DISTRIBUTED POWER ALLOCATION FOR SPECTRAL COEXISTING MULTISTATIC RADAR AND COMMUNICATION SYSTEMS BASED ON STACKELBERG GAME

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ABSTRACT

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 communication base station (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 results verify that the proposed scheme is effective on power allocation and CBS protection with reduced signaling overhead.

Index Terms— Distributed power allocation, Stackelberg game, Nash equilibrium (NE), spectral coexistence, multistatic radar

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]. The problem of delay estimation for spectrum sharing between orthogonal frequency division multiplexing (OFDM) radar and communication systems is studied in [3]. Reference [4] investigates power minimization-based robust OFDM radar waveform design for spectral coexisting radar and communications. The authors in [5] develop a joint framework for the overlaid communication systems and pulsed radars. Other existing works can refer to [6-8].

In decentralized networks [9][10], game theory has been adopted as a natural and efficient tool for distributed resource optimization problems [11], which provides a framework for analyzing interactions between rational but selfish players. Recently, some game-theoretic algorithms are developed for radar systems with different setups in [12-14]. The problem of non-cooperative game theoretic power allocation for multistatic radar in a spectrum sharing environment is addressed in [15] 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 [16]. 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 [17]. Although it has been applied in several studies [18-21], 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 gap motivates this paper.

In this paper, we develop a distributed power allocation framework for spectral coexisting multistatic radar and communication systems using hierarchical game theory. Specifically, we take the strategic behaviors of the CBS and radars into consideration and formulate the transmit power allocation process between them as a Stackelberg game. In the game model, the CBS acts as a leader and maximizes its own profit by pricing the interference. On the other hand, the radars are the followers of the formulated game, and compete selfishly in a non-cooperative Nash game to maximize their individual utilities based on the released interference prices from the CBS. The Nash equilibrium (NE) for the formulated game is derived. Then, the existence and uniqueness of the solution are analytically proved. Besides, an iterative method with low complexity and reduced signaling overhead is proposed. Finally, numerical simulations validate the convergence and effectiveness of the proposed scheme.

2. SYSTEM MODEL

Consider a multistatic radar consisting of M_{R} radars coexisting with a CBS in the same frequency band [15], as shown in Fig.1. The main aim of the multistatic radar is to minimize the radiated power of each radar by optimizing transmit

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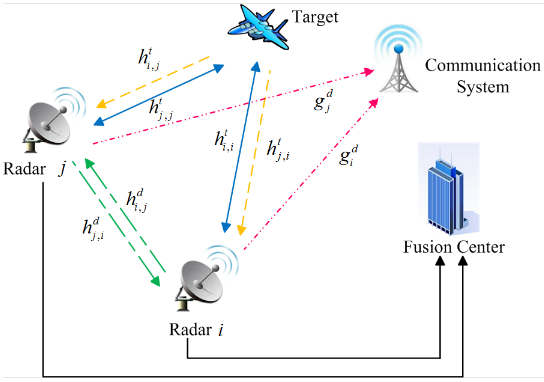

Fig. 1. Illustration of the system model.

power allocation subject to a desired signal-to-interference-plus-noise ratio (SINR) requirement for target detection and a maximum acceptable interference power threshold for CBS. The ith 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. 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 [16]. 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.

In the underlying system, each radar can determine the presence of a target by employing a binary hypothesis testing on the received signals based on the generalized likelihood ratio test [22], and sends the target information to the fusion center, which takes a final decision once the information coming from all the radars is collected. Thus, the probabilities of detection $p_{\mathrm{D},i}(\lambda_i, \gamma_i)$ and false alarm $p_{\mathrm{FA},i}(\lambda_i)$ are:

$$\begin{cases} p_{\mathrm{D},i}(\lambda_i, \gamma_i) = \left(1 + \dfrac{\lambda_i}{1-\lambda_i} \cdot \dfrac{1}{1+K\gamma_i}\right)^{1-K}, \\ p_{\mathrm{FA},i}(\lambda_i) = (1-\lambda_i)^{K-1}, \end{cases} \tag{1}$$

where λ_i is the detection threshold, K is the number of received pulses in the time-on-target. γ_i denotes the SINR received at radar i, which can be given by:

$$\gamma_i = \frac{h^t_{i,i} P_i}{\sum_{j=1, j\neq i}^{M_{\mathrm{R}}} c_{i,j}\left(h^d_{i,j} P_j + h^t_{i,j} P_j\right) + \sigma_w^2} = \frac{h^t_{i,i} P_i}{I_{-i}}, \tag{2}$$

where P_i is the transmit power of radar i, $h^t_{i,i}$ represents the propagation gain for the radar i-target-radar i path, $h^t_{i,j}$ represents the propagation gain for the radar i-target-radar j path, $h^d_{i,j}$ represents the direct radar i-radar j path, $c_{i,j}$ denotes the cross correlation coefficient between the ith radar and jth radar, σ_w^2 denotes the noise power, and $I_{-i} = \sum_{j=1, j\neq i}^{M_{\mathrm{R}}} c_{i,j}\left(h^d_{i,j} P_j + h^t_{i,j} P_j\right) + \sigma_w^2$ denotes the total interference and noise received at the ith radar. The definitions of different propagation gains are omitted here due to space limitation. Refer to [15].

In the multistatic radar, to satisfy a desired target detection performance, the received SINR of each radar should be no less than the threshold $\gamma_{\min}$:

$$\gamma_i \geq \gamma_{\min}. \tag{3}$$

To guarantee the quality of service (QoS) of CBS, the total interference power generated by the multiple radars should not exceed a given threshold $T_{\max}$ at the CBS. Hence, to satisfy the interference power constraint, the sum interference power received at the CBS should be upper bounded:

$$\sum_{i=1}^{M_{\mathrm{R}}} P_i g_i^d \leq T_{\max}, \tag{4}$$

where g_i^d is the direct radar i-CBS path.

3. STACKELBERG GAME FORMULATION

Since the radars in the multistatic system are selfish, they act solely according to their own interests. From the CBS's point of view, these selfish moves result in inefficient resource utilization and the violation of the given interference constraint. In the following, we aim to formulate a distributed power allocation scheme among different radars to maximize their utilities without jeopardizing the QoS of CBS. The Stackelberg game matches the underlying model perfectly, which consists of a leader and several followers. The CBS acts as a leader, who decides the prices first through the maximization of its own profit. The radars act as the followers competing selfishly in a non-cooperative Nash game according to the price subsequently.

3.1. Leader Sub-Game

Here, the CBS plays the role as the leader to set prices to the received interference power from radars transmissions. The objective of the leader is to maximize its own utility, while limiting the interference caused by radars transmissions to protect communications. Then, the followers compete with each other for the power resource in a non-cooperative Nash game to maximize their individual utilities [17].

For this purpose, we define the utility function of the leader as follows:

$$U_{\mathrm{com}}(\boldsymbol{\xi}, \mathbf{P}) = \left[\sum_{i=1}^{M_{\mathrm{R}}} \xi_i P_i g_i^d - \frac{\left(\sum_{i=1}^{M_{\mathrm{R}}} P_i g_i^d - T_{\mathrm{tar}}\right)^2}{T_{\max}}\right] \times \varepsilon\left(T_{\max} - \sum_{i=1}^{M_{\mathrm{R}}} P_i g_i^d\right), \tag{5}$$

where $\boldsymbol{\xi} = [\xi_1, \cdots, \xi_{M_{\mathrm{R}}}]^T$ is the interference price vector, $\mathbf{P} = [P_1, \cdots, P_{M_{\mathrm{R}}}]^T$ is the transmit power vector, ξ_i is the unit interference price for radar i, $\varepsilon(\cdot)$ is step function, and

T_{tar} is the target interference power, which is much smaller than $T_{\max}$. Since the aggregate interference that the CBS can tolerate is restricted by (4), the CBS needs to find the best prices ξ_i to maximize its profit while guaranteeing that the interference constraint in (4) is met. Thus, the *leader-level* game can be formulated as:

$$\mathcal{P}_1: \quad \max_{\boldsymbol{\xi}} \ U_{\text{com}}(\boldsymbol{\xi}, \mathbf{P}), \tag{6a}$$

$$\text{s.t.}: \sum_{i=1}^{M_{\text{R}}} P_i g_i^d \le T_{\max}. \tag{6b}$$

Note that the optimization problem of CBS is to derive the optimal ξ_i's such that its utility is maximized based on the NE solution of the following sub-game.

3.2. Follower Sub-Game

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

$$U_{\text{rad},i}(P_i, \mathbf{P}_{-i}, \xi_i) = \ln(\gamma_i - \gamma_{\min}) - \xi_i P_i g_i^d, \tag{7}$$

where $\mathbf{P}_{-i} = [P_1, \cdots, P_{i-1}, P_{i+1}, \cdots, P_{M_{\text{R}}}]^T$ denotes the power allocation adopted by all radars apart from radar i. It is noteworthy that the utility function (7) consists of the achievable SINR part and the cost part. The more transmit power is allocated to radar i, the better target detection performance can be obtained, whereas more interference will be incurred to the CBS. Thus, there exists a tradeoff between the profit and cost in each radar. To maximize its profit, the *follower-level* game can be expressed by:

$$\mathcal{P}_2: \quad \max_{\mathbf{P}} \ U_{\text{rad},i}(P_i, \mathbf{P}_{-i}, \xi_i), \tag{8a}$$

$$\text{s.t.}: \begin{cases} C1: & \gamma_i \ge \gamma_{\min}, \forall i, \\ C2: & 0 \le P_i \le P_i^{\max}, \forall i. \end{cases} \tag{8b}$$

The constraint $C1$ implies that the achievable SINR value should be no less than $\gamma_{\min}$, and the constraint $C2$ stands that the transmit power of radar i is limited to $P_i^{\max}$.

Therefore, the Stackelberg game for the considered problem scenario has been formulated by combining sub-problems $\mathcal{P}_1$ and $\mathcal{P}_2$.

4. ANALYSIS OF THE GAME MODEL

In this section, we solve the resulting problem optimally by two steps. First, we derive the closed-form expression for the optimal transmit power of each radar with a fixed value of $\boldsymbol{\xi}$. Then, the optimal value for $\boldsymbol{\xi}$ is achieved in the second step via one-dimensional exhaustive search.

Taking the first derivative of $U_{\text{rad},i}(P_i, \mathbf{P}_{-i}, \xi_i)$ with respect to P_i, we can obtain the solution of $\mathcal{P}_2$ for radar i as:

$$P_i^{(n+1)} = \left[\frac{P_i^{(n)}}{\gamma_i^{(n)}} \gamma_{\min} + \frac{1}{\xi_i^{(n)} g_i^d} \right]_0^{P_i^{\max}}, \tag{9}$$

where $[x]_a^b = \max\{\min\{x, b\}, a\}$, and n is iteration index.

Theorem 1 (Existence): The non-cooperative Nash game model $\mathcal{P}_2$ has at least one NE.

Proof: At least one NE exists in the game $\mathcal{P}_2$ if for $\forall i$: **(i)** The transmit power P_i is a non-empty, convex and compact subset of some Euclidean space; **(ii)** The utility function $U_{\text{rad},i}(P_i, \mathbf{P}_{-i}, \xi_i)$ is continuous and quasi-concave in P_i.

It is obvious that the Condition **(i)** is satisfied. Then, we take the second order derivative of $U_{\text{rad},i}(P_i, \mathbf{P}_{-i}, \xi_i)$ with respect to P_i and obtain $\frac{\partial^2 U_{\text{rad},i}(P_i, \mathbf{P}_{-i}, \xi_i)}{\partial P_i^2} = -\frac{(h_{i,i}^t)^2}{I_{-i}^2(\gamma_i - \gamma_{\min})^2} < 0$. Thus, $U_{\text{rad},i}(P_i, \mathbf{P}_{-i}, \xi_i)$ is concave with respect to P_i. As a consequence, the utility function is continuous and quasi-concave, which completes the proof. ■

Theorem 2 (Uniqueness): The NE of the non-cooperative Nash game model $\mathcal{P}_2$ is unique.

Proof: To show that the NE of the game model $\mathcal{P}_2$ is unique, we need to prove that radar i's best response strategy function $f(P_i) = \frac{P_i}{\gamma_i}\gamma_{\min} + \frac{1}{\xi_i g_i^d}$ should be standard, which satisfies the following conditions [15]:

(i) Positivity: For $\forall i$, $f(P_i) > 0$;

(ii) Monotonicity: If $P_i^a > P_i^b$, then $f(P_i^a) > f(P_i^b)$;

(iii) Scalability: For $\forall \beta > 1$, $\beta f(P_i) > f(\beta P_i)$.

For Condition **(i)**, it is evident that $f(P_i) = \frac{P_i}{\gamma_i}\gamma_{\min} + \frac{1}{\xi_i g_i^d} > 0$, thus the positivity property is satisfied.

For Condition **(ii)**, if $P_i^a > P_i^b$, then $f(P_i^a) - f(P_i^b) > 0$, thus the monotonicity property is satisfied.

For Condition **(iii)**, since $\forall \beta > 1$, we obtain $\beta f(P_i) - f(\beta P_i) > 0$, thus the scalability property is satisfied. In conclusion, the best response function $f(P_i)$ is standard, and the NE of the game model $\mathcal{P}_2$ is unique. ■

Based on the above analysis, a distributed power allocation algorithm is developed, which is composed of two loops. In the inner loop, the radars compete with each other via a non-cooperative game. In the outer loop, the CBS updates the price ξ_i for each radar to maximize its own profit according to the received interference. It is noted that the inner loop can converge with any price as long as the conditions in *Theorem 2* are satisfied. The iterative algorithm is shown in **Algorithm 1**, where $(\cdot)^*$ denotes the NE solution, and Δ denotes the iterative step size.

Remark: After the CBS broadcasts the prices, each radar optimizes its own transmit power. The channel state information (CSI) needed at each radar is only the CSI on its own target surveillance channel, while treating other interference as noise. It is noteworthy that the CBS is required to sense the total received interference to update the prices. Thus, the CBS does not need to know the individual CSI between each radar and CBS, which reduces the signaling overhead [17].

5. NUMERICAL RESULTS

In this section, numerical results are dedicated to demonstrate the performance of the proposed game-theoretical scheme. To this end, we consider a multistatic radar system with $M_{\text{R}} = 4$ radars. The system parameters are set as follows: $P_i^{\max} = 5000\text{W}$, $\sigma_w^2 = 10^{-17}\text{W}$, $\gamma_{\min} = 10\text{dB}$,

Algorithm 1: Distributed Power Allocation Algorithm

Input: Set $\gamma_{\min}$, $T_{\max}$, $P_i^{(1)}$, $\xi_i^{(1)}$, $n = 1$, $\Delta > 0$, $\epsilon > 0$
Output: P_i^*, ξ_i^* $(\forall i)$

```
repeat
    repeat
        for i = 1, ..., M_R do
            Calculate P_i^(n) according to (9);
        end
    until |U_rad,i^(n+1) - U_rad,i^(n)| < ε;
    ξ_i^(n+1) ← ξ_i^(n) + Δ;
    n ← n + 1;
until |U_com^(n+1) - U_com^(n)| < ε;
Output the final solutions;
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$T_{\max} = 1.6 \times 10^{-14}$W, $T_{\text{tar}} = 10^{-17}$W, $\xi_i = 5 \times 10^{20} (\forall i)$. To evaluate the impact of the target RCS on the power allocation results, we assume the target's RCSs with respect to different radars are 0.5m^2, 1m^2, 6m^2, and 2m^2, respectively. The positions of multistatic radar, CBS, target, and other parameters are the same as in [15], which are omitted due to space limitation.

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 $\mathbf{P} = \{1000, 3000, 2000, 200\}$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 $\gamma_{\min} = 10$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 $T_{\max}$. 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.

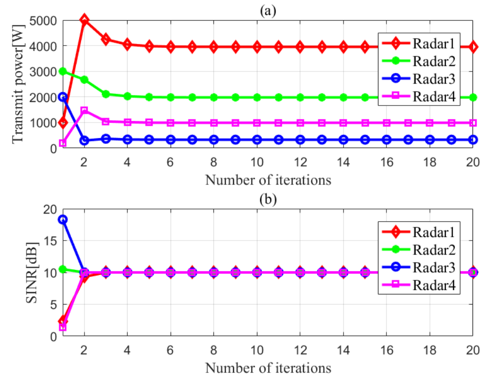

Fig. 2. The convergence behavior of multistatic radar system: (a) Power allocation results; (b) SINR.

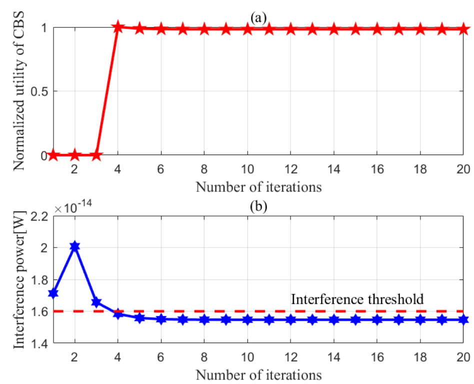

Fig. 3. The convergence behavior of CBS: (a) Normalized utility of CBS; (b) Interference power received at CBS.

6. 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.

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