Power Control Stackelberg Game in Cooperative Anti-Jamming Communications

Yan Li, Liang Xiao*, Jinliang Liu, Yuliang Tang
Dept. of Communication Engineering, Xiamen University, 361005, China
*Email: lxiao@xmu.edu.cn

Abstract—As wireless networks are vulnerable to malicious attacks, security issues have aroused more and more research interest. In this paper, we focus on the anti-jamming power control of transmitters in cooperative wireless network attacked by a smart jammer with the capability to sense the ongoing transmission power before making its jamming decision. Modeling the interaction between transmitters and a jammer as a Stackelberg game, we analyze the optimal strategies for both transmitters

[illegible] [2].

In recent years, jamming-resistant broadcast has been receiving a growing attention. As a traditional countermeasure ascenario as a Stackelberg game, where the source node is the leader and the jammer is the follower. The relay node as a vice-leader adjusts its strategy based on the source's strategy to help the source node efficiently. Then, by analyzing the optimization problems for this three players, the Stackelberg equilibrium (SE) of the game is obtained. Finally, the NE, in which the three players take actions simultaneously, is also derived to compare with the SE. As shown later in the paper, the optimal power control strategies obtained from the SE can minimize the worst-case damage caused by the jammer.

The rest of this paper is organized as follows. We briefly review related work in Section II. In Section III, we provide the system model and the problem we consider. The optimal power control strategy obtained from the Stackelberg equilibrium is derived in Section IV, while an exact closed form expression of Nash equilibrium strategy is presented in Section V. Numerical results are presented in Section VI. Finally, Section VII concludes our work.

II. Related Work

There have been quite a few papers which studied on power allocation in wireless networks, such as [14]–[16]. In [14], by employing a Stackelberg game between the source node and the relay nodes, Wang et al. achieved optimal relay selection and power allocation without knowledge of channel state information in multiuser cooperative wireless networks. The interaction between the BS and users was modeled as a Stackelberg game and a novel price-based power control algorithm for the base station of primary users was proposed in [15] to solve price-based power control problem in cognitive radio networks whose spectrum is shared. In [16], the power control problem for cooperative communication networks was studied by analyzing the cooperation behavior of selfish user nodes with cooperative games.

However, the power allocation problem becomes more sophisticated in an attacked wireless network where the presence of jammers has to be taken into consideration. The performance of anti-jamming and the efficient power allocation need to be considered simultaneously. A non-zero-sum game between transmitter and jammer was formulated in [17], which considered the transmission cost and proved the existence and uniqueness of the Nash equilibrium. UFH and power allocation were taken into consideration jointly in [18]. With the online learning theory, the proposed approach can determine both the hopping channels and the power allocation based on the history of channel status. In addition, based on the assumption of perfect knowledge, Wu et al. used an anti-jamming game to analyze the interaction between the secondary user and jammers and proposed a defense strategy using the Markov decision process approach in [19]. Meanwhile, two learning schemes were provided for secondary users to gain knowledge of jammers in the situations without perfect knowledge. For the eavesdropped wireless networks, Ghose et al. proposed a cooperative scheme to minimize the total transmission power under a secrecy rate constraint in [20].

III. System Model And Anti-jamming Game

We consider a simple cooperative wireless network attacked by a smart jammer, where a relay node helps the source broadcast a message on a single channel to the destination. The legitimate users (the source and relay node) and the malicious jammer can freely control their transmission power, respectively. Thus they can adjust their own transmission power to achieve the maximum utility. In order to assist the source efficiently, the relay node decides its own transmission power after rapidly learn the source's transmission power. On the other hand, once sensing the power of transmitters (the source and relay node), the smart jammer chooses its jamming power on the channel to make the damaging effect maximized.

Obviously, Stackelberg game, who is good at dealing with a situation where players take actions sequentially, is a really great tool to model the power control strategies in our system. Under the above analysis, we formulate the power control strategies as a Stackelberg game. We consider the source as a leader, the relay as a vice leader and the jammer as a follower in this game. Let $x = s$, r and j denote the source, the relay node and the jammer, respectively. The action of Player x is its own transmission power denoted by $P_x \in [0, \infty)$. Let $h_x > 0$ denote the fading channel gain between Player x and the receiver, and $C_x > 0$ be the transmission cost per unit power of Player x. The signal to interference plus noise ratio (SINR) at the receiver is given by

$$SINR = \frac{h_s P_s + h_r P_r}{N + h_j P_j}, \tag{1}$$

where N is the noise power.

For the source, its purpose is to achieve the maximum SINR with the minimum cost. Thus, the utility function of the source, which is the communication gain minus the cost, can be defined as

$$U_s(P_s, P_r, P_j) = \frac{h_s P_s + h_r P_r}{N + h_j P_j} - C_s P_s. \tag{2}$$

Similarly, the utility function of the relay node can be modeled as

$$U_r(P_s, P_r, P_j) = \frac{h_s P_s + h_r P_r}{N + h_j P_j} - C_r P_r. \tag{3}$$

However, the smart jammer aims at jamming the legitimate transmitters as soon as possible by initiating a jamming attack. Thus, any gains of the transmitters are the loss of the jammer. On the contrary, any costs of the legitimate users are the jamming gain. Accordingly, the utility function of the jammer is expressed as

$$U_j(P_s, P_r, P_j) = -\frac{h_s P_s + h_r P_r}{N + h_j P_j} + C_s P_s + C_r P_r - C_j P_j. \tag{4}$$

In this Stackelberg game, each player takes its best strategy to maximum its utility, respectively. In addition, for the simple, we assume the energy of these wireless radios is limitless. Even so, they would not choose oversize power to emit signal, because their utility become reduced with the increasing of

TABLE I

SUMMARY OF SYMBOLS AND NOTATIONS

$x(=s,r,j)$	Player x (source, relay node or jammer)
P_x	Transmission power of Player x
C_x	Transmission cost per unit Player x power
h_x	Channel gain between Player x and the receiver
N	Noise power
U_x	Utility function of Player x
$\hat{P}_x$	Behavior of Player x forecasted by the other players
P_x^{SE}	Stackelberg equilibrium strategy of Player x
P_x^{NE}	Nash equilibrium strategy of Player x

the cost to a certain degree. Thus, the optimal power control strategies in the game are given by

$$P_s^* = \arg\max_{P_s \geq 0} U_s(P_s, \hat{P}_r, \hat{P}_j), \quad (5)$$

$$P_r^* = \arg\max_{P_r \geq 0} U_r(\hat{P}_s, P_r, \hat{P}_j), \quad (6)$$

$$P_j^* = \arg\max_{P_j \geq 0} U_j(\hat{P}_s, \hat{P}_r, P_j), \quad (7)$$

where $\hat{P}_x$ is the behavior of Player x forecasted by the other players. Similarly to [12] and [13], we assume they have the full location knowledge of each other, with which they can use physical carrier sensing to estimate other's transmission power accurately (i.e., $\hat{P}_x = P_x$). For ease of reference, the usual used notations are summarized in Table I.

IV. Stackelberg Equilibrium In The Game

Through the above analysis, the game between the transmitters and the jammer involves solving three optimization problems: two from the viewpoint of transmitters and another from the viewpoint of jammer. In the Stackelberg game, based on the impact on the other players by its strategy, the source first chooses a best strategy to maximize its utility. Then considering the source's strategy and the impact on the jammer by its action, the relay node sends the message with the best power to achieve the maximum utility. Finally, after observing the strategy of the transmitters, the jammer emits the best jamming signal to get the highest utility. As a consequence, the game reaches its Stackelberg equilibrium, which consists of the optimal strategy of the three players. In order to derive the Stackelberg equilibrium, we need to analyze the impact on the jammer and the relay node by the source's action.

A. Optimal Jamming Strategy

In order to maximize the jammer's utility defined by (4), we need to solve the following optimization problem:

$$\max_{P_j \geq 0} U_j(P_s, P_r, P_j) = -\frac{h_s P_s + h_r P_r}{N + h_j P_j} + C_s P_s + C_r P_r - C_j P_j. \quad (8)$$

Lemma IV.1. *The optimal strategy of the jammer power allocation, P_j^{SE}, is given by:*

$$P_s^{SE} = \begin{cases} 0, & \Pi, \\ \frac{1}{h_j}\left[\sqrt{\frac{h_j(h_s P_s + h_r P_r)}{C_j}} - N\right], & otherwise, \end{cases} \quad (9)$$

where Π: $h_s P_s + h_r P_r \leq \frac{C_j}{h_j} N^2$.

Proof: First, we analyze the property of the utility function of the jammer, $U_j(P_s, P_r, P_j)$, by differentiating it,

$$\frac{\partial U_j(P_s, P_r, P_j)}{\partial P_j} = \frac{h_j(h_s P_s + h_r P_r)}{(N + h_j P_j)^2} - C_j, \quad (10)$$

$$\frac{\partial^2 U_j(P_s, P_r, P_j)}{\partial {P_j}^2} = \frac{-2 h_j^2 (h_s P_s + h_r P_r)}{(N + h_j P_j)^3}. \quad (11)$$

From (11), $U_j(P_s, P_r, P_j)$ is a concave function with respect to P_j. By setting (10) to 0, we can obtain $\tilde{P}_j = \frac{1}{h_j}\left[\sqrt{\frac{h_j(h_s P_s + h_r P_r)}{C_j}} - N\right]$. Thus $P_j^{SE} = \tilde{P}_j$ if $\tilde{P}_j > 0$ (i.e, $h_s P_s + h_r P_r > \frac{C_j}{h_j} N^2$). If $\tilde{P}_j \leq 0$, $U_j(P_s, P_r, P_j)$ decreases with P_j for $P_j \geq 0$, yielding $P_j^{SE} = 0$, and thus obtain (9). •

On the basis of above analysis, it is obvious that the optimal jamming strategy varies with the ongoing transmission power. If the jamming gain is less than the jamming cost caused by the ongoing low transmission power (i.e, $h_s P_s + h_r P_r \leq \frac{C_j N^2}{h_j}$), the jammer's best strategy is to ignore the present transmission. However, once the current transmission power exceeds a certain threshold (i.e, $h_s P_s + h_r P_r > \frac{C_j N^2}{h_j}$), the optimal jammer's strategy is to adjust the jamming power according to the current transmission power.

B. Optimal Relay Strategy

Similarly, for the relay node, based on (3), its optimal strategy can be derived from the following optimization problem:

$$\max_{P_r \geq 0} U_j(P_s, P_r) = \frac{h_s P_s + h_r P_r}{N + h_j P_j^{SE}} - C_r P_r. \quad (12)$$

Lemma IV.2. *The optimal strategy of relay node, P_r^{SE}, is given by:*

(13)

where

$$\Omega_1 : P_s \geq \max(\frac{C_j N^2}{h_s h_j}, \frac{{h_R}^2 C_j}{4 h_s h_j {C_r}^2}) \quad or \quad P_s < \frac{C_j N^2}{h_s h_j}, \frac{h_r}{N} \leq C_r,$$

$$\Omega_2 : \frac{C_j N^2}{h_s h_j} \leq P_s < \frac{{h_r}^2 C_j}{4 h_s h_j {C_r}^2} \quad or \quad P_s < \frac{C_j N^2}{h_s h_j}, \frac{h_r}{N} \geq 2C_r.$$

Proof: By plugging P_j^{SE} into (3), the utility function of the relay node, $U_r(P_s, P_r, P_j)$, is modified to:

$$U_r(P_s, P_r) = \begin{cases} \left(\frac{h_r}{N} - C_r\right) P_r + \frac{h_s}{N} P_s, & P_r \leq x_1, \\ \sqrt{\frac{C_j}{h_j}(h_s P_s + h_r P_r)} - C_r P_r, & P_r > x_1, \end{cases} \quad (14)$$

where $x_1 \cdot\ - h_s P_s$. Thus U_r is a linear function for $P_r \leq x_1$. When $P_r > x_1$, we have

$$\frac{\partial U_r(P_s, P_r)}{\partial P_r} = \frac{h_r}{2}\sqrt{\frac{C_j}{h_j(h_sP_s + h_rP_r)}} - C_r, \quad (15)$$

$$\frac{\partial^2 U_r(P_s, P_r)}{\partial P_r^2} = \frac{-h_r^2}{4(h_sP_s + h_rP_r)}\sqrt{\frac{C_j}{h_j(h_sP_s + h_rP_r)}}. \quad (16)$$

By (16), U_r is a concave function for $P_r > x_1$ and maximized by $\tilde{P}_r = \frac{h_r C_j}{4 h_j C_r^2} - \frac{h_s}{h_r}P_s$, if $\tilde{P}_r \geq 0$. To find the optimal P_r maximizing U_r, we consider the following two cases.

1) $P_s \geq \frac{C_j N^2}{h_s h_j}$ (i.e, $x_1 \leq 0$): U_r is only a concave function for $P_r \geq 0$. As $\tilde{P}_r \leq 0$ (i.e, $P_s \geq \frac{h_r^2 C_j}{4h_s h_j C_r^2}$), U_r decreases with P_r, and thus $P_r^{SE} = 0$. Otherwise, if $\tilde{P}_r > 0$, U_r is maximized on $\tilde{P}_r$ and we have $P_r^{SE} = \tilde{P}_r$.

2) $P_s < \frac{C_j N^2}{h_s h_j}$: U_r is a decreasing concave function for $P_r > x_1$. As $x_1 \leq \tilde{P}_r$ (i.e, $\frac{h_r}{C_r} \geq 2N$), U_r is increasing for $0 \leq P_r \leq x_1$. Thus $U_r(\tilde{P}_r)$ is the maximum value of U_r, that is, $P_r^{SE} = \tilde{P}_r$. However, when $x_1 > \tilde{P}_r$, if $\frac{h_r}{N} > C_r$, U_r increases with P_r for $0 \leq P_r \leq x_1$ and thus $P_r^{SE} = x_1$, but if $\frac{h_r}{N} \leq C_r$, U_r decreases with P_r for $0 \leq P_r \leq x_1$, so $P_r^{SE} = 0$. To sum up, we have (13). •

It can be observed that when the current power of the source learned by the relay is large enough (i.e, $P_s \geq \max(\frac{C_j N^2}{\ }, \frac{h_r^2 C_j}{\ })$), the optimal relay strategy is not sending any more. But when the power of the source and the transmission cost of the relay are both low (i.e, $P_s < \frac{C_j N^2}{h_s h_j}, \ \leq C_r$), the relay is too powerless to help the source. Otherwise, the relay's best strategy of is to adjust its power based on the current transmission power of the source.

C. Optimal Source Strategy

To find the source's optimal strategy, based on (2), we solve the following optimization problem:

$$\max_{P_s \geq 0} U_s(P_s) = \frac{h_sP_s + h_rP_r^{SE}}{N + h_jP_j^{SE}} - C_sP_s. \quad (17)$$

for the source node to find its optimal strategy.

Lemma IV.3. *The optimal strategy of the source P_s^{SE} is given by:*

$$P_s^{SE} = \begin{cases} \frac{h_sC_j}{4h_jC_s^2}, & \Phi 1, \\ \frac{C_jN^2}{h_sh_j}, & C_r \geq \frac{h_r}{N}, \frac{h_s}{2N} < C_s < \frac{h_s}{N}, \\ 0, & otherwise, \end{cases} \quad (18)$$

where $\Phi : C_r \leq \frac{h_r}{2N}, \frac{C_s}{C_r} < \frac{h_s}{2h_r}$ *or* $\frac{h_r}{2N} < C_r < \frac{h_r}{N}, C_s < \frac{h_s}{4N}$ *or* $C_r \geq \frac{h_r}{N}, C_s < \frac{h_s}{2N}$.

Proof. By substituting P_j^{SE} and P_r^{SE} into (2), the utility function of the source, U_s is revised to:

$$U_s(P_s) = \begin{cases} \sqrt{\frac{h_sP_sC_j}{h_j}} - C_sP_s, & P_s \geq \max(y_1, y_2), \\ -C_sP_s + \frac{C_jN}{h_j}, & P_s < y_1, C_r < \frac{h_r}{N} < 2C_r, \\ (\frac{h_s}{N} - C_s)P_s, & P_s < y_1, \frac{h_r}{N} \leq C_r, \\ \frac{h_rC_j}{2h_jC_r} - C_sP_s, & \text{otherwise}, \end{cases} \quad (19)$$

where $y_1 = \frac{C_jN^2}{h_sh_j}$ and $y_2 = \frac{h_r^2 C_j}{4h_sh_jC_r^2}$. Thus U_s is a linear function for $P_s < \max(y_1, y_2)$. When $P_s \geq \max(y_1, y_2)$, we have

$$\frac{\partial U_s(P_s)}{\partial P_s} = \frac{1}{2}\sqrt{\frac{h_sC_j}{h_jP_s}} - C_s, \quad (20)$$

$$\frac{\partial^2 U_s(P_s)}{\partial P_s^2} = -\frac{1}{4P_s}\sqrt{\frac{h_sC_j}{h_jP_s}}. \quad (21)$$

For $P_s \geq \max(y_1, y_2)$, U_s is a concave function and maximized by $\tilde{P}_s = \frac{h_sC_j}{4h_jC_s^2}$. To find the optimal P_s maximizing U_s, we consider the following three cases.

1) $\frac{h_r}{N} \geq 2C_r$ (i.e, $y_1 \leq y_2$): U_s is a decreasing linear function for $0 \leq P_s \leq y_2$. 1.1) if $\frac{h_s}{C_s} \leq \frac{h_r}{C_r}$ (i.e, $\tilde{P}_s \leq y_2$), U_s decreases with P_s for $P_s > y_2$ and thus $P_s^{SE} = 0$. 1.2) if $\frac{h_s}{C_s} > \frac{h_r}{C_r}$, U_s is maximized by $\tilde{P}_s$ for $P_s > y_2$. In order to find the maximum U_s, we need to compare $U_s(0)$ with $U_s(\tilde{P}_s)$. If $U_s(0) \geq U_s(\tilde{P}_s)$, we have $P_s^{SE} = 0$, otherwise, $P_s^{SE} = \tilde{P}_s$.

2) $C_r < \frac{h_r}{N} < 2C_r$: U_s decreases with P_s for $0 \leq P_s \leq y_1$. 2.1) if $\frac{h_s}{C_s} \leq 2N$ (i.e, $\tilde{P}_s \leq y_1$), U_s is a decreasing concave function for $P_s > y_1$ and thus $P_s^{SE} = 0$. 2.2) if $\frac{h_s}{C_s} > 2N$, $U_s(\tilde{P}_s)$ is the maximum value of U_s for $P_s > y_1$. Thus if $U_s(0) \geq U_s(\tilde{P}_s)$, we have $P_s^{SE} = 0$, otherwise, $P_s^{SE} = \tilde{P}_s$.

3) $\frac{h_r}{N} \leq C_r$: 3.1) if $\frac{h_s}{C_s} \leq 2N$ (i.e, $\tilde{P}_s \leq y_1$), for $P_s > y_1$, U_s is a decreasing concave function. In addition, if $\frac{h_s}{C_s} \leq N$, U_s is decreasing for $0 \leq P_s \leq y_1$ and thus $P_s^{SE} = 0$, but if not, U_s decreases with P_s for $0 \leq P_s \leq y_1$, thus $P_s^{SE} = y_1$. 3.2) if $\frac{h_s}{C_s} > 2N$, $U_s(\tilde{P}_s)$ is the maximum value of U_s for $P_s > y_1$. As $\frac{h_s}{C_s} > N$, U_s is increasing for $0 \leq P_s \leq y_1$, thus $P_s^{SE} = \tilde{P}_s$. •

In conclusion, the SE of the anti-jamming game is given by $(P_s^{SE}, P_r^{SE}, P_j^{SE})$. Based on (18), the source as the leader chooses its action in overall consideration of both the impacts on the relay and the jammer and the channel conditions for all of them. If the transmission costs of the source and relay node are both too large (i.e, $C_r \geq \ \ C_s \geq \frac{h_s}{N}$) or the transmission gain of the relay is better than it, the source's optimal strategy is stopping transmission. Otherwise, the best strategy of the source is to adjust its power based on all channel gains and the jamming cost of the jammer.

V. NASH EQUILIBRIUM OF ANTI-JAMMING GAME

In this section, the Nash Equilibrium (NE) of the anti-jamming game for comparison with the SE scheme is studied. Different from the smart jammer in the SE scheme with the capability to sense the ongoing transmission power before it makes a jamming decision, the jammer in the NE doesn't have this capability and it takes action at the same time with the transmitters. The NE of the common anti-jamming game is the optimal strategy of the static game.

Lemma V.1. The NE of the anti-jamming game is given by:

$$(P_s^{NE}, P_r^{NE}, P_j^{NE}) = \begin{cases} (\frac{h_s C_j}{h_j C_s^2}, 0, \frac{1}{h_j}(\frac{h_s}{C_s} - N)), & f_1, \\ (0, \frac{h_r C_j}{h_j C_r^2}, \frac{1}{h_j}(\frac{h_r}{C_r} - N)) & f_2, \\ (0,0,0), & f_3, \end{cases} \quad (22)$$

where $f_1 : C_s \le \frac{h_s}{N}, \frac{C_s}{C_r} \le \frac{h_s}{h_r}$; $f_2 : C_r \le \frac{h_r}{N}, \frac{C_s}{C_r} > \frac{h_s}{h_r}$, and $f_3 : C_s > \frac{h_s}{N}, C_r > \frac{h_r}{N}$.

Proof: The derivatives of the utility function (2), (3) and (4) are, respectively given by:

$$\frac{\partial U_s(P_s, P_r, P_j)}{\partial P_s} = \frac{h_s}{N + h_j P_j} - C_s, \quad (23)$$

$$\frac{\partial U_r(P_s, P_r, P_j)}{\partial P_r} = \frac{h_r}{N + h_j P_j} - C_r, \quad (24)$$

$$\frac{\partial U_j(P_s, P_r, P_j)}{\partial P_j} = \frac{h_j(h_s P_s + h_r P_r)}{(N + h_j P_j)^2} - C_j. \quad (25)$$

To compute the NE, we consider the following three cases.

1) $\frac{h_s}{C_s} \ge N, \frac{h_s}{C_s} \ge \frac{h_r}{C_r}$: Setting $\frac{\partial U_s(P_s, P_r, P_j)}{\partial P_s} = 0$, we have $\tilde{P}_j = \frac{1}{h_j}(\frac{h_s}{C_s} - N) \ge 0$ and the utility of the source is a certain number for any P_s. Let $P_j^{NE} = \tilde{P}_j$. As $\frac{\partial U_r(P_s, P_r, P_j)}{\partial P_r} \le 0$, U_r decreases with P_r and thus $P_r^{NE} = 0$. To make $P_j^{NE} = \tilde{P}_j$, we must have $P_j = \tilde{P}_j$ and thus $P_s^{NE} = \frac{h_s C_j}{h_j C_s^2}$.

2) $\frac{h_r}{C_r} \ge N, \frac{h_r}{C_r} > \frac{h_s}{C_s}$: Let $\frac{\partial U_r(P_s, P_r, P_j)}{\partial P_r} = 0$ and we have $\bar{P}_j = \frac{1}{h_j}(\frac{h_r}{C_r} - N) \ge 0$ and U_r is a certain value for any P_r. Set $P_j^{NE} = \bar{P}_j$. As $\frac{\partial U_s(P_s, P_r, P_j)}{\partial P_s} \le 0$, U_s decreases with P_s and thus $P_s^{NE} = 0$. In order to have $P_j^{NE} = \bar{P}_j$, we must have $\bar{P}_j = \tilde{P}_j$ and thus $P_r^{NE} = \frac{h_r C_j}{h_j C_r^2}$.

3) $N > \max(\frac{h_s}{C_s}, \frac{h_r}{C_r})$: as $\frac{\partial U_s(P_s, P_r, P_j)}{\partial P_s} < 0$, U_s decreases with P_s and thus $P_s^{NE} = 0$. Similarly, we can get $P_r^{NE} = 0$. By integrating P_s^{NE} and P_r^{NE} into (25), we have $\frac{\partial U_j(P_s, P_r, P_j)}{\partial P_j} < 0$ and thus $P_j^{NE} = 0$. Ultimately, we obtain (22). ∎

VI. Simulation Results

In this section, some simulations are performed to evaluate the performance of the proposed SE strategy in the Stackelberg-based anti-jamming game. The utilities of all players, $U_s(P_s, P_r, P_j)$, $U_r(P_s, P_r, P_j)$ and $U_j(P_s, P_r, P_j)$ given by (2), (3) and (4) are presented. In addition, the SINR of the SE strategy showed by (1) is also computed. In these simulations, we assume the transmission cost per unit power of Player x, $C_x = 1$ and the noise power, $N = 0.2$.

Fig. 1 indicates the impacts of h_j on the utilities of all players with the proposed SE strategy compared with the NE strategy with $h_s = 0.5$ and $h_r = 0.5$. The utilities of the source and relay node decrease with h_j, while the utility of the jammer increases with h_j. The reason is that the higher value of h_j indicates the better channel condition for the jammer. In addition, the jammer's utility in the SE strategy is higher than the NE strategy, because the jammer can rapidly learn the ongoing power before making a decision in the SE strategy, which is much smarter than the jammer in the NE strategy.

The SINR in the SE and NE strategy is presented in Fig. 2, showing that the SINR decreases with the fading channel gain of the jammer, h_j, due to the jammer is more damaging when h_j increases. As mentioned before, the jammer in the SE strategy is more intelligent than that in the NE strategy. Consequently, the SINR achieved by the SE strategy is less than that achieved by the NE strategy. In addition, for a fixed h_s and h_j, for example $h_s = 0.6$ and $h_j = 0.1$, the SINR increases from 3 to 3.5 in the SE strategy while increases from 6 to 7 in the SE strategy when the fading channel gain of the relay node h_r increases from 0.2 to 0.7. Similarly, if h_r and h_j are fixed, the SINR also increases with h_s. This is because the increasings of h_s and h_r indicate a better channel

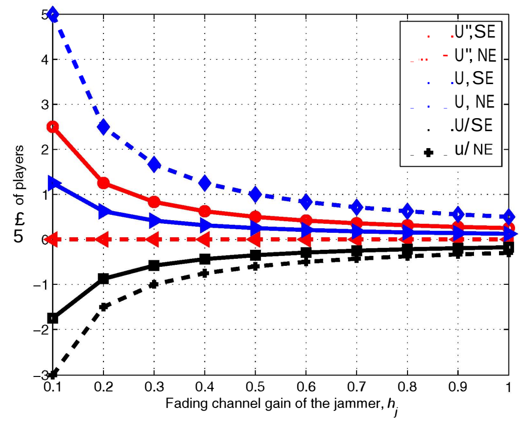

Fig. 1. The utilities of all players versus the fading channel gain of the jammer, h_j, in a cooperative wireless network with $C_s = C_r = C_j = 1$, $h_s = 0.5$, $h_r = 0.5$ and $N = 0.2$.

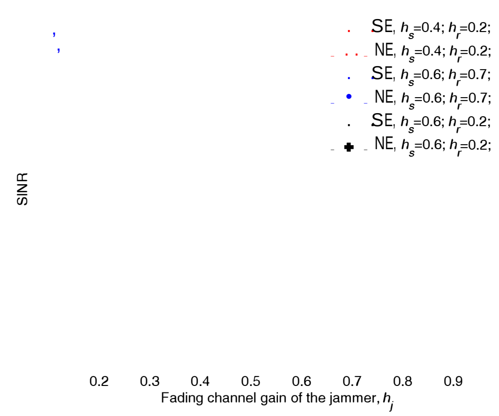

Fig. 2. The SINR versus the fading channel gain of the jammer, h_j, in a cooperative wireless network with $C_s = C_r = C_j = 1$, and $N = 0.2$.

condition for the source and relay node, respectively, which directly results in a higher transmission power received by the receiver.

VII. CONCLUSION

In a cooperative wireless network, where a relay node helps the source send a message attacked by a smart jammer, we have investigated the anti-jamming power control of the source and relay node. Using Stackelberg game to model the behaviors of the transmitters and the jammer, we have analyzed the optimal strategy for both the transmitters and the jammer and thus derived the Stackelberg equilibrium of the game. In addition, the Nash Equilibrium of the anti-jamming game is also derived for comparison with the SE scheme. Moreover, the impacts of the fading channel gains of the transmitters and the jammer on their utilities and the SINR have been researched, respectively. Simulation results have shown that a smart jammer with the capability to sensing the ongoing transmission power before making a jamming decision can destroy a wireless network more seriously than a common jammer without such a sensing capability. For example, when the fading channel gains of the source and relay node are both 0 5 and the jammer's channel gain is 0 1 , the total utility of the source and relay nodes in NE strategy is 5 while the total utility in SE strategy is only 3 . 75 Meanwhile, the utilities of the transmitters and the SINR decrease while the jammer's utility increases when the fading channel gain of the jammer increases. On the other hand, the SINR is improved when the fading channel gains of the transmitters increase.

REFERENCES

[1] L. Xiao, Q. Yan, W. Lou, and Y Hou, "Proximity-based security using ambient radio signals," in / 8 8) '8*)!8 *((4) 8 8 pp. 1609–1613, 2013.

[2] W. Xu, W Trappe, Y Zhang, and T. Wood, "The feasibility of launching and detecting jamming attacks in wireless networks," in ,* 8 8) '8 7(+ 8 %' 88 * 8 26*,&%))#8 *(+42%)#8 % * pp. 46–57, 2005.

[3] A. Goldsmith, %, ' 11 8(4)% 2%*8 Cambridge university press, 2005.

[4] T. Jin, G. Noubir, and B. Thapa, "Zero pre-shared secret key establishment in the presence of jammers," in / 8 8)2 '8(+ 8 %' 88 * 8 26*,&%))#8 *(+42%)#8 * % pp. 219–228, 2009.

[5] M. Strasser, S. Capkun, and M. Cagalj, "Jamming-resistant key establishment using uncoordinated frequency hopping," in / 8 8 7(+ 8 4,%3)8 8,%5 7 pp. 64–78, 2008.

[6] L. Xiao, H. Dai, and P Ning, "Jamming-resistant collaborative broadcast using uncoordinated frequency hopping," 8 ,)1 8)!8 *,)1 8 4,%3 vol. 7, no. 1, pp. 297–309, 2012.

[7] L. Xiao, H. Dai, and P Ning, "Mac design of uncoordinated fh-based collaborative broadcast," 8 %, ' 11 8(8 22 , vol. 1, no. 3, pp. 261–264, 2012.

[8] C. Li, H. Dai, L. Xiao, and P Ning, "Communication efficiency of anti-jamming broadcast in large-scale multi-channel wireless networks," 8 -)1 8%#) '8 11%) vol. 60, no. 10, pp. 5281–5292, 2012.

[9] D. Fudenberg and J. Tirole, (8 $ *0 8 MIT Press, 1991.

[10] L. Xiao, W Lin, Y Chen, and K. Liu, "Indirect reciprocity game modeling for secure wireless networks," in / 8 8) '8*) 8 *((4) 8 pp. 928–933, 2012.

[11] L. Xiao, J. Liu, Y Li, N. Mandayam, and H. V Poor, "Prospect theoretic analysis of anti-jamming communications in cognitive radio networks," in / 8 8 '* '8*((4) 8*)!8 '* *(pp. 1–6, 2014.

[12] D. Yang, J. Zhang, X. Fang, A. Richa, and G. Xue, "Optimal transmission power control in the presence of a smart jammer," in / 8 8 '* '8*((4) 8*)!8 '* *(pp. 5506–5511, 2012.

[13] D. Yang, G. Xue, J. Zhang, A. Richa, and X. Fang, "Coping with a smart jammer in wireless networks: A stackelberg game approach," 8 ,)1 8%, ' 118 *((4) vol. 12, no. 8, pp. 4038–4047, 2013.

[14] B. Wang, Z. Han, and K. Liu, "Distributed relay selection and power control for multiuser cooperative communication networks using stackelberg game," 8 ,)1 8 %' 8(+42%)# vol. 8, no. 7, pp. 975–990, 2009.

[15] Z. Wang, L. Jiang, and C. He, "A novel price-based power control algorithm in cognitive radio networks," 8 *((4) 8 22 , vol. 17, no. 1, pp. 43–46, 2013.

[16] G. Zhang, P Li, D. Zhou, K. Yang, and E. Ding, "Optimal power control for wireless cooperative relay networks: a cooperative game theoretic approach,")2 '84. '8" *((4) 8712 (vol. 26, no. 11, pp. 1395–1408, 2013.

[17] E. Altman, K. Avrachenkov, and A. Garnaev, "A jamming game in wireless networks with transmission cost," in / 8*"8 8 2007 24, 8*2 1%8)8(+42 ,8 % vol. 4465, pp. 1–12, 2007.

[18] K. Xu, Q. Wang, and K. Ren, "Joint ufh and power control for effective wireless anti-jamming communication," in ,* 8 8)2 '8 *)!8 *(+42 ,8((4) 8) * *(pp. 738–746, 2012.

[19] Y Wu, B. Wang, K. J. R. Liu, and T. Clancy, "Anti-jamming games in multi-channel cognitive radio networks," 81 '8, 18*((4) 8 vol. 30, no. 1, pp. 4–15, 2012.

[20] S. Ghose and R. Bose, "Power allocation strategy using node cooperation for transmit power minimization under correlated fading," in ,* 8 8 2%*) '8)!8 *((4) 8 pp. 1–5, 2013.