IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 13, 2018, accepted December 27, 2018, date of publication January 18, 2019, date of current version February 8, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2893459

Power Control in Relay-Assisted Anti-Jamming Systems: A Bayesian Three-Layer Stackelberg Game Approach

ZHIBIN FENG[1,2], (Student Member, IEEE), GUOCHUN REN[1], JIN CHEN[1], XIAOBO ZHANG[1], YIJIE LUO[1], MENG WANG[1], AND YUHUA XU[1,2], (Member, IEEE)

[1]College of Communications Engineering, Army Engineering University of PLA, Nanjing 210000, China
[2]Science and Technology on Communication Networks Laboratory, Shijiazhuang 050002, China

Corresponding author: Guochun Ren (guochunren@yeah.net)

This work was supported in part by the National Natural Science Foundation of China under Grant 61671473 and Grant 61771488, in part by the Natural Science Foundation for Distinguished Young Scholars of Jiangsu Province under Grant BK20160034, and in part by the Open Research Foundation of Science and Technology on Communication Networks Laboratory.

ABSTRACT This paper investigates the multi-user power control problem in relay-assisted anti-jamming systems. Because of the hierarchical confrontation characteristics between users and jammer, we take the incomplete information and observation error into consideration and formulate an anti-jamming Bayesian three-layer Stackelberg game, in which primary users act as leaders, relay users act as vice-leaders, and jammer acts as a follower. Both users and jammer have the ability to sense others' transmission power and choose optimal power to realize the maximum of utility. Based on the backward induction method, we propose a multi-user hierarchical iterative algorithm to obtain the Stackelberg equilibrium (SE) and prove the existence and uniqueness of SE. Finally, simulation results are compared with the Nash equilibrium to verify the effectiveness of the proposed game. Moreover, both the influence of incomplete information and the observation error on utility are analyzed.

INDEX TERMS Power control, anti-jamming, three-layer Stackelberg game, Stackelberg equilibrium.

I. INTRODUCTION

Wireless anti-jamming technology has played an important role in ensuring the security and reliability of communication so far, and it will become a hot topic for a long time in the future. Many anti-jamming technologies have been proposed in power domain [1]–[10], frequency domain [11]–[18], and spatial domain [19]–[23], among which the power anti-jamming technology was generally considered as a direct and effective method. While in relay-assisted communication networks, the existing power anti-jamming work mainly focused on the single-user situation [6], [7], which had achieved some effects but couldn't satisfy the multi-user condition. In this study, considering the incomplete information and observation error, we investigate the multi-user power control problem in relay-assisted communication networks.

In power domain [1]–[10], the anti-jamming technology usually adopts the method of adjusting transmission power to ensure the normal communication, which is a direct way to realize anti-jamming communication and has already been widely used. However, in power anti-jamming field, the existing technologies are not perfect enough due to the limitations of application environment. Generally, there are still some problems haven't been solved. Firstly, the multi-user situation which is common to see in wireless communication was rarely investigated. Secondly, considering the antagonisms between user and jammer, both the incomplete information and observation error need to be considered simultaneously.

In this paper, we mainly study the power control problem of multi-user in relay-assisted communication networks. For jammer, it aims at reducing communication quality by adjusting jamming power. To improve anti-jamming ability, users need an effective power control method to choose optimal transmission power when facing different jamming strategies, which is meaningful to guarantee reliable communication. However, it is hard to obtain the optimal power strategy and we mainly face the following challenges: (i) The single-user power control optimization approach can't be used directly in multi-user situation because of the joint constraint condition and operation complexity. (ii) User should act as leader to have first advantage compared to jammer in the communication. (iii) We need to take the incomplete information and observation error into consideration simultaneously.

Considering the hierarchical confrontation characteristics between users and jammer, we propose an anti-jamming Bayesian three-layer Stackelberg game. In the formulated game, the users are consisted of primary users which act as leaders and relay users which act as vice-leaders, while the jammer acts as follower. Given the utility functions of primary users, relay users and jammer, we derive the closed-form expressions of Stackelberg Equilibrium (SE) based on the duality optimization theory [33], [34] and obtain the optimal power strategy. The main contributions of this paper are summarized as follows:

- In the multi-user situation, considering the incomplete information and observation error, a Bayesian three-layer Stackelberg game is formulated to model and analyze the power control problem in relay-assisted communication networks, in which primary users act as leaders, relay users act as vice-leaders and jammer acts as follower.
- The Stackelberg Equilibrium (SE) is obtained as the optimal power strategy. In order to obtain SE, we propose a multi-user hierarchical iterative algorithm (MHIA). Moreover, both the existence and uniqueness of SE are proved.
- Simulation results are given to analyze the influence of observation error, radius of fluctuation, jamming distance and jamming cost on utility. We also compare the users' utilities of SE and Nash Equilibrium (NE) to prove the effectiveness of game proposed in this paper.

In the rest of this paper, we analyze the related work in Section II. In Section III, we establish system model and give relative formulation about the power control problem. In Section IV, we propose an anti-jamming Bayesian three-layer Stackelberg game and obtain optimal power strategy based on Stackelberg Equilibrium. Moreover, the existence and uniqueness of SE are proved. Simulation results and some necessary discussions are shown in Section V. In Section VI, we draw a conclusion from the above analysis.

II. RELATED WORK

There is no doubt that anti-jamming communication technology has increasingly captured considerable attention and a large number of studies have been accomplished in the recent years. In [24] and [25], the authors introduced game theoretic to analyze wireless communication. In [26], the authors formulated a non-zero-sum game to model the communication process with transmission cost. A zero-sum game was proposed to analyze the relationship between secondary user and jammer in [14]. In [27], a stochastic game was modeled in multi-agent scene. In [28], considering the incomplete information, the authors proposed a Bayesian game to analyze the attacks in wireless networks. Based on the hierarchical confrontation characteristics between user and jammer, the authors adopted Stackelberg game [1]–[10] which is a appropriate tool to model the anti-jamming problem. In [1], the authors analyzed two models about the single-channel and multi-channel problem. Moreover, the optimal strategy was obtained through Stackelberg Equilibrium (SE), and the existence of SE was also proved. In [2], considering the observation error, the authors proposed a Stackelberg game to model the anti-jamming problem that user acted as leader firstly, and then jammer acted as follower. In [3], the authors investigated the anti-jamming communication under incomplete information. In [4], a cooperative anti-jamming mechanism based on price was proposed, and a multiple-leader one-follower Stackelberg game was formulated to solve the anti-jamming transmission problem. In [5], the authors combed the anti-jamming technologies under different scenarios.

Introduction of relay further expends communication application scenario and can help user improve communication quality effectively [29]–[32]. In relay-assisted anti-jamming communication networks [6], [7], the relay node was existed to help the source node transmit messages and guarantee communication quality, which acted as vice-leader in the Stackelberg game. The relay selection problem was also considered in [7] as there are multi relays to select at the same time. However, as the number of users increasing gradually in the communication system, relay need to allocate power for different channels simultaneously under the joint constraint condition, and the methods in [6] and [7] are no longer applicable to multi-user situation. Moreover, the incomplete information and observation error shouldn't be ignored.

With the development of anti-jamming technology, the multi-user situation [8], [9] were also investigated. Considering the mutual interference [8] among users, the authors proposed a sub-gradient based Bayesian Stackelberg iterative algorithm to realize the power optimization problem in multi-user situation, while the jammer acted as leader and users acted as followers in the proposed game. In [9], the authors proposed two game under different decision-making scenarios that users and jammer made strategies based on sense or not. While in the actual communication, jammer makes malicious jamming attack mainly depends on user's transmission situation to avoid ineffective jamming, which decides the role assignment that user is leader and jammer is follower, but it was not considered in [8] and [9].

Different from the existing work, we formulate a Bayesian three-layer Stackelberg game that primary users act as leaders, relay users act as vice-leaders, and jammer acts as follower, which is common to see in relay-assisted communication networks. Moreover, because of the hierarchical competitive relationships between users and jammer, the incomplete information and observation error are also considered in this paper.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

We assume that there exist multiple transmitters as primary users (PUs), a relay and a intelligent jammer in

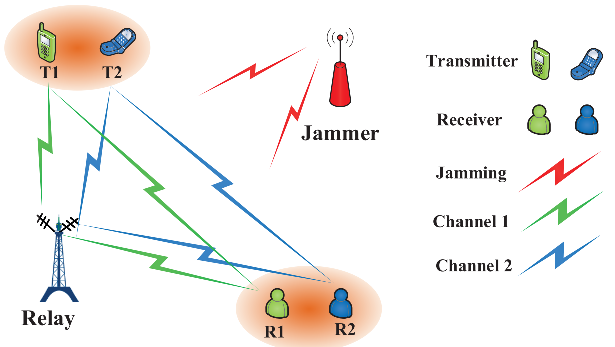


FIGURE 1. Communication attacked by jammer in wireless relay-assisted anti-jamming systems.

communication networks, and the relay have many antennas as relay users (RUs) to help PUs broadcast messages to legitimate receivers, which is shown in Fig. 1. Each user-pair contains of a primary user (PU) and a relay user (RU), transmitting messages on the common channel. In order to guarantee each user-pair has an independent channel so that the co-channel mutual interference can be avoided, the channels are pre-allocated to all user-pairs before communication. Moreover, both users and jammer could sense others' power, and then make strategies to achieve the maximum of utility, which is reflected in the model that PUs transmit messages firstly, then RUs choose power to help PUs transmit packets after knowing PUs' strategies, and jammer selects its jamming power based on the sense result of users' power in the last.

In the above model, the available channel set is $\mathcal{K} = [1, 2, \ldots, K]$. We define the primary user set as $\mathcal{M} = [1, 2, \ldots, M]$, and power set as $\mathcal{P} = [p_1, \ldots, p_m, \ldots, p_M]$, in which $p_m\ (m \in \mathcal{M})$ denotes the mth PU's transmission power on the mth channel, and $p_{-m} = [p_1, \ldots, p_{m-1}, p_{m+1}, \ldots, p_M]$ denotes the primary users' transmission power set except the mth PU. Similarly, the relay user set is $\mathcal{N} = [1, 2, \ldots, N]$. PUs and RUs are corresponding one by one in the model, i.e., $K = M = N$. All the RUs' power set is $\mathcal{Q} = [q_1, \ldots, q_n, \ldots, q_N]$, in which $q_n\ (n \in \mathcal{N})$ denotes the nth RU's transmission power on the nth channel, and $q_{-n} = [q_1, \ldots, q_{n-1}, q_{n+1}, \ldots, q_N]$ denotes the relay users' transmission power set except the nth RU. J denotes the total jamming power on all channels. Moreover, the background noise is denoted as N_0. Inspired by the path-loss model [35], [36] which has been widely used in the communication, the channel gain between the mth PU, nth RU and the legitimate receiver are denoted as $\alpha_m = d_m^{-\delta}$ and $\eta_n = v_n^{-\delta}$, where δ is the pass-loss factor, d_m and v_n denote the distance of between the mth PU, nth RU and the legitimate receiver, respectively. Similarly, the channel gain of jamming link is denoted as $\beta = w^{-\delta}$, where w denotes the distance between jammer and the legitimate receiver. For convenience, we list some necessary notations related to this paper in Table 1.

TABLE 1. Summation of used notations.

Notations	Explanation
PU	primary user
RU	relay user
$\mathcal{M}$	set of all the PUs
$\mathcal{N}$	set of all the RUs
$\mathcal{K}$	set of all the available channels
p_m	the mth PU's transmission power
q_n	the nth RU's transmission power
$\tilde{p}_m$	the mth PU's power observed by jammer
$\tilde{q}_n$	the nth RU's power observed by jammer
J_k	jamming power on the kth channel
J	total jamming power on all channels
$\tilde{J}$	jammer's power observed by users
α_m	gain between the mth PU and receiver
η_n	gain between the nth RU and receiver
β	gain between the jammer and receiver
$\mathcal{P}$	set of PUs' power
$\mathcal{Q}$	set of RUs' power
p_{-m}	set of PUs' power except the mth PU
q_{-n}	set of RUs' power except the nth RU
C_m	unit power cost of the mth PU
D_n	unit power cost of the nth RU
E	unit power cost of jammer
$p_{m\max}$	the maximum of the mth PU's power
$q_{\max}$	the maximum of relay's power
$J_{\max}$	the maximum of jamming power
N_0	background noise
p_m^*	optimal power of the mth PU
q_n^*	optimal power of the nth RU
J^*	optimal power of jammer
$\mathcal{P}^*$	set of PUs' optimal power
$\mathcal{Q}^*$	set of RUs' optimal power
p_{-m}^*	set of PUs' optimal power except the mth RU
q_{-n}^*	set of RUs' optimal power except the nth RU

Assumption 1: For PUs and RUs, considering the existence of incomplete information [3], we assume the channel gain β has X positive states, which contains $\beta_1, \ldots, \beta_x, \ldots, \beta_X$. The transmission cost C_m of the mth PU has Y positive states, which contains $C_{m1}, \ldots, C_{my}, \ldots, C_{mY}$. Similarly, the transmission cost D_n of the nth RU has Z positive states, which contains $D_{n1}, \ldots, D_{nz}, \ldots, D_{nZ}$. The joint probability distribution of β, C_m and β, D_n can be defined as $\pi_m(\beta_x, C_{my})$ and $\nu_n(\beta_x, D_{nz})$ respectively, and we can get $\sum_{x=1}^{X}\sum_{y=1}^{Y}\pi_m(\beta_x, C_{my}) = 1$, $\sum_{x=1}^{X}\sum_{z=1}^{Z}\nu_n(\beta_x, D_{nz}) = 1$.

Assumption 2: For jammer, considering it is uncertain about user information, we assume the channel gain α_m, η_n of the mth PU-receiver pair and nth RU-receiver pair has H and L positive states respectively, which contains $\alpha_{m1}, \ldots, \alpha_{mh}, \ldots, \alpha_{mH}$ and $\eta_{n1}, \ldots, \eta_{nl}, \ldots, \eta_{nL}$. The transmission cost E of jammer has T positive states, which contains $E_1, \ldots, E_t, \ldots, E_T$. The joint probability distribution of α_m, η_n, E can be defined as $\sigma(\alpha_{mh}, \eta_{nl}, E_t)$, and we can get $\sum_{h=1}^{H}\sum_{l=1}^{L}\sum_{t=1}^{T}\sigma(\alpha_{mh}, \eta_{nl}, E_t) = 1$.

B. PROBLEM FORMULATION

In relay-assisted communication networks, a cooperative group consisted of multi user-pairs is competitive with the malicious jammer. Considering the hierarchical competitive relationships and constraint of incomplete information, we use the Stackelberg Game, which is an effective tool to build the anti-jamming model, to solve the power control optimization problem. Based on the formulated model, we propose a Bayesian three-layer Stackelberg game, in which PUs act as leaders, and RUs act as vice-leaders, while jammer acts as follower.

Considering the observation error of jammer, we define the error factor $\varepsilon_m = |\tilde{p}_m - p_m|/p_m$ and $\varepsilon_n^{(r)} = |\tilde{q}_n - q_n|/q_n$, where $\tilde{p}_m, \tilde{q}_n$ are the jammer's estimated power of the mth PU and nth RU. Similarly, for users, the error factor can be defined as $\varsigma_k = |\tilde{J}_k - J_k|/J_k$, where $\tilde{J}_k$ denotes jammer's power on the kth channel estimated by user. Moreover, as shown in Fig. 2, the jamming model belongs to partial band jamming. Jammer transmits signals on all channels at the same time and allocates power equally to each channel[1], which meets the following power constraint condition:

$$\begin{cases} J_1 = \cdots = J_k = \cdots = J_K \\ \sum_{k=1}^{K} J_k < J_{\max} \end{cases} \tag{1}$$

where J_k ($k \in \mathcal{K}$) denotes the jammer's power on the kth channel, and $J_{\max}$ denotes the maximum jamming power of jammer.

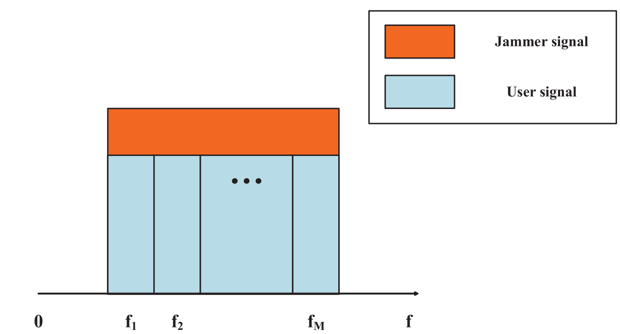


FIGURE 2. Signal frequency spectrum chart.

Inspired by [1]–[3], we give the utility function based on Signal-on-Interference-plus-Noise Ratio (SINR) which has been widely used. We define the jammer's utility with the incomplete information of the PU's, RU's channel gain α, η and jammer's unit power cost E in the following:

$$V = -\sum_{i=1}^{M}\sum_{h=1}^{H}\sum_{l=1}^{L}\sum_{t=1}^{T}\sigma(\alpha_{ih}, \eta_{il}, E_t)\frac{\alpha_{ih}\tilde{p}_i + \eta_{il}\tilde{q}_i}{N_0 + \beta J_i} - \sum_{h=1}^{H}\sum_{l=1}^{L}\sum_{t=1}^{T}\sigma(\alpha_{ih}, \eta_{il}, E_t)E_t J. \tag{2}$$

where $\sigma(\alpha_{ih}, \eta_{il}, E_t)$ denotes the joint probability distribution of α_i, η_i and E.

[1]To simplify the model, we assume jammer allocates power equally to each channel. Considering jammer could allocate different power on different channel to achieve a better jamming effect, we will investigate it in the future study under discrete power strategy scenario.

Similarly, considering the incomplete information of jammer's channel gain β and unit power cost D of RUs, the utility of relay (i.e., the total utilities of all RUs) is defined as:

$$R = \sum_{i=1}^{M}\sum_{x=1}^{X}\sum_{z=1}^{Z}\nu_i(\beta_x, D_{iz})(\frac{\alpha_i p_i + \eta_i q_i}{N_0 + \beta_x \tilde{J}_i} - D_{iz}q_i). \tag{3}$$

where $\nu_i(\beta_x, D_{iz})$ denotes the joint probability distribution of β and D_i.

Similar to the utility function above, considering the incomplete information of channel gain β and unit power cost C_m of the mth PU, we define the mth PU's utility as:

$$U_m = \sum_{x=1}^{X}\sum_{y=1}^{Y}\pi_m(\beta_x, C_{my})(\frac{\alpha_m p_m + \eta_m q_m}{N_0 + \beta_x \tilde{J}_m} - C_{my}p_m). \tag{4}$$

where $\pi_m(\beta_x, C_{mz})$ denotes the joint probability distribution of β and C_m.

According to the utility functions given above, all users and jammer aim to achieve the maximum of respective utility, and the power control optimization problem can be solved by the three-layer programming method, which is shown as follows:

$$\begin{cases} \max\limits_{p_m} U_m(p_m, q_m, J_m) \\ \text{subject to} : p_m \le p_{m\max} \\ \quad \textit{The optimal solution} : (q_m^*, J_m^*) \\ \quad \begin{cases} \max\limits_{q_n} R(\mathcal{P}, q_n, q_{-n}, J) \\ \text{subject to} : \sum_{n=1}^{N} q_n \le q_{\max} \\ \quad \textit{The optimal solution} : (J^*) \\ \quad \begin{cases} \max\limits_{j} V(\mathcal{P}, \mathcal{Q}, J) \\ \text{subject to} : J \le J_{\max} \end{cases} \end{cases} \end{cases} \tag{5}$$

IV. THE POWER OPTIMIZATION STRATEGY BASED ON BAYESIAN THREE-LAYER STACKELBERG GAME

In this section, we define the Nash Equilibrium (NE) and Stackelberg Equilibrium (SE) firstly. Then we figure out the optimal power of follower, vice-leaders, leaders successively and propose a multi-user hierarchical iterative algorithm (MHIA) to obtain SE. Moreover, we prove the existence and uniqueness of SE. In the last, the close-form expressions of NE was given.

As users and jammer select transmission power independently and simultaneously, we model the power control problem as a static game, and Nash Equilibrium (NE) [37], [38] can be viewed as the optimal strategy of the static game. After achieving NE, no user could have a higher utility by changing transmission power unilaterally.

While in the proposed anti-jamming Bayesian three-layer Stackelberg game, there exist multi primary users act as leaders, relay users act as vice-leaders and a jammer acts as follower. Primary users take actions firstly and they have first advantages to choose certain power strategies so as to maximize their utilities under the constraint condition, which means primary users have the higher priority compared to

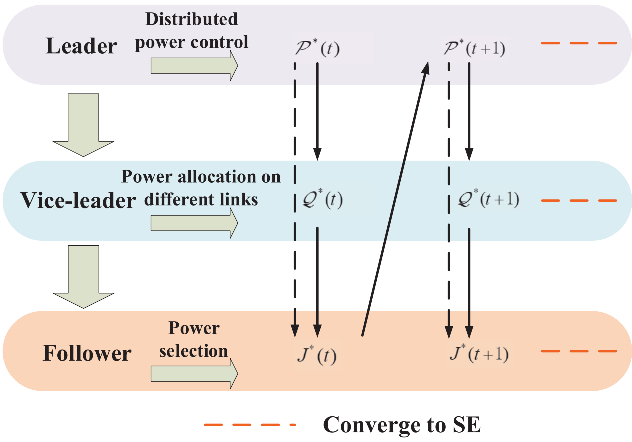


FIGURE 3. The specific schematic of the Bayesian three-layer Stackelberg Game.

relay users and jammer. Then the vice-leaders sub-game converges to equilibrium based on the observation of primary users' power and relay users choose optimal strategies maximize relay's utility. After observing primary users' and relay users' transmission power, the jammer updates jamming power until the follower sub-game converges to equilibrium in the last and acts as follower in the game. Through several iterations, we obtain Stackelberg Equilibrium as the optimal joint strategy of PUs, RUs and jammer, which can be expressed as $(\mathcal{P}^*, \mathcal{Q}^*, j^*)$ and is shown in Fig. 3. $\mathcal{P}^* = [p_1^*, \ldots, p_m^*, \ldots, p_M^*]$ and $\mathcal{Q}^* = [q_1^*, \ldots, q_n^*, \ldots, q_N^*]$ denote the optimal power strategy set of all PUs and RUs respectively, in which p_m^* denotes the mth PU's optimal power, and q_n^* denote the nth RU's optimal power. j^* denotes the sum of optimal jamming power on all channels. The optimal strategy obtained from SE maximizes the utilities of users and jammer. Under power constraints, for any user or jammer, the optimal strategy should satisfy the following conditions:

$$\begin{cases} V\left(\mathcal{P}^*, \mathcal{Q}^*, J^*\right) \geq V\left(\mathcal{P}^*, \mathcal{Q}^*, J\right), \\ R\left(\mathcal{P}^*, q_n^*, q_{-n}^*, J^*\right) \geq R\left(\mathcal{P}^*, q_n, q_{-n}^*, J^*\right), \\ U_m\left(p_m^*, q_m^*, J_m^*\right) \geq U_m\left(p_m, q_m^*, J_m^*\right). \end{cases} \tag{6}$$

where $q_{-n}^* = [q_1^*, \ldots, q_{n-1}^*, q_{n+1}^*, \ldots, q_N^*]$ denotes the optimal power strategy set of all RUs except the nth RU.

A. FOLLOWER SUB-GAME

In the Stackelberg Game, the backward induction method is an effective method to achieve SE. For jammer, it observes the PUs' and RUs' transmission power firstly, and then it changes jamming power to realize the maximum of utility. Because of the observation error, the power control optimization problem of jammer can be denoted as:

$$\begin{aligned} J &= \arg\ \max V(\tilde{p}_1, \ldots, \tilde{p}_M, \tilde{q}_1, \ldots, \tilde{q}_N, J), \\ & s.t.\ 0 \leq J \leq J_{\max}, \quad J = \sum_{k=1}^{K} J_k,\ J_1 = J_2 = \cdots = J_K. \end{aligned} \tag{7}$$

Considering the incomplete information, we assume the ith PU's, RU's channel gain α_i, η_i and jamming cost E are mutually independent. For jammer, α_i has H states and the probability of α_{ih} is φ_{ih}, $\sum_{h=1}^{H} \varphi_{ih} = 1$. Similarly, η_i has L states, E has T states, and the probability of η_{il}, E_t are κ_{il}, θ_t respectively, and $\sum_{l=1}^{L} \kappa_{il} = 1$, $\sum_{t=1}^{T} \theta_t = 1$. So the utility of jammer can be simplified as follows:

$$\begin{aligned} & V(\tilde{p}_1, \ldots, \tilde{p}_M, \tilde{q}_1, \ldots, \tilde{q}_N, J, \mu) \\ & \quad = -\sum_{i=1}^{M} \frac{\sum\limits_{h=1}^{H} \varphi_{ih}\alpha_{ih}\tilde{p}_i + \sum\limits_{l=1}^{L} \kappa_{il}\eta_{il}\tilde{q}_i}{N_0 + \beta J/M} - \sum_{t=1}^{T} \theta_t E_t J. \end{aligned} \tag{8}$$

Theorem 1: The jammer's optimal power J^* is given by:

$$\begin{aligned} & J^* = \begin{cases} J^{\Delta}, & \Pi 1, \\ 0, & otherwise. \end{cases} \\ & \Pi 1 : \sum_{i=1}^{M} (\sum_{h=1}^{H} \varphi_{ih}\alpha_{ih}\tilde{p}_i + \sum_{l=1}^{L} \kappa_{il}\eta_{il}\tilde{q}_i) \\ & \qquad > M(\sum_{t=1}^{T} \theta_t E_t + \mu) N_0^2 \Big/ \beta \end{aligned} \tag{9}$$

where J^{Δ} is shown in equation (14).

Proof: The utility function of jammer is a concave function because of:

$$\frac{\partial^2 V}{\partial J^2} = \frac{-2\beta^2 \left[\sum\limits_{i=1}^{M} (\sum\limits_{h=1}^{H} \varphi_{ih}\alpha_{ih}\tilde{p}_i + \sum\limits_{l=1}^{L} \kappa_{il}\eta_{il}\tilde{q}_i)\right]}{M^2 (N_0 + \beta J/M)^3} < 0. \tag{10}$$

Therefore, it is a convex optimization problem for jammer to obtain the optimal jamming strategy. Jammer's utility is concave and it has the unique maximal value only when making the first derivative equal to 0. Based on duality optimization theory [33], [34], the jammer's Lagrange function can be denoted as follows after introducing the nonnegative dual variable μ:

$$\begin{aligned} & L_j(\tilde{p}_1, \ldots, \tilde{p}_M, \tilde{q}_1, \ldots, \tilde{q}_M, J, \mu) \\ & \quad = -\sum_{i=1}^{M} \frac{\sum\limits_{h=1}^{H} \varphi_{ih}\alpha_{ih}\tilde{p}_i + \sum\limits_{l=1}^{L} \kappa_{il}\eta_{il}\tilde{q}_i}{N_0 + \beta J/M} - \sum_{t=1}^{T} \theta_t E_t J \\ & \qquad + \mu(J_{\max} - J). \end{aligned} \tag{11}$$

Then, we can obtain the Lagrange function in the following:

$$D(\mu) = \max_{J \geq 0}\ V(\tilde{p}_1, \ldots, \tilde{p}_M, \tilde{q}_1, \ldots, \tilde{q}_M, J, \mu). \tag{12}$$

Moreover, the dual problem is $d^* = \min\limits_{\mu \geq 0}\ D(\mu)$.

Based on Karush-Kuhn-Tucker (KKT) conditions [33], [34], we let:

$$\begin{aligned} \frac{\partial L_j}{\partial J} &= \frac{\beta \left[\sum\limits_{i=1}^{M} (\sum\limits_{h=1}^{H} \varphi_{ih}\alpha_{ih}\tilde{p}_i + \sum\limits_{l=1}^{L} \kappa_{il}\eta_{il}\tilde{q}_i)\right]}{M(N_0 + \beta J/M)^2} \\ & \qquad - (\sum_{t=1}^{T} \theta_t E_t + \mu) = 0. \end{aligned} \tag{13}$$

and we can get the jamming power:

$$J^{\Delta}=\frac{M}{\beta}\left\{\sqrt{\frac{\beta\left[\sum\limits_{i=1}^{M}(\sum\limits_{h=1}^{H}\varphi_{ih}\alpha_{ih}\tilde{p}_i+\sum\limits_{l=1}^{L}\kappa_{il}\eta_{il}\tilde{q}_i)\right]}{M(\sum\limits_{t=1}^{T}\theta_t E_t+\mu)}}-N_0\right\} \tag{14}$$

■

Because of the non-negativity of power, we add the condition $\Pi 1$ to further classify the optimal jamming power. When the current jammer's observation of users' transmission power $\sum_{i=1}^{M}(\sum_{h=1}^{H}\varphi_{ih}\alpha_{ih}\tilde{p}_i+\sum_{l=1}^{L}\kappa_{il}\eta_{il}\tilde{q}_i)$ is larger than $M(\sum_{t=1}^{T}\theta_t E_t+\mu)N_0^2/\beta$, jammer would choose optimal jamming power J^{Δ}. Otherwise, jammer would choose to ignore the present transmission and adjust jamming power to 0.

B. VICE-LEADER SUB-GAME

Similarly, the RUs' power control optimization problem can be expressed as:

$$\begin{aligned} q_n &= \arg\max R\left(\mathcal{P},q_n,q_{-n},J\left(\mathcal{P},\mathcal{Q}\right)\right),\\ &s.t.\ 0\le\sum_{n=1}^{N}q_n\le q_{\max},\quad q_n\in\mathcal{Q},\ n\in\mathcal{N}. \end{aligned}\tag{15}$$

For relay users, the jammer's channel gain β and the nth RU's transmission cost D_n are mutually independent, among which, β has X states and the probability of β_x is γ_x, $\sum_{x=1}^{X}\gamma_x=1$. Similarly, D_n has Z states and the probability of D_{nz} is χ_{nz}, $\sum_{z=1}^{Z}\chi_{nz}=1$. Taking J^* into equation (3), and the utility of relay is:

$$R=\begin{cases}\sum\limits_{x=1}^{X}\gamma_x\sqrt{\dfrac{M(\sum\limits_{t=1}^{T}\theta_t E_t+\mu)\left[\sum\limits_{i=1}^{M}(\alpha_i p_i+\eta_i q_i)\right]}{\beta_x}}\\ \quad-\sum\limits_{i=1}^{M}\sum\limits_{z=1}^{Z}\chi_z D_{iz}q_i, & q\wedge>q\vee,\\ \sum\limits_{i=1}^{M}\dfrac{\alpha_i p_i+\eta_i q_i}{N_0}-\sum\limits_{i=1}^{M}\sum\limits_{z=1}^{Z}\chi_{iz}D_{iz}q_i, & otherwise.\end{cases}\tag{16}$$

where $q\wedge$, $q\vee$ are expressed as follows:

$$\begin{aligned} q\wedge &= \sum_{i=1}^{M}\eta_i q_i,\\ q\vee &= \sum_{x=1}^{X}\gamma_x\left[M(\sum_{t=1}^{T}\theta_t E_t+\mu)N_0^2\Big/\beta_x-\sum_{i=1}^{M}\alpha_i p_i\right]. \end{aligned}$$

Theorem 2: The *nth* vice-leader's optimal power q_n^* is given by:

$$q_n^*=\min(q_n^{\Delta},q_{\max}-\sum_{i\neq n}q_i),\quad n\in\mathcal{N}.$$

$$\begin{aligned} q_n^{\Delta} &= \begin{cases} q_n', & \Pi 2,\\ q_n'', & \Pi 3,\\ 0, & otherwise.\end{cases}\\ \Pi 2 &: q_n''\le 0, q_n'>0\ or\ q_n''>0,\quad q_n''<q_n',\\ \Pi 3 &: q_n''>0,\quad q_n''\ge q_n',\ k_n>0. \end{aligned}\tag{17}$$

Proof: According to the utility of relay, we can find R is a linear function about q_n with a slope of $k_n=\eta_n/\mathrm{N}_0-\sum_{z=1}^{Z}\chi_{nz}D_{nz}$ when $q\wedge\le q\vee$, and the critical value of q_n is:

$$\begin{aligned} q_n'' &= \frac{1}{\eta_n}(q\vee-\sum_{i\neq n}\eta_i q_i)\\ &= \frac{1}{\eta_n}\sum_{x=1}^{X}\gamma_x\left[\frac{M(\sum\limits_{t=1}^{T}\theta_t E_t+\mu)N_0^2}{\beta_x}-\sum_{i=1}^{M}\alpha_i p_i\right]\\ &\quad-\frac{1}{\eta_n}\sum_{i\neq n}\eta_i q_i. \end{aligned}\tag{18}$$

When $q\wedge>q\vee$, since:

$$\begin{aligned} \frac{\partial^2 R}{\partial q_n^2} &= -\frac{\eta_n^2}{4}\sum_{x=1}^{X}\gamma_x\sqrt{\frac{M(\sum\limits_{t=1}^{T}\theta_t E_t+\mu)}{\beta_x}}\\ &\quad\times\left[\sum_{i=1}^{M}(\alpha_i p_i+\eta_i q_i)\right]^{-\frac{3}{2}}<0. \end{aligned}\tag{19}$$

it is a concave function.

Similarly, after introducing the nonnegative dual variable ψ, we get the Lagrange function as follows:

$$\begin{aligned} &L_r(p_1,\ldots,p_M,q_1,\ldots,q_N,\psi_1,\ldots,\psi_N)\\ &=\sum_{x=1}^{X}\gamma_x\sqrt{\frac{M(\sum\limits_{t=1}^{T}\theta_t E_t+\mu)\left[\sum\limits_{i=1}^{M}(\alpha_i p_i+\eta_i q_i)\right]}{\beta_x}}\\ &\quad-\sum_{i=1}^{M}\sum_{z=1}^{Z}\chi_{iz}D_{iz}q_i+\sum_{i=1}^{M}\psi_i(q_{\max}-q_i). \end{aligned}\tag{20}$$

Similar to the solution process in part A, we have:

$$\begin{aligned} \frac{\partial L_r}{\partial q_n} &= \frac{\eta_n}{2}\sum_{x=1}^{X}\gamma_x\sqrt{\frac{M(\sum\limits_{t=1}^{T}\theta_t E_t+\mu)}{\beta_x\left[\sum\limits_{i=1}^{M}(\alpha_i p_i+\eta_i q_i)\right]}}\\ &\quad-\left(\sum_{z=1}^{Z}\chi_{nz}D_{nz}+\psi_n\right)=0. \end{aligned}\tag{21}$$

the power is obtained by solving the optimization problem and it is shown as follows:

$$q_n' = \frac{M\eta_n(\sum_{t=1}^{T}\theta_t E_t + \mu)}{4(\sum_{z=1}^{Z}\chi_z D_{iz} + \psi_n)^2}(\sum_{x=1}^{X}\gamma_x \frac{1}{\sqrt{\beta_x}})^2 - \frac{1}{\eta_n}(\sum_{i=1}^{M}\alpha_i p_i + \sum_{m\neq i}\eta_m q_m). \quad (22)$$

On the basis of the analysis above, the nth RU's optimal strategy can be obtained through the following discussion:

1) $q_n'' \leq 0, q_n' > 0$ *or* $q_n'' > 0, q_n'' < q_n'$: In these cases, the utility increases when $q_n \leq q_n'$ and decreases when $q_n > q_n'$, so the utility reaches the maximum value at $q_n = q_n'$, i.e., $q_n^{\Delta} = q_n'$.
2) $q_n'' > 0, q_n'' \geq q_n', k_n > 0$: In this case, we can find the utility function is a linear increasing function when $0 < q_n \leq q_n''$ and a decreasing function when $q_n > q_n''$, so the maximum of utility is reached at $q_n = q_n''$, i.e., $q_n^{\Delta} = q_n''$.
3) $q_n'' \leq 0, q_n' \leq 0$ *or* $q_n'' > 0, q_n'' \geq q_n', k_n \leq 0$: In the first case, the utility function is a decreasing function when $q_n > 0$; in the second case, the utility function is also a decreasing function but the difference from the former case is that it decreases linearly when $q_n < q_n''$. In the two cases, the utility reaches the maximum value at $q_n = 0$, i.e., $q_n^{\Delta} = 0$.
4) To summarize, because of the upper limit of relay transmission power, the total power of all the relay users can't exceed $q_{\max}$, so we have $q_n^* = \min(q_n^{\Delta}, q_{\max} - \sum_{i\neq n} q_i)$.

■

Through the discussion above, RUs can get the optimal transmission power through analysing the numerical relationship between q_n', q_n'' and k_n. When $q_n'' \leq 0, q_n' \leq 0$, we can get $p_n \geq p_n''$ which is expressed in equation (29), i.e., the nth PU's transmission power meets the current communication, or when $q_n'' > 0, q_n'' \geq q_n', k_n \leq 0$, we can get $\sum_{z=1}^{Z}\chi_{nz}D_{nz} \geq \eta_n/\mathrm{N}_0$, i.e. transmission cost of the nth RU is too high to absorb in the current state. In the above two cases, the RU chooses to not send messages and adjusts transmission power to zero. Otherwise, it will select the optimal power to improve communication quality based on equation (17).

C. LEADER SUB-GAME

Similarly, the PUs' power control optimization problem can be expressed as:

$$\begin{aligned} p_m &= \arg\max U_m(p_m, q_m(\mathcal{P}, q_{-m}), J_m(\mathcal{P}, \mathcal{Q})), \\ &\quad s.t.\ 0 \leq p_m \leq p_{m\max}, \quad p_m \in \mathcal{P},\ m \in \mathcal{M}. \end{aligned} \quad (23)$$

Similarly, for primary users, the jammer's channel gain β and transmission cost C_m are mutually independent. Among which, β has X states and the probability of β_x is γ_x, i.e., $\sum_{x=1}^{X}\gamma_x = 1$. C_m has Y states and the probability of C_{my} is ω_y, i.e., $\sum_{y=1}^{Y}\omega_{my} = 1$. Taking J_m^* and q_m^* into equation (4), we can get the utility of the mth PU in different cases as follows:

$$U_m = \begin{cases} \sum_{x=1}^{X}\gamma_x\alpha_m p_m\sqrt{\dfrac{M(\sum_{t=1}^{T}\theta_t E_t + \mu)}{\beta_x\sum_{i=1}^{M}(\alpha_i p_i + \eta_i q_i)}} - \sum_{y=1}^{Y}\omega_{my}C_{my}p_m, & \Pi 4, \\ \dfrac{M\eta_m(\sum_{t=1}^{T}\theta_t E_t + \mu)}{2(\sum_{z=1}^{Z}\chi_{mz}D_{mz} + \psi_m)}(\sum_{x=1}^{X}\gamma_x\dfrac{1}{\sqrt{\beta_x}})^2 - \dfrac{2(\sum_{z=1}^{Z}\chi_{mz}D_{mz} + \psi_m)}{\eta_m}\sum_{i\neq m}(\alpha_i p_i + \eta_i q_i) - \sum_{y=1}^{Y}\omega_{my}C_{my}p_m, & \Pi 5, \\ \dfrac{\sum_{x=1}^{X}\gamma_x\left[M(\sum_{t=1}^{T}\theta_t E_t + \mu)N_0^2\Big/\beta_x - \sum_{i\neq m}\alpha_i p_i\right] - \sum_{i\neq m}\eta_i q_i}{N_0} - \sum_{y=1}^{Y}\omega_{my}C_{my}p_m, & \Pi 6, \\ \dfrac{\alpha_m p_m}{N_0} - \sum_{y=1}^{Y}\omega_{my}C_{my}p_m, & \Pi 7, \\ \sum_{x=1}^{X}\gamma_x(\alpha_m p_m + q_{\max} - \sum_{i\neq m} q_i)\sqrt{\dfrac{M(\sum_{t=1}^{T}\theta_t E_t + \mu)}{\beta_x\sum_{i=1}^{M}(\alpha_i p_i + \eta_i q_i)}} - \sum_{y=1}^{Y}\omega_{my}C_{my}p_m, & \Pi 8, \\ \dfrac{\alpha_m p_m + q_{\max} - \sum_{i\neq m} q_i}{N_0} - \sum_{y=1}^{Y}\omega_{my}C_{my}p_m, & \Pi 9, \end{cases} \quad (24)$$

where the value of q_m^*, J_m^* under different cases are shown as follows:

$$\begin{cases} \Pi 4 \; q_m'' \le 0, q_m' \le 0: \\ \quad q_m^* = 0, J_m^* = J^{\Delta}; \\ \Pi 5 \; q_i'' \le 0, q_m' > 0 \;\; or \;\; q_m'' > 0, q_m'' < q_m': \\ \quad q_m^* = q_i', J_m^* = J^{\Delta}; \\ \Pi 6 \; q_m'' > 0, q_m'' \ge q_m', k_m > 0: \\ \quad q_m^* = q_i'', J_m^* = 0; \\ \Pi 7 \; q_m'' > 0, q_m'' \ge q_m', k_m \le 0: \\ \quad q_m^* = 0, J_m^* = 0; \\ \Pi 8 \; q_{\max} - \sum\limits_{i \ne m} q_i > q_m'': \\ \quad q_m^* = q_{\max} - \sum\limits_{i \ne m} q_i, J_m^* = J^{\Delta}; \\ \Pi 9 \; q_{\max} - \sum\limits_{i \ne m} q_i \le q_m'': \\ \quad q_m^* = q_{\max} - \sum\limits_{i \ne m} q_i, J_m^* = 0. \end{cases} \tag{25}$$

in the cases of $\Pi 4, \Pi 5, \Pi 6, \Pi 7$, the RUs' transmission power meets $\sum_{i=1}^{M} q_i < q_{\max}$, while in the cases of $\Pi 8$, $\Pi 9$, $\sum_{i=1}^{M} q_i = q_{\max}$.

Theorem 3: The *mth* leader's optimal power p_m^* is given by:

$$p_m^* = \begin{cases} p_m^{\Delta}, & \Pi 4, \; p_m^{\Delta} > 0, \\ p_m', & \Pi 8, \; p_m' > 0, \\ p_m'', & \Pi 7, \; b_m > 0 \; or \; \Pi 9, \; b_m > 0, \\ 0, & otherwise. \end{cases} \tag{26}$$

where $p_m^{\Delta}, p_m'', p_m'$ are shown in equation (28), (29), (31), respectively.

Proof: According to the utility function above, we discuss the following cases:

1) $\Pi 4$: It is a concave function, since:

$$\frac{\partial^2 U_m}{\partial p_m^2} = \sum_{x=1}^{X} \gamma_x \alpha_m^2 \sqrt{\frac{\sum\limits_{t=1}^{T} \theta_t E_t + \mu}{\beta_x}} D^{-\frac{3}{2}} \left(\frac{3\alpha_m p_m}{4D} - 1\right) < 0,$$
$$D = \sum_{i=1}^{M} (\alpha_i p_i + \eta_i q_i).$$

Similarly, after introducing the nonnegative dual variable λ_m, we get the Lagrange function as follows:

$$L_m = \sum_{x=1}^{X} \gamma_x \alpha_m p_m \sqrt{\frac{M(\sum\limits_{t=1}^{T} \theta_t E_t + \mu)}{\beta_x \sum\limits_{i=1}^{M} (\alpha_i p_i + \eta_i q_i)}} - \sum_{y=1}^{Y} \omega_{my} C_{my} p_m + \lambda_m (p_{m\max} - p_m).$$

$$\frac{\partial L_m}{\partial p_m} = 0 \;\; \Rightarrow \frac{1}{\sqrt{B+C}} - \frac{C}{2(B+C)^{\frac{3}{2}}} = A$$
$$\Rightarrow 4A^2 C^3 + (12A^2 B - 1)C^2 + (12A^2 B^2 - 4B)C + 4A^2 B^3 - 4B^2 = 0.$$
$$\begin{cases} A = \dfrac{\sum\limits_{y=1}^{Y} \omega_{my} C_{my} p_m + \lambda_m}{\sum\limits_{x=1}^{X} \gamma_x \alpha_m \sqrt{M(\sum\limits_{t=1}^{T} \theta_t E_t + \mu) \Big/ \beta_x}}, \\ B = \sum\limits_{i \ne m} \alpha_i p_i + \sum\limits_{i=1}^{M} \eta_i q_i, \quad C = \alpha_m p_m. \end{cases} \tag{27}$$

After solving the unary cubic equation of C, we get:

$$p_m^{\Delta} = \frac{C}{\alpha_m} \tag{28}$$

Considering the non-negativity of power, if $p_m^{\Delta} > 0$, we can obtain $p_m^* = p_m^{\Delta}$, else $p_m^* = 0$.

2) $\Pi 5, \Pi 6$: Based on the utility function, we can find it is a linear decreasing function and the primary user's utility reachs the maximum at $p_m = 0$, i.e., $p_m^* = 0$.

3) $\Pi 7, \Pi 9$: In this case, the utility function is a linear function with a slope of $b_m = \frac{\alpha_m}{N_0} - \sum\limits_{y=1}^{Y} \omega_{my} C_{my}$, and we can get:

$$p_m'' = \frac{1}{\alpha_m} \sum_{x=1}^{X} \gamma_x \frac{M(\sum\limits_{t=1}^{T} \theta_t E_t + \mu) {N_0}^2}{\beta_x} - \frac{1}{\alpha_m} \left(\sum_{i \ne m} \eta_i q_i + \sum_{i \ne m} \alpha_i p_i\right). \tag{29}$$

When $b_m > 0$, the utility function is an increasing function and it will reach the maximum at $p_m = p_m''$, i.e., $p_m^* = p_m''$; when $b_m \le 0$, the utility function is a decreasing function and it will reach the maximum at $p_m = 0$, i.e., $p_m^* = 0$.

4) $\Pi 8$: Similar to $\Pi 4$, the utility ia a concave function, A, B, C have the same value as in $\Pi 4$, and we have:

$$\frac{1}{\sqrt{B+C}} - \frac{C + q_{\max} - \sum\limits_{i \ne m} q_i}{2(B+C)^{\frac{3}{2}}} = A \tag{30}$$

After getting the closed-form expression of C, we get:

$$p_m' = \frac{C}{\alpha_m} \tag{31}$$

Considering the non-negativity of power, if $p_m' > 0$, we can obtain $p_m^* = p_m'$, else $p_m^* = 0$.

■

Based on the analysis above, we can conclude that when power cost of the *m*th PU is too high or current transmission power meets the communication requirement, the *m*th PU chooses to stop transmitting. Otherwise, it will choose the optimal power based on equation (26).

Through the sub-gradient update method [34], we can derive the dual variable $\lambda_m (m \in \mathcal{M})$, $\psi_n (n \in \mathcal{N})$, μ through iterations:

$$\begin{cases} \lambda_m(t+1) = \left[\lambda_m(t) - \Delta^t_{\lambda_m}(p_{m\max} - p_m(t+1))\right]^+, \\ \psi_n(t+1) = \left[\psi_n(t) - \Delta^t_{\psi_n}(q_{\max} - q_n(t+1))\right]^+, \\ \mu(t+1) = \left[\mu(t) - \Delta^t_{\mu}(J_{\max} - J(t+1))\right]^+. \end{cases} \tag{32}$$

where t represents the iteration number, $\Delta^t_{\lambda_m}$, $\Delta^t_{\psi_n}$ and Δ^t_{μ} represents the iteration step of the *mth* PU, *nth* RU and jammer, respectively. The optimal power control strategy can be obtained through the multi-user hierarchical iterative algorithm (MHIA), which is shown in **Algorithm 1**.

D. EXISTENCE AND UNIQUENESS OF STACKELBERG EQUILIBRIUM

Theorem 4: Stackelberg Equilibrium would always exist in the formulated anti-jamming Bayesian Three-layer Stackelberg game.

Proof: For relay users, after given PUs' transmission power set $\mathcal{P}$, the vice-leader subgame reduced to a non-cooperative game. And the strategy space of vice-leaders is a non-empty, compact and convex subset of some Euclidean space. Moreover, the RUs' utilities are continuous and concave with respect to q_n. So there exists the best response (BR) in the vice-leader subgame which had been proved in [39]. Similarly, for the jammer, when obtained PUs' and RUs' transmission power set $\mathcal{P}, \mathcal{Q}$, there also exists the best response in the follower subgame. Let $BR(\mathcal{P})$, $BR(\mathcal{P}, \mathcal{Q})$ denotes the relay user's and jammer's best response, respectively. Based on the above analysis, the SE can be defined as follows:

$$\begin{cases} R(\mathcal{P}, q_n^*, q_{-n}, BR(\mathcal{P}, q_n^*, q_{-n})) \\ \quad \geq R(\mathcal{P}, q_n, q_{-n}, BR(\mathcal{P}, q_n, q_{-n})); \\ U_m(p_m^*, BR(p_m^*, p_{-m}), BR(p_m^*, p_{-m}, \mathcal{Q})) \\ \quad \geq U_m(p_m, BR(p_m, p_{-m}), BR(p_m, p_{-m}, \mathcal{Q})). \end{cases} \tag{33}$$

Thus it can be proved that there exist q_n^*, p_m^* which need to satisfy the following condition:

$$\begin{cases} R(\mathcal{P}, q_n^*, q_{-n}, BR(\mathcal{P}, q_n^*, q_{-n})) \\ \quad = \sup\limits_{q_n \geq 0} R(\mathcal{P}, q_n, q_{-n}, BR(\mathcal{P}, q_n, q_{-n})); \\ U_m(p_m^*, BR(p_m^*, p_{-m}), BR(p_m^*, p_{-m}, \mathcal{Q})) \\ \quad = \sup\limits_{p_m \geq 0} U_m(p_m, BR(p_m, p_{-m}), BR(p_m, p_{-m}, \mathcal{Q})). \end{cases} \tag{34}$$

Based on the proof above, the SE always exists in the formulated Bayesian three-layer Stackelberg game. ■

Theorem 5: Stackelberg Equilibrium is unique in the formulated anti-jamming Bayesian three-layer Stackelberg game.

Algorithm 1 Multi-User Hierarchical Iterative Algorithm (MHIA)

1. Initialization

(a) Initialization of system parameters:
Set iteration count $t = 0$, the maximum iteration count $t_{\max}$, and the background noise N_0.

(b) Initialization of follower:
Jamming power $J(t)$, the maximum jamming power $J_{\max}$, channel gain β, dual variable $\mu(t)$, and jamming cost E.

(c) Initialization of vice-leaders:
The nth relay user's transmission power $q_n(t)$, the maximum transmission power of relay $q_{\max}$, channel gain η_n, dual variable $\psi_n(t)$, transmission cost D_n, $n \in \mathcal{N}$.

(d) Initialization of leaders:
The mth primary user's transmission power $p_m(t)$, the maximum transmission power of mth PU $p_{m\max}$, channel gain α_m, dual variable $\lambda_m(t)$, transmission cost C_m, $m \in \mathcal{M}$.

2. Repeat iterations

(a) $t = t + 1$.

(b) $J(t+1)$ can be obtained according to equation (9) based on $\tilde{p}_1(t), \ldots, \tilde{p}_m(t), \ldots, \tilde{p}_M(t)$ and $\tilde{q}_1(t), \ldots, \tilde{q}_n(t), \ldots, \tilde{q}_N(t)$.

(c) $q_n(t+1), n \in \mathcal{N}$ can be obtained according to equation (17) based on $J(t+1), q_1(t), \ldots, q_{(n-1)}(t), q_{(n+1)}(t), \ldots, q_N(t)$ and $p_1(t), \ldots, p_m(t), \ldots, p_M(t)$.

(d) $p_m(t+1), m \in \mathcal{M}$ can be obtained according to equation (26) based on $J(t+1), q_1(t+1), \ldots, q_n(t+1), \ldots, q_N(t+1)$ and $p_1(t), \ldots, p_{m-1}(t), p_{m+1}(t), \ldots, p_M(t)$.

(e) $\lambda_m(t+1) = \left[\lambda_m(t) - \Delta^t_{\lambda_m}(p_{m\max} - p_m(t+1))\right]^+$, $m \in \mathcal{M}$.

(f) $\psi_n(t+1) = \left[\psi_n(t) - \Delta^t_{\psi_n}(q_{\max} - q_n(t+1))\right]^+$, $n \in \mathcal{N}$.

(g) $\mu(t+1) = \left[\mu(t) - \Delta^t_{\mu}(J_{\max} - J(t+1))\right]^+$.

(h) until $t \geq t_{\max}$.

3. End iteration

Proof: According to jammer's utility function, we can get its second-order derivative $\partial^2 V / \partial J^2 < 0$ from equation (10) which means it is a concave function of J. Based on duality optimization theory [33], [34], there exists the unique best response $BR(\mathcal{P}^*, \mathcal{Q}^*)$ for the jammer. Similarly, the relay's utility is a concave function of because of $\partial^2 R / \partial q_n^2 < 0$ from equation (19), so the best response of relay user $BR(\mathcal{P}^*)$ is unique. Moreover, each primary user has a unique power p_m^* which had been analyzed in Section IV-C. Therefore, the SE is unique in the formulated anti-jamming Bayesian three-layer Stackelberg game. ■

E. NASH EQUILIBRIUM OF THE STATIC GAME

Different from the Stackelberg game, when all the users and jammer choose respective transmission power simultaneously, we can model the power control problem as a static game. Moreover, Nash Equilibrium as the optimal strategy of the static game is obtained and compared with Stackelberg Equilibrium.

Theorem 6: The Nash Equilibrium exists in the static game.

Proof: Based on the utility function of primary user, relay and jammer, we can get:

$$\frac{\partial U_m}{\partial p_m} = \frac{\alpha_m}{N_0 + \sum\limits_{x=1}^{X} \frac{\gamma_x \beta_x \tilde{J}}{M}} - \sum_{y=1}^{Y} \omega_{my} C_{my} \tag{35}$$

$$\frac{\partial R}{\partial q_n} = \frac{\eta_n}{N_0 + \sum\limits_{x=1}^{X} \frac{\gamma_x \beta_x \tilde{J}}{M}} - \sum_{z=1}^{Z} \chi_{nz} D_{nz} \tag{36}$$

$$\frac{\partial V}{\partial J} = \frac{\frac{\beta}{M}\left[\sum\limits_{i=1}^{M}\left(\sum\limits_{h=1}^{H}\varphi_{ih}\alpha_{ih}\tilde{p}_i + \sum\limits_{l=1}^{L}\kappa_{il}\eta_{il}\tilde{q}_i\right)\right]}{\left(N_0 + \frac{\beta J}{M}\right)^2} - \sum_{t=1}^{T}\theta_t E_t \tag{37}$$

Based on the analysis above, we can obtain NE through the following cases:

1) Case 1 : $N_0 \le \alpha_i \Big/ \left(\sum_{y=1}^{Y} \omega_{iy} C_{iy}\right)$ *and* $\alpha_i \Big/ \left(\sum_{y=1}^{Y} \omega_{iy} C_{iy}\right) \ge \eta_i \Big/ \left(\sum_{z=1}^{Z} \chi_{iz} D_{iz}\right)$. In this case, we can let $\partial U_i \big/ \partial p_i = 0$ and obtain $J^{\Delta} = M\left[\alpha_i \Big/ (\sum_{y=1}^{Y} \omega_y C_{iy}) - N_0\right] \Big/ (\sum_{x=1}^{X} \gamma_x \beta_x)$. Taking J^{Δ} into equation (37), and we find relay's utility decreases with q_i because $\partial R \big/ \partial q_i < 0$, i.e., $q_i^* = 0$. In order to make $J^* = J^{\Delta}$, taking q_i^*, J^* into $\partial V \big/ \partial J = 0$ and we can get:

$$p_i^* = \frac{1}{\alpha_i}\left[\frac{M\alpha_i^2 \sum\limits_{t=1}^{T}\theta_t E_t}{(\sum\limits_{x=1}^{X}\gamma_x\beta_x)(\sum\limits_{y=1}^{Y}\omega_{iy}C_{iy})^2} - \sum_{m\neq i}\alpha_m p_m\right] \tag{38}$$

2) *Case* 2 : $N_0 \le \eta_i \Big/ \left(\sum_{z=1}^{Z} \chi_{iz} D_{iz}\right)$ *and* $\alpha_i \Big/ \left(\sum_{y=1}^{Y} \omega_{iy} C_{iy}\right) < \eta_i \Big/ \left(\sum_{z=1}^{Z} \chi_{iz} D_{iz}\right)$. Similar to Case 1, we set $\partial R \big/ \partial q_i = 0$ and obtain $J^{\Delta} = M\left[\eta_i \Big/ (\sum_{z=1}^{Z} \chi_{iz} D_{iz}) - N_0\right] \Big/ (\sum_{x=1}^{X} \gamma_x \beta_x)$. Taking J^{Δ} into equation (36), and we find primary user's utility decreases with p_i because $\partial U_i \big/ \partial p_i < 0$, i.e., $p_i^* = 0$. In order to make $J^* = J^{\Delta}$, taking p_i^*, J^* into $\partial V \big/ \partial J = 0$ and we can get:

$$q_i^* = \frac{1}{\eta_i}\left[\frac{M\eta_i^2 \sum\limits_{t=1}^{T}\theta_t E_t}{(\sum\limits_{x=1}^{X}\gamma_x\beta_x)(\sum\limits_{z=1}^{Z}\chi_{iz}D_{iz})^2} - \sum_{m\neq i}\eta_m q_m\right] \tag{39}$$

3) *Case* 3 : $N_0 > \max\left(\alpha_i \Big/ \left(\sum_{y=1}^{Y} \omega_{iy} C_{iy}\right), \eta_i \Big/ \left(\sum_{z=1}^{Z} \chi_{iz} D_{iz}\right)\right)$. As $\partial U_i \big/ \partial p_i \le 0$, $\partial R \big/ \partial q_i \le 0$, U_i, R is a decreasing function of p_i, q_i respectively, i.e., $p_i^* = 0$, $q_i^* = 0$. After integrating p_i^*, q_i^* into equation (38), we get $\partial V \big/ \partial J < 0$ and $J^* = 0$.

Based on the analysis above, when the channel state and transmission cost meet Case 1, i.e., the primary user's cost is low and its channel gain meets transmission demand, primary user adjusts optimal power and relay user stop helping PU transmit any more. While in situation Case 2, when the relay user's cost is small and its channel gain is large, it would select power to transmit messages. Contrarily, if both primary user's and relay user's cost are too high, all the users will stop transmission temporarily. And jammer would choose whether to transmit jamming signals based on the current communication status. ■

In the above analysis, we derive the closed-form expressions of Stackelberg equilibrium (SE) in the Bayesian Stackelberg game, and Nash equilibrium (NE) in the static game, respectively. Under the Stackelberg game frame, the hierarchical characteristics between users and jammer can be better reflected. To further verify the effectiveness of Stackelberg game, simulation results are shown in Section IV.

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, we set simulation parameters firstly, then we show some simulation results and give the relative discussions. We analyze the power convergence process of the proposed game firstly. Then, we compare both users' and jammer's utilities of Stackelberg Equilibrium and Nash Equilibrium under observation error. In the last, we analyze the influence of incomplete information, jamming distance and jamming cost on utility.

In the simulation, we assume the transmission cost C_1, C_2, D_1, D_2, E (for the convenience of simulation, we consider $M = 2$) all have two states $[0.2, 0.25]$, $[0.15, 0.25]$, $[0.2, 0.3]$, $[0.3, 0.4]$ and $[0.5, 0.6]$ in turn with the same probability distribution $[p, 1-p]$. In [3] and [9], the radius of fluctuation d was used to describe the incomplete information of channel gain, which represents the observation error ratio of actual channel gain. For jammer, it is uncertain about the real channel gain α_m, η_n of different transmission links, and it assumes the gain α_m, η_n has states $[\alpha_m, \alpha_m + d\alpha_m]$, $[\eta_n, \eta_n + d\eta_n]$ respectively with the same probability distribution $[p, 1-p]$. The distance between PU1, PU2, RU1, RU2 and legitimate receiver are set as $d_1 = 18$km, $d_2 = 16$km, $v_1 = 15$km, $v_2 = 13$km, respectively. And the distance between jammer and receiver is set as $w = 22.5$km. The noise power $N_0 = -54$dBm. The dual variable $\lambda_1 = \lambda_2 = \psi_1 = \psi_2 = \mu = 1$, and the iteration steps $\Delta^t_{\lambda_m}$, $\Delta^t_{\psi_n}$ and Δ^t_{μ} are set as 0.1. The rest of parameters are $\delta = 2$, $p = 0.5$, $p_{1\max} = 6$W, $p_{2\max} = 8$W, $q_{\max} = 10$W, $j_{\max} = 10$W. The initial power $p_1 = 2$W, $p_2 = 1$W, $q_1 = 0$, $q_2 = 0$, $J = 0$.

A. POWER CONVERGENCE OF THE PROPOSED GAME

The convergence to Stackelberg Equilibrium is shown in Fig. 4. In the beginning of Bayesian three-layer Stackelberg game, primary users choose initial power to transmit messages. In order to ensure the communication quality, relay users select optimal power to help PUs forward information and guarantee communication quality. Then jammer increases jamming power to deteriorate the communication performance, which causes the decline of transmission power because of the strong interference. The advantage of the proposed scheme is that both PUs and RUs could choose low power under strong interference or high power under weak interference to increase communication quality, because users can make strategies after knowing the optimal strategy of jammer. After about 15 iterations, all users and jammer have converged to the Stackelberg Equilibrium, which also verifies the existence of SE.

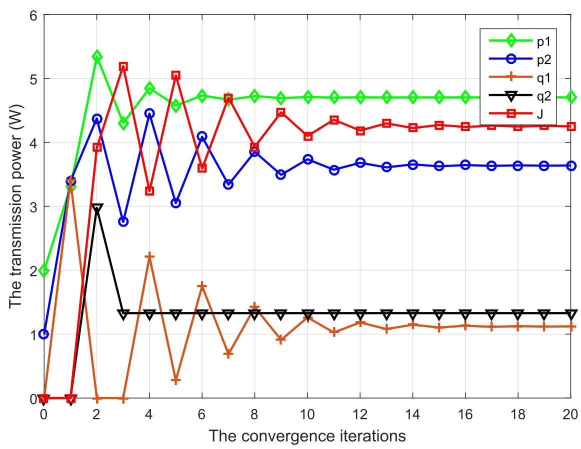


FIGURE 4. Power convergence of users and jammer.

B. THE UTILITY COMPARISON OF SE AND NE UNDER OBSERVATION ERROR

Fig. 5 shows the influence of observation error ε (ε here refers to ε_i) on the primary users' utilities of SE and NE. Under the same observation error, the primary users of SE have a higher utility compared to NE, which proves the effectiveness of proposed game. The observation error ε_i means the deviation between the ith primary user's actual transmission power and jammer's observation result. It can be seen from the diagram that primary user's utility is an increasing function of ε_i, because a greater observation error represents the users' information observed by jammer deviates more

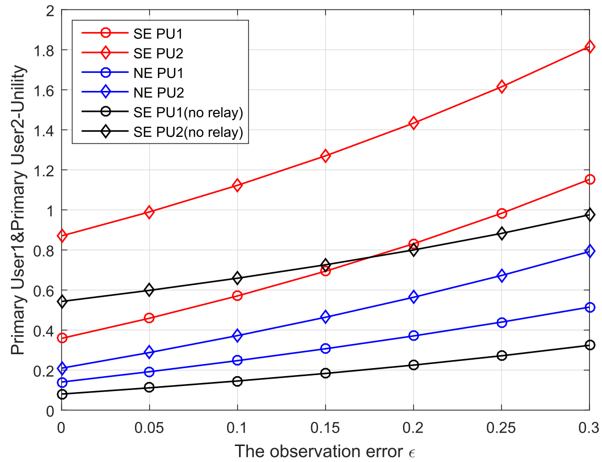


FIGURE 5. Primary users' performance comparison under observation error.

from the actual value, which is beneficial to users. Moreover, a Bayesian two-layer Stackelberg game is formulated in the non-relay situation, and the SE of Bayesian two-layer and three-layer Stackelberg game are compared. As shown in Fig. 5, users' utilities are prominently improved compared to the non-relay situation, which showed the existence of relay can effectively improve users' utilities.

In Fig. 6, we can find the relay's utility is a increasing function of observation error ε (ε here refers to $\varepsilon_i^{(r)}$) and the utility of SE is lower than NE, among which $\varepsilon_i^{(r)}$ means the deviation between the ith relay user's actual transmission power and jammer's observation result. On the contrary, the jammer's utility of SE is higher than NE, because jammer would learn the users' transmission power rapidly and make a strategy then in the proposed game. And jammer's utility is a decreasing function of observation error ε (ε here refers to ε_i and $\varepsilon_i^{(r)}$) because the greater observation error is, the larger deviation between jammer's observation result and actual value is, which affects jammer's decision-making and causes a lower utility.

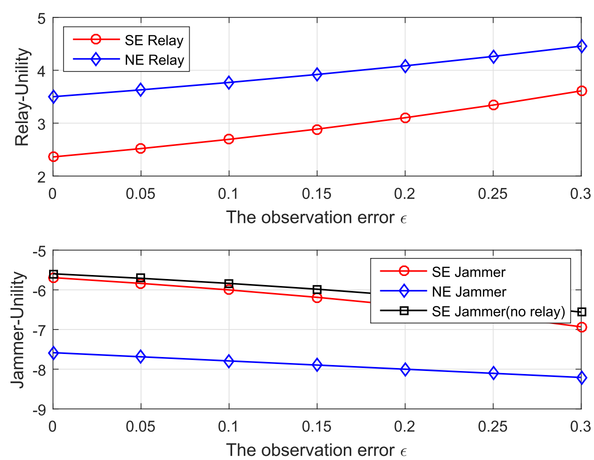


FIGURE 6. Relay's and jammer's performance comparison under observation error.

C. THE INFLUENCE OF INCOMPLETE INFORMATION, JAMMING DISTANCE AND JAMMING COST ON UTILITY

In Fig. 7, it is clear to find the influence of radius of fluctuation d on primary users' utilities. For the ith primary user, the radius of fluctuation d means the jammer's observation error ratio of actual channel gain α_i on its transmission link. It can be seen from the diagram that primary user's utility is an increasing function of d, i.e., the higher radius of fluctuation d is, the higher primary user's utility is because users' information observed by jammer deviates more from the actual value.When radius of fluctuation d is zero, it means jammer could obtain the exact information of channel gain α_i, thus current primary users' utilities are the lowest compared to other values of d.

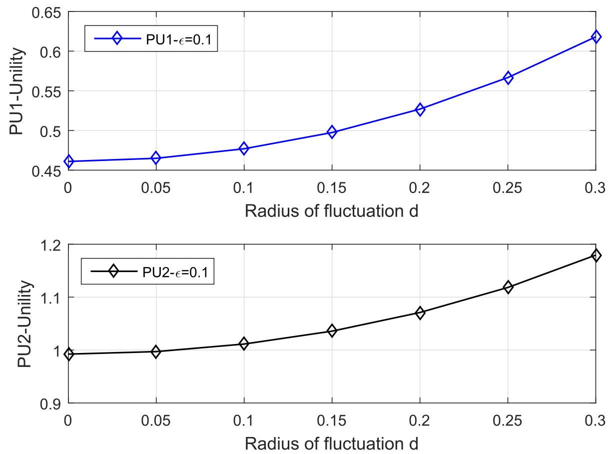


FIGURE 7. **The influence of radius of fluctuation on primary users' utilities.**

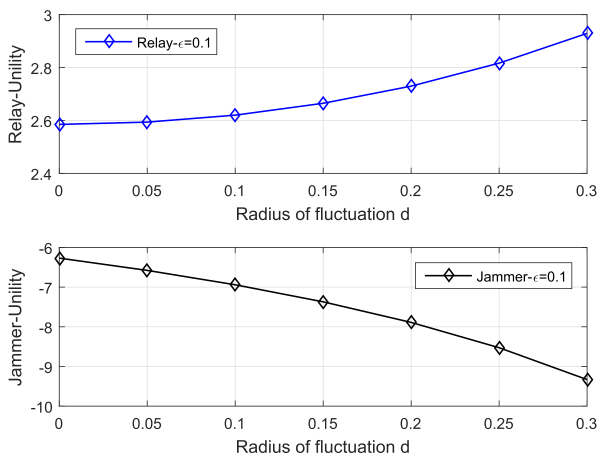


FIGURE 8. **The influence of radius of fluctuation on relay's and jammer's utility.**

In Fig. 8, we can find the relationships between radius of fluctuation d and relay's and jammer's utility. For relay, radius of fluctuation d represents the uncertainty of the channel gain η to jammer, i.e., the existence of d would cause jammer can't obtain the complete information of relay user's gain. So relay's utility increases with d. Conversely, for jammer, the existence of radius of fluctuation d means it can't know users' and relay's channel gain completely, which leads to the decrease of utility.

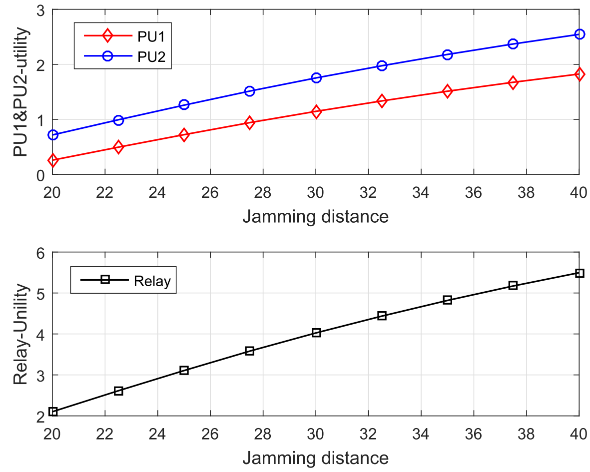


FIGURE 9. **The influence of jamming distance on primary users' and relay's utilities.**

In Fig. 9, we can see the influence of the jamming distance on utilities of users and relay. Based on the simplified path-loss model $\beta = w^{-\delta}$, the increase of jamming distance causes the decrease of channel gain β. For jammer, its utility is a negative function and an increasing function of β, while users are opposite to jammer, the utilities of primary users and relay are decreasing functions of β. In the simulation, we adjust jamming distance from 20km to 40km with change of 2.5km each time. We find the greater jamming distance is, the lower channel gain β is, and the higher users' and relay's utilities are, which corresponds with the analysis above. In Fig. 10, the increase of jamming cost means jammer need pay a higher price under the same jamming power, which reduces the influence of jammer and causes the decrease of jammer's utility, while improves the primary users' and relay's utilities correspondingly at the same time.

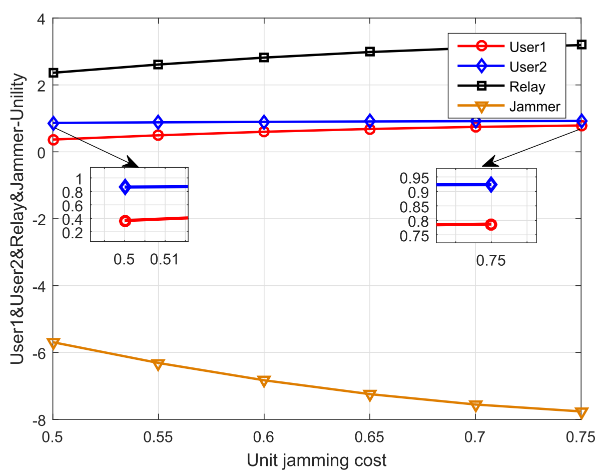


FIGURE 10. **The influence of jamming cost on utility.**

VI. CONCLUSIONS

In this paper, we mainly investigated the power control problem in relay-assisted anti-jamming communication systems. Considering the competitive interactions between users and jammer, an anti-jamming Bayesian three-layer Stackelberg game was proposed, in which primary users acted as leaders, relay users acted as vice-leaders and jammer acted as follower. The transmission power of users and jammer converged to Stackelberg Equilibrium (SE) by continuous iterations, and we also gave the proof of the existence and uniqueness of SE. Moreover, simulation results were shown to prove the effectiveness of the proposed game, and we also analyzed the influence of observation error, incomplete information, jamming distance and jamming cost on utility. In the future, we will take the channel allocation and co-channel mutual interference into consideration to further improve the communication anti-jamming ability.

REFERENCES

[1] D. Yang, G. Xue, J. Zhang, A. Richa, and X. Fang, "Coping with a smart jammer in wireless networks: A Stackelberg game approach," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 4038–4047, Aug. 2013.

[2] L. Xiao, T. Chen, J. Liu, and H. Dai, "Anti-jamming transmission Stackelberg game with observation errors," *IEEE Commun. Lett.*, vol. 19, no. 6, pp. 949–952, Jun. 2015.

[3] L. Jia, F. Yao, Y. Sun, Y. Niu, and Y. Zhu, "Bayesian Stackelberg game for antijamming transmission with incomplete information," *IEEE Commun. Lett.*, vol. 20, no. 10, pp. 1991–1994, Oct. 2016.

[4] X. Kang, R. Zhang, and M. Motani, "Price-based resource allocation for spectrum-sharing femtocell networks: A stackelberg game approach," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 538–549, Apr. 2012.

[5] L. Jia, Y. Xu, Y. Sun, S. Feng, and A. Anpalagan, "Stackelberg game approaches for anti-jamming defence in wireless networks," *IEEE Wireless Commun. Mag.*, vol. 25, no. 6, pp. 120–128, Dec. 2018.

[6] Y. Li, L. Xiao, J. Liu, and Y. Tang, "Power control Stackelberg game in cooperative anti-jamming communications," in *Proc. GAMENTS*, Nov. 2014, pp. 93–98.

[7] L. Xiao, Y. Li, J. Liu, and Y. Zhao, "Power control with reinforcement learning in cooperative cognitive radio networks against jamming," *J. Supercomput.*, vol. 71, no. 9, pp. 3237–3257, Sep. 2015.

[8] Y. Xu *et al.*, "A one-leader multi-follower Bayesian-Stackelberg game for anti-jamming transmission in UAV communication networks," *IEEE Access*, vol. 6, pp. 21697–21709, 2018.

[9] L. Yu, Q. Wu, Y. Xu, G. Ding, and L. Jia, "Power control games for multi-user anti-jamming communications," *Wireless Netw.*, pp. 1–10, Jan. 2018.

[10] X. Tang, P. Ren, Y. Wang, Q. Du, and L. Sun, "Securing wireless transmission against reactive jamming: A Stackelberg game framework," in *Proc. IEEE GLOBECOM*, Dec. 2015, pp. 1–6.

[11] M. M. G. Asadullah and G. L. Stuber, "Joint iterative channel estimation and soft-chip combining for a MIMO MC-CDMA anti-jam system," *IEEE Trans. Commun.*, vol. 57, no. 4, pp. 1068–1078, Apr. 2009.

[12] Y. Xu, J. Wang, Q. Wu, J. Zheng, L. Shen, and A. Anpalagan, "Dynamic spectrum access in time-varying environment: Distributed learning beyond expectation optimization," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5305–5318, Dec. 2017.

[13] K. Zhang, Y. Mao, S. Leng, and S. Fang, "Efficient anti-jamming strategies in multi-channel wireless networks," in *Proc. IEEE. ICCP*, Oct. 2013, pp. 109–112.

[14] Y. Wu, B. Wang, K. J. R. Liu, and T. C. Clancy, "Anti-jamming games in multi-channel cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 1, pp. 4–15, Jan. 2012.

[15] X. Liu, Y. Xu, L. Jia, Q. Wu, and A. Anpalagan, "Anti-jamming communications using spectrum waterfall: A deep reinforcement learning approach," *IEEE Commun. Lett.*, vol. 22, no. 5, pp. 998–1001, May 2018.

[16] L. Jia, Y. Xu, Y. Sun, S. Feng, L. Yu, and A. Anpalagan, "A game-theoretic learning approach for anti-jamming dynamic spectrum access in dense wireless networks," *IEEE Trans. Veh. Technol.*, to be published.

[17] A. Bhattacharya, S. Audhya, and K. Sinha, "An anti-jamming protocol based on secret reallocation of channels," in *Proc. 3rd Int. Conf. Recent Adv. Inf. Technol. (RAIT)*, vol. 10, Mar. 2016, pp. 154–159.

[18] K. Pelechrinis, M. Iliofotou, and S. Krishnamurthy, "Denial of service attacks in wireless networks: The case of jammers," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 2, pp. 245–257, 2nd Quart., 2011.

[19] L. Yin-Ting, Z. Shu-Yi, S. Dan, S. Yuan-Mao, and G. You-Gang, "Anti-jamming space-time processor with digital beamformer for satellite navigation," in *Proc. IEEE. CEEM*, Nov. 2015, pp. 31–35.

[20] Y. Du, Y. Gao, J. Liu, and X. Xi, "Frequency-space domain anti-jamming algorithm assisted with probability statistics," in *Proc. Int. Conf. Inf. Technol. Appl.*, Nov. 2013, pp. 5–8.

[21] H. Shajaiah, J. Mahal, and C. Clancy, "Resource management with anti-Jamming capability for cognitive space communication systems," in *Proc. IEEE Mil. Commun. Conf.*, Nov. 2016, pp. 144–149.

[22] D. Wang, J. Li, W. Gong, and S. Wu, "Attitude aided space-time multi-beamformer anti-jamming approach for satellite navigation receiver," in *Proc. 12th Int. Conf. Signal Process. (ICSP)*, Oct. 2014, pp. 368–372.

[23] X. Jianhong, W. Linyu, and H. Lilian, "Application of anti-jam antenna based on space-time signal processing," in *Proc. 2nd Int. Conf. Inf. Sci. Eng.*, Dec. 2010, pp. 1007–1010.

[24] M. K. Hanawal, M. J. Abdel-Rahman, and M. Krunz, "Game theoretic anti-jamming dynamic frequency hopping and rate adaptation in wireless systems," in *Proc. IEEE. 12th WiOpt*, May 2014, pp. 247–254.

[25] Y. Xu, J. Wang, Q. Wu, A. Anpalagan, and Y.-D. Yao, "Opportunistic spectrum access in unknown dynamic environment: A game-theoretic stochastic learning solution," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1380–1391, Apr. 2012.

[26] E. Altman, K. Avrachenkov, and A. Garnaev, "A jamming game in wireless networks with transmission cost," in *Proc. NET-COOP*, Jun. 2007, pp. 1–12.

[27] M. A. Aref and S. K. Jayaweera, "A novel cognitive anti-jamming stochastic game," in *Proc. CCAA*, Jun. 2017, vol. 30, no. 1, pp. 1–4.

[28] Y. E. Sagduyu, R. A. Berry, and A. Ephremides, "Jamming games in wireless networks with incomplete information," *IEEE Commun. Mag.*, vol. 49, no. 8, pp. 112–118, Aug. 2011.

[29] Y. Yang, H. Hu, J. Xu, and G. Mao, "Relay technologies for WiMax and LTE-advanced mobile systems," *IEEE Commun. Mag.*, vol. 47, no. 10, pp. 100–105, Oct. 2009.

[30] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[31] A. Mehmood, M. Mukherjee, S. H. Ahmed, H. Song, and K. M. Malik, "NBC-MAIDS: Naïve Bayesian classification technique in multi-agent system-enriched IDS for securing IoT against DDoS attacks," *J. Supercomput.*, vol. 74, no. 10, pp. 5156–5170, 2018.

[32] D. Liu *et al.*, "Self-organizing relay selection in UAV communication networks: A matching game perspective," *IEEE Wireless Commun. Mag.*, to be published. [Online]. Available: https://arxiv.org/abs/1805.09257

[33] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[34] G. Ding, Q. Wu, and J. Wang, "Sensing confidence level-based joint spectrum and power allocation in cognitive radio networks," *Wireless Pers. Commun.*, vol. 72, no. 1, pp. 283–298, Jan. 2013.

[35] A. Goldsmith, *Wireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[36] R. El-Bardan, S. Brahma, and P. K. Varshney, "Strategic power allocation with incomplete information in the presence of a jammer," *IEEE Trans. Commun.*, vol. 64, no. 8, pp. 3467–3479, Aug. 2016.

[37] A. B. MacKenzie and L. A. DaSilva, *Game Theory for Wireless Engineers*, San Rafael, CA, USA: Morgan & Claypool, 2006.

[38] Q. D. Lã, Y. H. Chew, and B.-H. Soong, *Potential Game Theory Applications in Radio Resource Allocation*. New York, NY, USA: Springer, 2016.

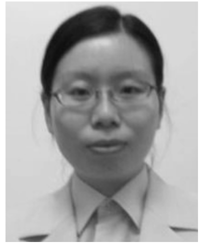
[39] J. B. Rosen, "Existence and uniqueness of equilibrium points for concave N-person games," *Econometrica*, vol. 33, no. 3, pp. 520–534, Jul. 1965.

ZHIBIN FENG received the B.S. degree in communication engineering from the Beijing Institute of Technology, Beijing, China, in 2017. He is currently pursuing the M.S. degree with the College of Communication Engineering, Army Engineering University of PLA. His current research interests include game theory, learning theory, and communication anti-jamming technology.

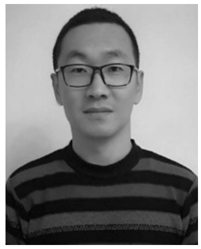
GUOCHUN REN received the B.S. degree in wireless communication and the M.S. degree in communications engineering and information system from the Institute of Communications Engineering, Army Engineering University of PLA, Nanjing, China, in 1989 and 1994, respectively, where he is currently a Professor. His current research interests include wireless communications networks and cognitive radio Networks.

JIN CHEN received the B.S. degree in wireless communication, the M.S. degree, and the Ph.D. degree in communications engineering and information system from the Institute of Communications Engineering, Army Engineering University of PLA, Nanjing, China, in 1993, 1996, and 1999, respectively, where she is currently a Professor. Her current research interests include wireless communications networks and cognitive radio networks.

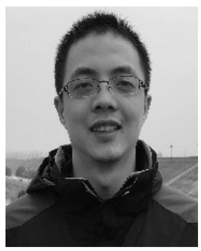
XIAOBO ZHANG received the B.S. degree in communications engineering and the M.S. degree in communications and information systems from the PLA University of Science and Technology, in 2006 and 2009, respectively. He is currently pursuing the Ph.D. degree with the College of Communication Engineering, Army Engineering University of PLA. His current research interests include wireless network security and intelligent anti-jamming technology.



YIJIE LUO received the B.S. and M.S. degrees in information and communication engineering from the Nanjing University of Aeronautics and Astronautics, Jiangsu, in 2004 and 2007, respectively. She is currently pursuing the Ph.D. degree with the College of Communication Engineering, Army Engineering University of PLA. Her current research interests include D2D communications, physical layer security, game theory, and learning theory.



MENG WANG received the B.S. degree and the M.S. degree in instructional technology from the Nanjing Normal University, in 2006 and 2009, respectively. His current research interests include wireless network security, game theory, and intelligent anti-jamming technology.



YUHUA XU received the B.S. degree in communications engineering and the Ph.D. degree in communications and information systems from the College of Communications Engineering, PLA University of Science and Technology, in 2006 and 2014, respectively. He is currently with the College of Communications Engineering, Army Engineering University of PLA, as an Associate Professor. He has published several papers in international conferences and reputed journals in his research area. His research interests include UAV communication networks, opportunistic spectrum access, learning theory, and distributed optimization techniques for wireless communications. He received the Certificate of Appreciation as an Exemplary Reviewer of the IEEE Communications Letters, in 2011 and 2012. He was selected to receive the IEEE Signal Processing Society's 2015 Young Author Best Paper Award and the Funds for Distinguished Young Scholars of Jiangsu Province, in 2016.