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Distributed Power Allocation for Spectral Coexisting Multistatic Radar and Communication Systems Based on Stackelberg Game

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1. Introduction

With the rapid development of wireless services and mobile telecommunications, the radio frequency spectrum is becoming scarce and increasingly crowded [1]. The concept of spectrum sharing between radar and communication systems has brought considerable attention worldwide due to its potential to enhance spectrum efficiency [2].

In decentralized networks, game theory has been adopted as a natural and efficient tool for distributed resource optimization problems [3]. The problem of non-cooperative game theoretic power allocation for multistatic radar in a spectrum sharing environment is addressed in [4] for the first time, where the profit of each radar is defined by taking into account the target detection performance and aggregate interference at communication base station (CBS). The Nash bargaining-based spectrum sharing protocol is presented in [5]. However, the above static spectrum sharing protocols cannot fully mobilize the initiative of CBS. Stackelberg game can be employed to capture the hierarchical competition with different design objectives [6]. Although it has been applied in several studies [6][7], to the best of our knowledge, there are no published references that investigate this hierarchical interactions between the spectral coexisting multistatic radar and CBS systems.

This paper studies the problem of Stackelberg game based distributed power allocation for spectral coexisting multistatic radar and communication systems. The strategy aims to minimize the radiated power of each radar by optimizing transmit power allocation for a desired signal-to-interference-plus-noise ratio (SINR) meanwhile the CBS is protected from the interference of radar transmissions. We formulate this distributed power allocation process as a Stackelberg game, where the CBS is a leader and the radars are the followers. The Nash equilibrium (NE) for the formulated game is derived. Then, the existence of the NE and uniqueness of the solution are analytically proved. Moreover, an iterative algorithm is developed to solve the resulting problem. Finally, numerical simulations validate the convergence and effectiveness of the proposed scheme.

2. Game-Theoretic Formulation

Consider a multistatic radar consisting of multiple radars coexisting with a CBS in the same frequency band, as shown in Fig.1. The main aim of the multistatic radar is to minimize the radiated power of each radar by optimizing transmit power allocation subject to a desired SINR requirement for target detection and a maximum acceptable interference power threshold for CBS. The i-th radar receives the echoes from the target due to its transmitted signals as well as the signals from the other radars, both scattered off the target and through a direct path. The waveforms emitted from different radars may not be orthogonal because of the absence of radar transmission synchronization, which could induce considerable mutual interference.

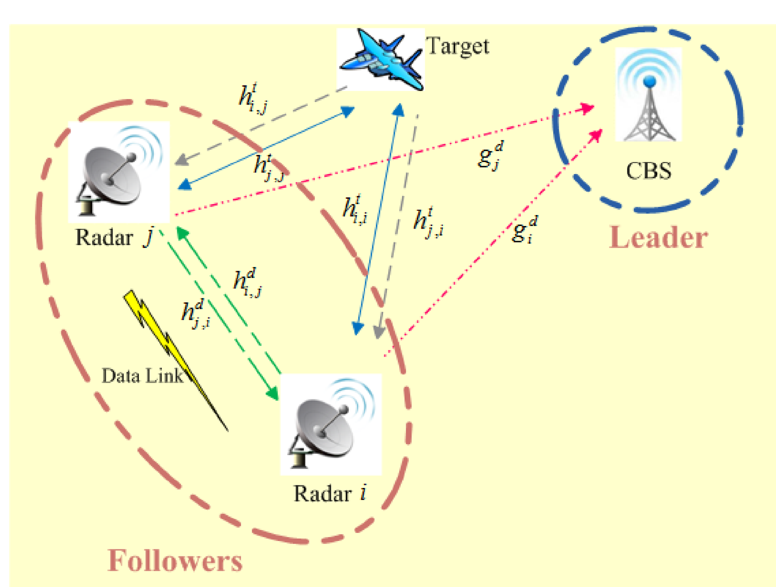

Fig.1. System model

Assume that successive interference cancellation technique is employed at each radar receiver to remove both direct and target scattered communication signals from the observed signal. At the CBS, it is also assumed that the radar transmitted signal scattered off the target is much weaker than that coming through the direct path from the radar transmitter, which is ignored for simplicity.

Here, the CBS plays the role as the leader to set prices to the received interference power from radars transmissions, whose utility function is defined as:

$$U_{\text{com}}(\boldsymbol{\xi},\mathbf{P}) = \left[\sum_{i=1}^{M_{\text{R}}} \xi_i P_i g_i^d - \frac{\left(\sum_{i=1}^{M_{\text{R}}} P_i g_i^d - T_{\text{tar}}\right)^2}{T_{\max}}\right] \times \varepsilon\left(T_{\max} - \sum_{i=1}^{M_{\text{R}}} P_i g_i^d\right),$$

Thus, the *leader-level* game can be formulated as follows:

$$\mathcal{P}_1: \quad \max_{\boldsymbol{\xi}} \; U_{\text{com}}(\boldsymbol{\xi},\mathbf{P}), \qquad \text{s.t.}: \sum_{i=1}^{M_{\text{R}}} P_i g_i^d \leq T_{\max}.$$

As the followers, with the fixed price, the utility function of radar i is defined as:

$$U_{\text{rad},i}(P_i,\mathbf{P}_{-i},\xi_i) = \ln(\gamma_i - \gamma_{\min}) - \xi_i P_i g_i^d,$$

To maximize its profit, the *follower-level* game can be expressed by:

$$\mathcal{P}_2: \quad \max_{\mathbf{P}} \; U_{\text{rad},i}(P_i,\mathbf{P}_{-i},\xi_i), \qquad \text{s.t.}: \begin{cases} C1: & \gamma_i \geq \gamma_{\min}, \forall i, \\ C2: & 0 \leq P_i \leq P_i^{\max}, \forall i. \end{cases}$$

Theorem 1 (Existence): At least one NE exists for the non-cooperative Nash game if:
(i) The transmit power is a non-empty, convex and compact subset of some Euclidean space.
(ii) The utility function is continuous and quasi-concave in the transmit power.

Theorem 2 (Uniqueness): The NE of the non-cooperative Nash game is unique.
Proof: To prove the uniqueness of NE in the game model, the best response function should be a standard function, which satisfies the *positivity*, *monotonicity*, and *scalability*. Refer to [4] for more details. ■

3. Numerical Results and Analysis

We first demonstrate the convergence performance of our proposed power allocation strategy. Fig.2 depicts the convergence process of multistatic radar system for different initial power allocation results, where the game model is initialized with **P** = {1000, 3000, 2000, 200} W. It can be seen from Fig.2 (a) that, the proposed scheme converge quickly with less than 6 iterations required to reach the unique NE values regardless of the initial strategies of the players. Moreover, one can notice that more transmit power is assigned to Radar 1 and Radar 2 to maintain the desired SINR performance, which is due to the fact that the target's RCSs with respect to these two radars are much smaller than others. Fig.2 (b) shows the SINR convergence performance of different radars, where the achieved SINR values tend to converge to 10 dB when the number of iterations approaches 5. It should be noted that the proposed power allocation scheme can guarantee fairness among all radars in the system.

Next, the convergence process of CBS is examined by the results in Fig.3. Correspondingly, Fig.3 (a) presents the convergence behavior for the utility function of CBS, where the utility of CBS reaches the equilibrium value as the number of iterations increases. Fig.3 (b) shows the change in the interference power the CBS receives due to the radar transmissions. As expected, our strategy respects the aggregate interference constraint. More specifically, the aggregate interference received at CBS for the proposed strategy is below the maximum interference tolerant limit. This is because the CBS can coordinate the interference power from the radar transmissions through updating the prices. Hence, the QoS requirement of CBS can be guaranteed by ensuring the multistatic radar system do not generate high interference to the CBS.

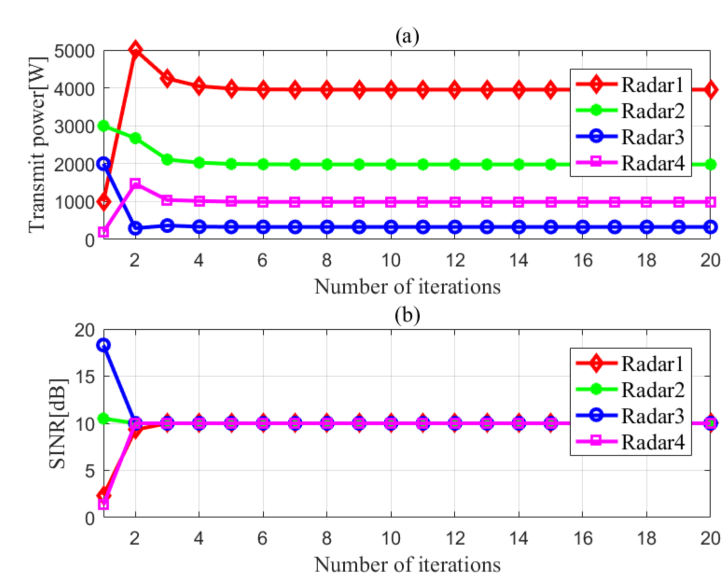

Fig.2. The convergence behavior of multistatic radar system: (a) Power allocation results; (b) SINR.

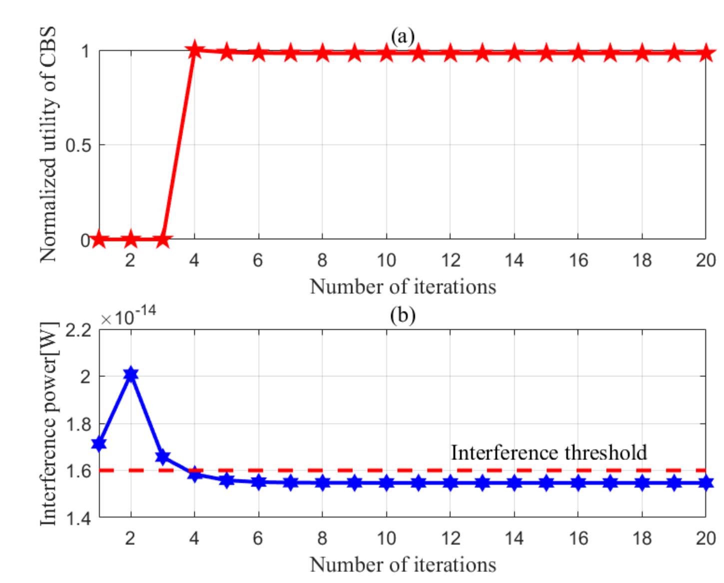

Fig.3. The convergence behavior of CBS: (a) Normalized utility of CBS; (b) Interference power received at CBS.

4. Conclusion Remarks

In this paper, we have studied the problem of distributed power allocation for spectral coexisting multistatic radar and communication systems. The main aim is to minimize the radiated power of each radar subject to a specified SINR requirement for target detection and a maximum aggregate interference tolerant threshold for CBS. Considering the strategic behaviors of the multistatic radar and CBS, we have formulated a Stackelberg game for the considered problem scenario, where the CBS is the leader and the radars are the followers. The game model jointly investigated the revenue maximization of the CBS by pricing and utility maximization of multiple radars by power allocation. The NE of the formulated game was derived, then the existence and uniqueness of the NE were analytically proved. Also, a distributed iterative power allocation method with lower signaling overhead was developed to solve the resulting problem. Finally, numerical results were provided to verify the convergence and performance of the proposed strategy.

5. References

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