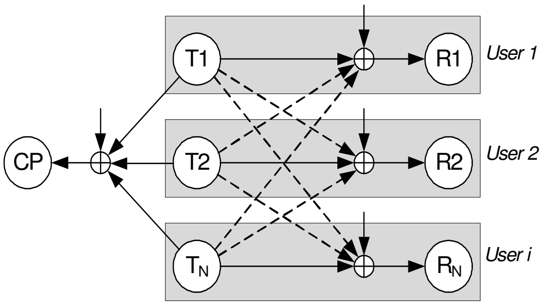

Figure 1. Scenario for spectrum access among secondary users where 'CP' is a control point, 'T' is a transmitter, and 'R' is a receiver.

The signal model is given by the following:

$$r_i = \frac{s_i}{L} + P_i + I_i \tag{1}$$

where r_i is received signal by the i-th SU receiver, s_i is transmitted signal by the i-th SU transmitter, L is a path loss in the channel between transmitter and receivers of i-th SUs , I_i is interference at the i-th receiver, and P_i is Additive Gaussian Noise (AWGN) of i-th SU:

$$P_i = k \cdot T_i \cdot B_i \tag{2}$$

where k is the Boltzmann constant, T_i is the i-th receiver temperature, and B_i is the ith receiver's bandwidth.

In the proposed model transmitters may transmit signals with the transmission power in the range $P_{t,imin} < P_{t,i} < P_{t,imax}$ with ΔP_t step. The relationship between received and transmitted power (in dBm) in the model can be expressed as:

$$P_{r,i}(dBm) = P_{t,i} - L(d_{rj,ti}) \tag{3}$$

where $P_{r,i}$ is useful signal received by receiver r_i from transmitter t_i, $P_{t,i}$ is transmitted power to the receiver r_j from transmitter t_i, $d_{rj,ti}$ is the distance between them. Path loss (in dB) can be determined as:

$$L(d_{rj,ti}) = L_0 + 10\alpha \log_{10}\left(\frac{d_{rj,ti}}{d_0}\right) \tag{4}$$

where the value of L_0 is based on a free space assumption from a transmitter, t_i , to d_0 and is defined by (5), α is the path loss exponent, and d_0 is reference distance.

$$L_0 = 10\log_{10}\left(\frac{4\pi d_0 f_c}{c}\right)^2 \tag{5}$$

where f_c is the transmit frequency and c is the speed of light.

We have assumed that nodes know location, i.e. coordinates, of each other. Thus the distance between two nodes can be defined as follows:

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{6}$$

where x_i, x_j, y_i, y_j are the coordinates of i-th and j-th nodes.

To avoid harmful interference (I) we protect the users by placing CP in the network. CP monitors interference level not to exceed I_{max} threshold and requests a user to decrease its TX power in the case when the condition in (7) is violated. We note that the problems on CP placement and interference temperature limit are out of scope of this paper.

$$P_{R,i,CP} \le \frac{I_{\max}}{NA} \tag{7}$$

where NA is the number of active transmitters and meet $NA \le N$ requirement. The total value of interference measured at the CP ($\hat{I}_{ri}$) for i-th receiver is expressed as:

$$\hat{I}_{r_i}(dBm) = 10\log_{10}\sum_{\substack{k=1\\k\neq i}}^{N} P_{r_i}(t_k) = 10\log_{10}\sum_{\substack{k=1\\k\neq i}}^{N}\frac{P_t(t_k)}{L(t_k \to CP)} \tag{8}$$

where $P_r(t_k)$ is the received power (or interference) from t_k transmitter as measured at CP, $P_t(t_k)$ is the emitted power by t_k transmitter, and $L(t_k \to CP)$ is path loss in the channel.

III. GAME MODEL

Thanks to the game theory, the network designers are equipped with the tools required for the application of balanced network resources. The game theory is based on the concept of a game defined in normal form: $\Gamma = \langle N, A, \{u_i\}\rangle$ where Γ is a particular game, $N=\{1, 2, \ldots, n\}$ is a finite set of players (decision makers), $A = A_1 \times A_2 \times \ldots \times A_n$ is the total action space with A_i as the adaptation space (or actions) available to player i, and $\{u_i\}=\{u_1, u_2,\ldots, u_n\}$ is the set of utility (objective) functions that the players wish to maximize.

The network model described in Section II can be imparted as a game as follows:

- *Players*: The set of all decision making SUs can be seen collaborating users $N=\{t_1, t_2, \ldots, t_i\}$;
- *Actions*: The set of available inputs, A_i (are the transmission powers at SU's, i.e. P_{ti});
- *Utility function*: See Section III-A;

A. Utility Function

Utility is an assignment of values to the current operating state such that the closer the user comes to satisfying some goal, the greater the value assigned to the operating state. We consider the design of a relatively simpler utility function so as to limit the complexity with processing in PPDR operations. Here we design a utility function with which we achieve the following objectives:

i) Maximize the SINR or equivalently maximizing the information rate, *R*, formally given by the Shannon's law $R = log_2(1+SINR)$; note that in our case we consider the SINR at the RX end which we assume to be communicated by the RX to TX by some signaling means;

ii) Minimize the transmit power, P_{ti}, to save power as well as reduce interference to the environment measured as received (interference) power, P_{Ii} , at *i*-th receiver.

Hence, the utility function can be expressed as,

$$U(P_{ti}, P_{Ii}) = \exp(-P_{ti})[1 + SINR_i] \tag{9}$$

where maximizing *U* will jointly minimize the power usage and maximize the information rate to a certain extent. In (10) $SINR_i$ is as follows

$$SINR_i = \frac{P_{ri}}{P_i + \hat{I}_{r_i}}; \quad \begin{cases} I_{r_i} \sim N(0, I_{r_i}) \\ P_i \sim (0, P_i) \end{cases} \tag{10}$$

where I_{ri} is the interference at the *i*-th receiver (see (8)).

Then our overall objective is to maximize $U(P_{ti}, P_{Ii})$ with respect to P_{ti} given by

$$\hat{P}_t = \arg\max_{P_t} \{u; P_{r,ti\to CP} + P_{t,tk\to CP} \le I_{\max}\} \tag{11}$$

B. Transmit Power Optimization

In this section, based on the above mentioned utility function $U(P_{ti}\ ,\ P_{Ii})$ we derive the optimal point for the transmit power level at a particular transmitter. Let us redefine the utility function in general terms without considering the subscripts, given by $U=exp(-P)[1+P/LP_0]$, where, *P* is the transmit power, *L* is the pathloss and P_0 is the aggregated interference and noise power levels. To derive the optimum transmit power levels we consider the first order partial derivative of *U* with respect to *P*, given by,

$$\frac{\partial U}{\partial P} = U' = \frac{1}{LP_0}\exp(-P)[1 - P - LP_0] \tag{12}$$

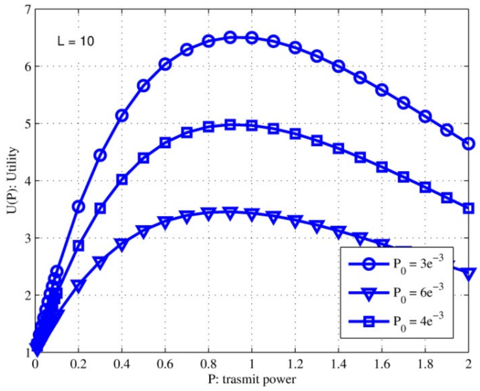

Figure 2. Utility function displaying the optimum transmit power levels at 1-LP_0, for various of P_0.

The optimum point is achieved when *U'*=0 and from (12) we see that it is obtained when $P_{opt}=1 - LP_0$. Moreover, to prove that out strategy proposed in (11) is optimum, we consider the second order derivative of *U* in (13) and prove that $U(P_{opt})$ is a global maxima of *U*.

$$\frac{\partial^2 U}{\partial P^2} = U'' = \frac{1}{LP_0}\exp(-P)[P - 2 + LP_0] \tag{13}$$

Therefore, from (13) we observe that $U''\ (P_{opt})<0$, $\forall P \in R^+$, hence giving us a global maxima. Figure 2 shows an example of the utility function and the corresponding optimum values for various P_0.

C. Power Control

In this section we explain how we find optimal operation conditions using game theory and optimization approach.

1) Game theory

Table I represents the algorithm which finds an equilibrium operation point for two networks. However, it can be easily upgrated for *n* networks. Formally, the algorithm provides each player in the game model with the highest possible utility with respect to transmit and interference power. In fact, the proposed power control algorithm has three main conditions which have to be met.

TABLE I. ALGORITHM TO FIND AN EQUILIBRIUM FOR GAME

```
Step 1. Check if the total maximum interference
level in the area is violated. If no, go to ‘3’.
Step 2. Identify interfering user(s) and decrease
its TX power for ΔP value.
Step 3. Check if information rate of each user is
higher or equal to the minimal threshold. If yes,
go to 5.
Step 4. Increase the TX power of respective user
for ΔP value and go to ‘1’.
Step 5. Calculate utility of each user and check
if this value is higher or equal to the
historical utility value of each respective user.
If yes go to ‘1’, if no decrease the TX power for
ΔP value and go to ‘1’.
```

The total interference (I_{max}) in the network must be less or equal than its max. level. CP performs this task and when this condition is violated it analyses which transmitter interferes too much: $P_{R,i\to CP} \le I_{\max}/N$. As soon as CP reveals this transmitter it requests to decrease its TX power for ΔP value.

Information rate (R) in the network must be high enough to support the minimal value, R_{min}, in order to provide a user with a desirable performance. If a transmitter can not follow this condition with the established transmit power, the dedicated receiver requests to improve it on ΔP_t value.

The highest utility (U) could be obtained at low transmit power level. With the decrease of power level we also decrease the information rate. To avoid the infinite loop which adjusts the power with respect to the desirable *R* and *U* we introduce the notion of historical utility (U_h). It characterizes the past calculations of utility. U_h informs the algorithm about the power rates at which a user achieves an acceptable utility. If the utility of a corresponding transmitter is less than the U_h, its transmit power has to be decreased for ΔP_t . Otherwise, the algorithm keeps the last value of utility until a parameter changed in the network.

2) Optimization

Optimization approach (see Table II) is more straightforward. It iterates all possible combinations of available parameters and calculates the utilities. As shown in next section, this approach may not be reliable in all cases since it does not secure mutual interest of the users.

TABLE II. ALGORITHM TO FIND THE BEST UTILITIES

```
Step 1. Calculate the utilities based on all
possible iterations of available parameters.
Step 2. Check if the values satisfy the minimal
information rate and maximal total interference.
If no exclude these values.
```

IV. SIMULATION RESULTS

In this section we verify the power control algorithms described in Section III.C by means of simulations. In the game theory approach we set the initial TX power values and then the algorithm adjusts the transmission levels of each user. In contrast, in optimization approach we set the range of available TX power levels and the algorithm finds the best ones during the iteration of all the available parameters. Table III summarizes the simulation parameters.

We simulate three scenarios for two SUs. In Scenario 1 and Scenario 2 in order to evaluate utility variance and TX power adjustment we keep the same distance between CP and *i*-th transmitter, but change TX power. In Scenario 2 and Scenario 3, in contrast, we keep TX power and evaluate the behaviour of utility and TX power with respect to the distance between CP and *i*-th transmitter. TX power range for 'Optimization' approach covers full TX power difference between SU_1 and SU_2 in 'Game theory' approach for better evaluation of adjustment mechanism. Figure 3 and Figure 4 show the best transmission power levels based on game theory and optimization approaches respectively.

TABLE III. SIMULATION PARAMETERS

	Scenario 1	**Scenario 2**	**Scenario 3**
TX power, dBm 'Game theory' approach	SU_1=6, SU_2=1	SU_1=3, SU_2=11	SU_1=3, SU_2=11
	SU_3=11	SU_3=11	SU_3=11
TX power, dBm 'Optimization' approach	SU_1=[0…7], SU_2=[7…0]	SU_1=[0…11], SU_2=[11…0]	SU_1=[0…11], SU_2=[11…0]
ΔP_t , dBm	1 (for two users); 0.1 (for three users)		
Distance CP-Tx_i, m	3.5		7
Min. information rate	320Mbits/s		
TX frequency, GHz	3.2		
Bandwidth, MHz	500		
Path loss exponent	SU_1=3, SU_2=2, SU_3=3		

Game theory approach demonstrates how the transmitters adjust their parameters with respect to each other. TX1 achieves smooth operation at 0 dBm in six ticks and does not adjust its parameters anymore. In contrast, TX2 reaches stable operation at 0 dBm in 25 ticks. After the iteration of all possible combinations of parameters, the optimization approach (see Figure 4) shows that the best utility for the users can be achieved at 0 dBm transmission power. In this scenario the results of both approaches successfully coincide. However, as it is shown in Figure 3, the game theory approach in comparison to the optimization one is highly sensitive to transmission power of each user. Figure 5 shows the power adjustment for scenario 2 using game theory approach. The transmitters reach stable operation faster (3 and 7 ticks respectively) than in scenario 1. Game theory approach shows that the optimal transmission levels for transmitter 1 and 2 are 6 and 10 dBm respectively. Optimization approach (see Figure 6), as in scenario 1, demonstrates that the best utilities can be achieved solely at 0 dBm of both users. Besides, the utilities for the optimization approach in scenario 2 are better than in scenario 1 because we have excluded four transmission values (8, 9, 10, 11 dBm) which affect the user's utility negatively (see Section III.A).

In scenario 3 we keep the same simulation parameters except for the distance between the CP and a transmitter. The simulation curves shown in Figure 7 ensure the sensitivity of game theory approach to this parameter. It takes more ticks and higher transmission power for TX1, i.e 9 dBm, to achieve the stable operation and necessary information rate at longer distance. The results obtained using the optimization approach (see Figure 8) does not coincide with the game theory ones. It happens due to optimization approach's straightforward nature: it simply calculates the utility function which is restricted in high power transmission levels and low SINR at RX side and does not respect the interests of other transmitters in the area.

We would like to note that the optimization approach has a very high computation cost, which is feasible only for very limited set of SU, and it is not realistic in real settings such as for PPDR operations. Due to this we continue the evaluation of power control algorithm by the game theory approach only. New setting includes three scenarios with three TXs. In general, we keep the same simulation parameters as for three previous scenarios for two users in the setting. TX3 in new setting transmits at 11 dBm level and ΔP is changed to 0.1.

Figure 9 shows that power adjustment for three TXs and decreased ΔP value takes much more time (231 ticks). The optimal transmission levels for three TXs are +5, -5.1, -5.1 dBm respectively. This result is completely different to scenario 1 with two TXs in the setting where the optimal level for both TXs was 0 dBm (see Figure 3). Figure 10 and Figure 11 demonstrate the power adjustment for three TXs for scenarios 2 and 3 respectively. These scenarios have identical transmission parameters except for the distance between the CP and a transmitter. It takes 273 ticks to reach optimal transmission level in both scenarios. Also the optimal transmission level for TX1 and TX2 is -5.1 dBm. However, the optimal transmission level for TX3 is 8 and 6 dBm in scenario 2 and 3 respectively.

V. CONCLUSION

In this paper we have addressed the power control problem for cognitive wireless networks in the context of secondary spectrum sharing in public safety communications. The power control was modeled as game theoretic and optimization approaches. For the game theoretic approach we have proposed utility function which maximizes the rate whilst minimizing the required TX power and then compared the results with optimization approach. Simulation results have demonstrated that the optimization approach is a straightforward one and is not sensitive to the transmission power levels of other users. The game theory approach, in contrast, is sensitive to the transmission power levels and is cheaper in terms of computation cost, which is beneficial for PPDR operations. Our future work is to extend the power control for a more generic network model.

ACKNOWLEDGMENT

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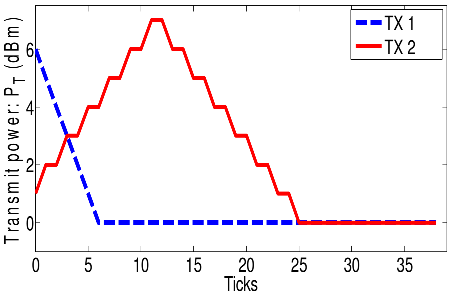

Figure 3. TX power adjustment for scenario 1 (game theory approach, two SUs).

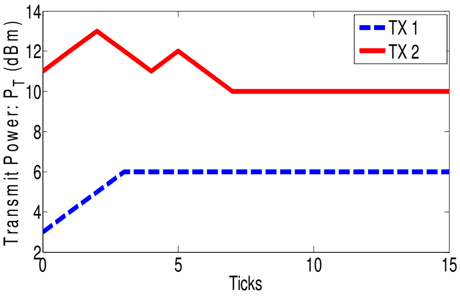

Figure 5. TX power adjustment for scenario 2 (game theory approach, two SUs).

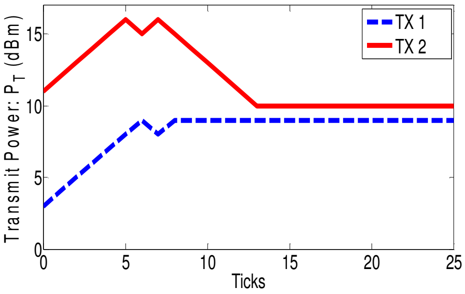

Figure 7. TX power adjustment for scenario 3 (game theory approach, two SUs).

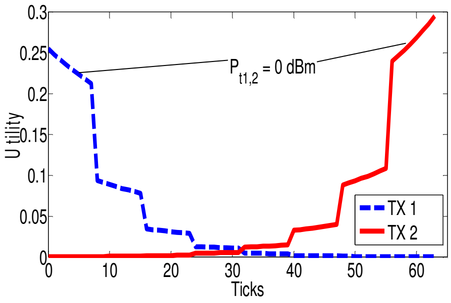

Figure 4. Utility variance with respect to transmit power and SINR parameters for scenario 1 (optimization approach).

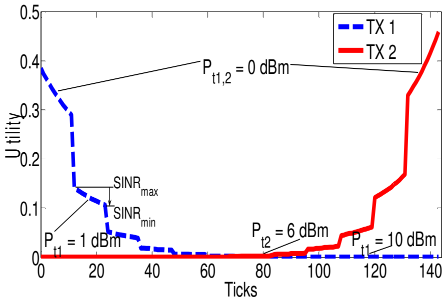

Figure 6. Utility variance with respect to transmit power and SINR parameters for scenario 2 (optimization approach).

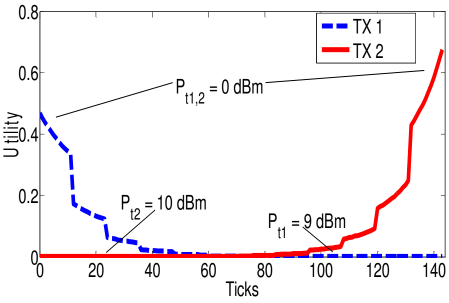

Figure 8. Utility variance with respect to transmit power and SINR parameters for scenario 3 (optimization approach).

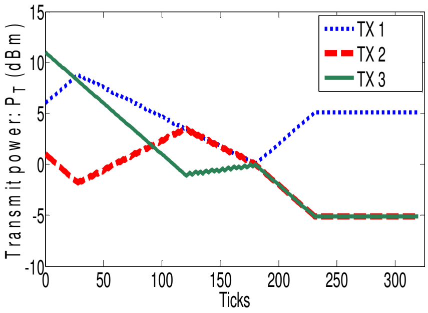

Figure 9. TX power adjustment for scenario 1 (game theory approach, three SUs).

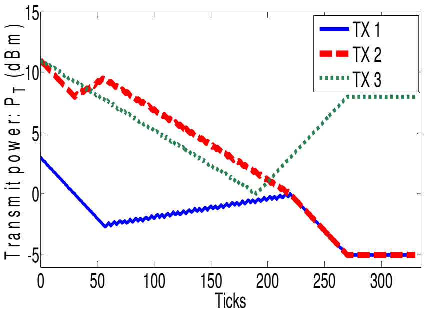

Figure 10. TX power adjustment for scenario 2 (game theory approach, three SUs).

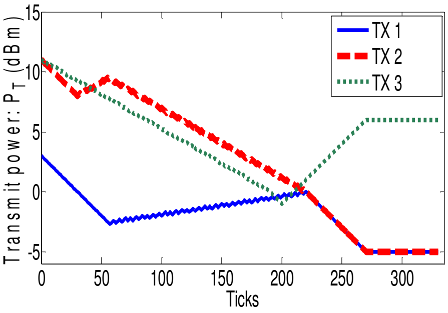

Figure 11. TX power adjustment for scenario 2 (game theory approach, three SUs).

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