Mitigation of Jamming Attacks via Deception

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***Abstract*— This paper considers the problem of mitigating jamming attacks by aiming to deceive the jammer. Specifically, in the presence of a jammer, to defend a transmitter-receiver pair sending (real) information, the paper proposes the novel technique of sending fake information over a second transmitter-receiver pair in order to deceive the jammer into investing some of its jamming power budget for jamming the channel carrying fake information. The paper develops a leader-follower model where the jammer (acting as the follower) adopts it's jamming strategy after sensing the communication activities on the channels carrying the real and fake information, while the system (acting as the leader) adopts its power allocation strategy prior to the jammer. The paper characterizes the optimal power allocation strategy of the system considering the jammer to be non-strategic in nature, as well as characterizes the Subgame Perfect Nash Equilibrium (SPNE) strategy of the leader-follower game considering both the system and the jammer to be strategic entities. Extensive simulation results are provided to gain insights into the deception strategies developed in the paper.**

***Index Terms*—Jamming, Deception, Game Theory.**

I. Introduction

Wireless communication systems are often susceptible to the jamming attack in which adversaries attempt to overpower transmitted signals by intentionally injecting noise, thereby lowering the signal-to-noise ratio (SNR). Lowering the SNR, in turn, can significantly reduce the achievable rate of a communication system [1]. Mitigation of jamming attacks is an important problem and has received attention in the past [2]–[12], [14]. For example, [2] develops a cross-layer technique for mitigation of jamming attacks under given behavior of the jammer. The works in [3]–[12] model the interaction between transmitter-receiver pairs and a jammer using Game Theory [13] and investigate attack-defense strategies at equilibrium under strategic considerations. The authors in [6], [7], [10] investigate equilibrium points in the form of pure strategies, while in [3]–[5], [8], [9], [11] the authors investigate mixed strategy equilibrium points that maximize the utility functions defined. For instance, the authors in [6] formulate a zero-sum power allocation game between a transmitter and a jammer and prove the existence of a pure strategy Nash Equilibrium (NE) point and also characterize it under restrictive conditions. Again, in [4], [5] the authors characterize a mixed strategy power allocation strategy considering satisfaction of a given SNR threshold as the criteria for having successful communications. In [12], the authors investigate the interaction between a multiple input multiple output (MIMO) radar and a jammer in the context of target detection and investigate strategic power allocation profiles. The authors in [14] consider the problem of analyzing optimal jamming attacks from a signal detection theory perspective.

In this paper, unlike any technique proposed by past work to the best of our knowledge, we propose a novel mitigation technique that employs a transmitter-receiver pair to send fake information on a channel to lure a jammer into investing some of its jamming power budget to jam the channel carrying the fake information, thereby reducing the amount of power invested in jamming the channel being used by another transmitter-receiver pair to transmit real information. For instance, use of a transmitter-receiver pair to send fake information can be used in a battlefield to defend critical information being sent by another transmitter-receiver pair in the presence of a jammer. We model the interaction between our system, comprised of real and fake transmitter-receiver pairs, and the jammer using a leader-follower model, with the jammer (acting as the follower) capable of performing sensing to determine the transmission powers on channels for optimizing the jamming strategy, and the transmitter-receiver pairs (acting as the leader) being allocated their transmission powers prior to the jammer choosing its jamming strategy. Specifically, the main contributions of the paper are as follows.

- To defend a transmitter-receiver pair against a jammer who can adopt its jamming strategy after performing sensing to determine the transmitted powers on channels, we propose to transmit fake information between a second transmitter-receiver pair so as to deceive the jammer into investing some of its jamming power budget for jamming the channel carrying the fake information.
- We first characterize the optimal strategy of the system for allocating transmission powers on the real and fake channels against a non-strategic jammer with a given jamming behavior.
- We then consider the system and the jammer to be both strategic in nature, and model the problem as a leader-follower game and show the existence of a pure strategy Subgame Perfect Nash Equilibrium (SPNE) power allocation profile as well as characterize it.
- Extensive simulation results are provided to gain insights

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into the deception-based mitigation techniques presented. The rest of the paper is organized as follows. Section II considers the jammer to be non-strategic in nature and presents the optimal deception strategy for a given behavior of the jammer. Section III considers both the system and the jammer to be strategic in nature and characterizes the SPNE of the leader-follower game. Section IV provides simulation results to gain insights into the deception strategies presented in this paper. Finally, Section V concludes the paper.

II. Deception-based Mitigation of Non-strategic Jamming

Consider a transmitter, say T_1, which wants to send some (real) information using Channel 1 to a receiver, say R_1. To defend the communication between $T_1 - R_1$ against a jammer J, in this paper, we propose to have a second transmitter T_2 send fake information using Channel 2 to a receiver R_2 in order to deceive and make the jammer spend some of its jamming power to jam the communication between $T_2 - R_2$. This is shown in Fig. 1. Channel 1 and Channel 2 are considered to be orthogonal channels. In this paper, we refer to $T_1 - R_1$ and $T_2 - R_2$ as the *system*. Next, we describe our model in detail from the system's and the jammer's perspectives.

A. System's and the Jammer's Model

1) System's Model: Suppose that the power allocated by the system to transmitter T_i on channel i is P_i^T, with the power budget of the system across the two channels being P^T. Again, suppose that the jammer J jams channel i with power P_i^J, with the power budget of the jammer across the two channels being P^J. In such a scenario, we consider the utility of the system to be the achievable rate between $T_1 - R_1$ (that carries the real information), which becomes,

$$R_T = B_1 \log\left(1 + \frac{P_1^T \eta_1^T}{N_1 + P_1^J \eta_1^J}\right) \tag{1}$$

where, B_1 is the bandwidth of Channel 1, N_1 is the noise power on Channel 1, η_1^T is the gain of the channel between $T_1 - R_1$, and η_1^J is the gain of the channel between J and R_1. The goal of the system is to allocate transmission powers to T_1 and T_2 such that its utility (1) is maximized, knowing that the jammer will adopt it jamming behavior after sensing the two channels to determine communication activity on them. Specifically, the optimization problem of the system is,

$$\max_{P_1^T, P_2^T} R_T \tag{2a}$$

$$s.t\ P_1^T + P_2^T = P^T \tag{2b}$$

2) Jammer's Model: We consider the jammer to be capable of sensing the communication activity on the two channels before adopting its jamming strategy (thereby acting as the follower). To this end, we express the received power r_i^J at the jammer of a signal transmitted by T_i at power P_i^T as,

$$r_i^J = P_i^T \eta_{iJ} \tag{3}$$

where, η_{iJ} is the gain of the channel between T_i and J (refer Fig. 1). In this section, we consider the jammer to be non-strategic in nature and seek to find the optimal strategy of the system for allocating transmission powers to T_1 and T_2 against a given behavior of the jammer. Specifically, in this section, we consider the jammer to determine channel i as being used by $T_i - R_i$ if the strength of the signal transmitted by T_i on channel i becomes greater than or equal to a threshold τ at the jammer. Based on the determination of communication activities on the two channels, the jammer is considered to split its power equally on the two channels when it decides both channels are being used, to use it entire budget for jamming a single channel in case the jammer decides one of the channels is being used, or to not jam at all in the case where the jammer does not detect communication activity on any channel. The power allocation strategy (P_1^J, P_2^J) of the jammer, where P_i^J is the power allocated by the jammer to jam channel i, is summarized below.

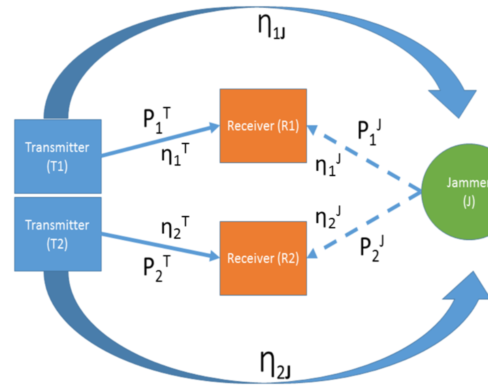


Fig. 1: Model for deception-based mitigation of jamming.

$$(P_1^J, P_2^J) = \begin{cases} (0,0) & \text{if } r_1^J < \tau \text{ and } r_2^J < \tau \\ (P^J, 0) & \text{if } r_1^J \geq \tau \text{ and } r_2^J < \tau \\ (0, P^J) & \text{if } r_1^J < \tau \text{ and } r_2^J \geq \tau \\ (\frac{P^J}{2}, \frac{P^J}{2}) & \text{if } r_1^J \geq \tau \text{ and } r_2^J \geq \tau \end{cases} \tag{4}$$

where, P^J is the power budget of the jammer. Next, we characterize the optimal power allocation strategy of the system against the aforementioned jamming behavior.

B. Optimal Power Allocation Strategy of the System

In the next theorem, we characterize the optimal power allocation strategy for transmitters T_1 and T_2 from the system's perspective against the jamming behavior given in (4).

Theorem 1. *The optimal power allocation strategy $(P_1^{T^*}, P_2^{T^*})$ for transmitters T_1 and T_2 that solves (2) against the jamming behavior given in (4) is as follows.*

- *Case I: If $P^T \leq \frac{N_1 + \frac{P^J}{2}\eta_1^J}{N_1}\frac{\tau-\delta}{\eta_{1J}} + \frac{\tau}{\eta_{2J}}$ and $P^T \leq \frac{N_1 + P^J \eta_1^J}{N_1}\frac{\tau-\delta}{\eta_{1J}}$, then $(P_1^{T^*}, P_2^{T^*}) = (\frac{\tau-\delta}{\eta_{1J}}, P^T - \frac{\tau-\delta}{\eta_{1J}})$, where $\delta > 0$ is an arbitrarily small value.*
- *Case II: If $P^T \geq \frac{N_1 + \frac{P^J}{2}\eta_1^J}{N_1}\frac{\tau-\delta}{\eta_{1J}} + \frac{\tau}{\eta_{2J}}$ and $P^T \geq \frac{\tau}{\eta_{2J}}\frac{N_1 + (P^J \eta_1^J)}{\frac{P^J \eta_1^J}{2}}$, then $(P_1^{T^*}, P_2^{T^*}) = (P^T - \frac{\tau}{\eta_{2J}}, \frac{\tau}{\eta_{2J}})$.*

- *Case III: If the conditions in Case I and Case II are not satisfied, then* $(P_1^{T^*}, P_2^{T^*}) = (P^T, 0)$.

Proof. The three possible values of jamming power than can be allocated to Channel 1 (i.e., the channel used by $T_1 - R_1$ for transmitting real information) are 0, $P^J/2$ and P^J. The jammer will not allocate any power to Channel 1 when $r_1^J < \tau$ (i.e., $P_1^T \eta_{1J} < \tau$), so that the maximum possible power that can be allocated by T_1 on Channel 1 in such a scenario is $P_1^T = \frac{\tau-\delta}{\eta_{1J}}$, where $\delta > 0$ is an arbitrarily small value. Thus, for the scenario where the jammer does not jam Channel 1, the maximum rate that can be obtained on Channel 1 is,

$$R_T(P_1^T = \frac{\tau - \delta}{\eta_{1J}}, P_1^J = 0) = B_1 \log \left[1 + \frac{\frac{\tau-\delta}{\eta_{1J}} \eta_1^T}{N_1}\right] \tag{5}$$

Again, the jammer will jam both channels with a power of $\frac{P^J}{2}$ when it detects transmissions on both channels. Thus, to obtain the best possible rate on Channel 1 when the jammer jams both channels, Channel 2 (the channel carrying fake information) must be allocated $P_2^T = \frac{\tau}{\eta_{2J}}$, which is the least amount of power that leads to the detection of transmission on Channel 2 at the jammer, with Channel 1 being allocated $P_1^T = P^T - \frac{\tau}{\eta_{2J}}$. Thus, the maximum possible rate on Channel 1 when the jammer jams both channels is,

$$R_T(P_1^T = P^T - \frac{\tau}{\eta_{2J}}, P_1^J = \frac{P^J}{2}) = B_1 \log \left[1 + \frac{(P^T - \frac{\tau}{\eta_{2J}})\eta_1^T}{N_1 + \frac{P^J}{2}\eta_1^J}\right] \tag{6}$$

Finally, if the jammer only detects transmission on Channel 1, the jammer will jam Channel 1 with the entire jamming power budget. Thus, in such a scenario, the maximum possible rate on Channel 1 can be obtained by allocating $P_1^T = P^T$ and $P_2^T = 0$ so that the rate on Channel 1 becomes,

$$R_T(P_1^T = P^T, P_1^J = P^J) = B_1 \log \left[1 + \frac{P^T \eta_1^T}{N_1 + P^J \eta_1^J}\right] \tag{7}$$

Clearly, it would become optimal for the system to allocate powers to T_1 and T_2 so that the jammer does not jam Channel 1 (by allocating $(P_1^{T^*}, P_2^{T^*}) = (\frac{\tau-\delta}{\eta_{1J}}, P^T - \frac{\tau-\delta}{\eta_{1J}})$) when (5) $\geq$ (6) and (5) $\geq$ (7), which yields the two conditions in Case I. Again, it would become optimal for the system to allocate powers so that the jammer jams each channel with a power of $\frac{P^J}{2}$ (by allocating $(P_1^{T^*}, P_2^{T^*}) = \left(P^T - \frac{\tau}{\eta_{2J}}, \frac{\tau}{\eta_{2J}}\right)$) when (6) $\geq$ (5) and (6) $\geq$ (7), which yields the two conditions in Case II. Finally, note that, in the scenario where (5) $\geq$ (6) but (5) $\leq$ (7), as well as in the scenario where (6) $\geq$ (5) but (6) $\leq$ (7), $R_T(P_1^T = P^T, P_1^J = P^J)$ is greater than or equal to both $R_T(P_1^T = \frac{\tau-\delta}{\eta_{1J}}, P_1^J = 0)$ and $R_T(P_1^T = P^T - \frac{\tau}{\eta_{2J}}, P_1^J = \frac{P^J}{2})$, so that the system's utility in such scenarios can be maximized by allocating $(P_1^{T^*}, P_2^{T^*}) = (P^T, 0)$. Thus, Case III follows. This proves the theorem. □

In the next section, we consider the system and the jammer to be strategic in nature using game theoretic tools.

III. Deception-based Mitigation of Strategic Jamming

In this section, we consider both the system and the jammer to be strategic entities and analyze the scenario using Game Theory [13]. We again consider the system to use $T_1 - R_1$ for sending real information, and $T_2 - R_2$ for sending fake information to deceive the jammer. The system is considered to be the leader who determines the transmission powers of T_1 and T_2, subject to a power budget P^T, with a goal to maximize the rate between $T_1 - R_1$. The jammer, on the other hand, without knowing that $T_2 - R_2$ is being used to communicate fake information, acts as the follower who senses the two channels to determine the transmission power on each of the channels and then decides on a jamming power allocation, subject to a jamming power budget P^J, so as to minimize the sum of the rates of the two channels. Next, we describe the optimization problems from the system's side and the jammer's side using Game Theory.

A. Optimization from System's and Jammer's perspective

We first describe the optimization problem from the system's side and then the jammer's optimization problem.

1) System's Optimization Problem: Suppose that the system allocates power P_i^T to transmitter T_i operating on channel i subject to a power budget P^T, and that the jammer allocates power P_i^J to jam channel i subject to a jamming power budget P^J. In our model, the leader (system) makes the first choice and the follower (jammer) reacts optimally to the leader's selected choice. The optimization problem from the system's perspective can be formulated as follows.

$$\max_{P_1^T, P_2^T} R_T \tag{8a}$$

$$s.t \; P_1^T + P_2^T = P^T \tag{8b}$$

where, R_T is defined in (1).

2) Jammer's Optimization Problem: The jammer is considered to be capable of sensing the two channels to determine the transmission powers on the channels for optimizing the jamming strategy. The goal of the jammer, being unaware of the fact that only $T_1 - R_1$ carries real information, is to allocate jamming powers on the two channels such that the sum of the rate of the two channels is minimized. Specifically, we consider the utility of the jammer to be,

$$R_J = \sum_{i=1}^{2} B_i \log \left(1 + \frac{P_i^T \eta_i^T}{N_i + P_i^J \eta_i^J}\right) \tag{9}$$

where, B_i is the bandwidth of channel i, N_i is the noise power on channel i, η_i^T is the gain of the channel between $T_i - R_i$, and η_i^J is the gain of the channel between J and R_i. Thus, the optimization problem of the jammer can be formulated as,

$$\min_{P_1^J, P_2^J} R_J \tag{10a}$$

$$s.t \; P_1^J + P_2^J = P^J \tag{10b}$$

Next, we prove the existence of a Subgame Perfect Nash Equilibrium (SPNE) of the game described above.

B. Existence of SPNE

LEMMA 1. *For a given power allocation (P_1^T, P_2^T) of the system, the utility function of the jammer (9) is a convex function of P_1^J.*

Proof. Since $P_2^J = P^J - P_1^J$, the utility of the jammer can be expressed as,

$$R_J = B_1 \log\left(1 + \frac{P_1^T \eta_1^T}{N_1 + P_1^J \eta_1^J}\right) + B_2 \log\left(1 + \frac{P_2^T \eta_2^T}{N_2 + (P^J - P_1^J)\eta_2^J}\right) \tag{11}$$

The second derivative of the first term in (11) w.r.t P_1^J is,

$$\frac{B_1 \eta_1^T P_1^T}{\ln 2}\big[(N_1 + P_1^J \eta_1^J + \eta_1^T P_1^T)^{-2}(N_1 + P_1^J \eta_1^J)^{-2} + (N_1 + P_1^J \eta_1^J + \eta_1^T P_1^T)^{-1}(N_1 + P_1^J \eta_1^J)^{-2}\big] \tag{12}$$

Clearly, (12) is greater than zero. Again, the second derivative of the second term in (11) w.r.t P_1^J is,

$$\frac{B_2}{\ln 2}[(N_2 + (P^J - P_1^J)\eta_2^J + \eta_1^T P_2^T)^{-2}(N_2 + (P^J - P_1^J)\eta_2^J)^{-1} + (N_2 + (P^J - P_1^J)\eta_2^J + \eta_1^T P_2^T)^{-1}(N_2 + (P^J - P_1^J)\eta_2^J)^{-2}] \tag{13}$$

Clearly, (13) is also greater than zero. Hence, $\frac{d^2 R_J}{d{P_1^J}^2} > 0$, implying that R_J is a convex function of P_1^J. □

LEMMA 2. *For a given jamming power allocation (P_1^J, P_2^J) of the jammer, the utility function of the system (1) is a concave function of P_1^T.*

Proof. The second derivative of the system's utility function (1) w.r.t P_1^T is

$$\frac{d^2 R_T}{d{P_1^T}^2} = -\frac{B_1}{\ln 2}\frac{\eta_1^T}{(N_1 + \eta_1^J P_1^J + \eta_1^T P_1^T)} \tag{14}$$

Clearly, $\frac{d^2 R_T}{d{P_1^T}^2} < 0$, which implies that R_T is a concave function of P_1^T. □

THEOREM 2. *A pure strategy SPNE to our leader-follower game exists.*

Proof. Since we have proved that, given (P_1^T, P_2^T), the utility of the jammer is a convex function of P_1^J, and given (P_1^J, P_2^J), the utility of the system is a concave function of P_1^T, we can conclude using the Debreu-Fan-Glicksberg theorem [13] that a pure strategy SPNE to our game exists. □

C. SPNE strategy of the system and the jammer

To characterize the SPNE strategy of the game, we first characterize the optimal strategy of the follower (jammer), and then characterize the optimal strategy of the system (leader) based on the optimal strategy that will adopted by the follower. In the next lemma, we present the optimal power allocation strategy of the jammer when the system adopts the power allocation strategy (P_1^T, P_2^T).

LEMMA 3. *Against the power allocation strategy (P_1^T, P_2^T) of the system, the optimal power allocation strategy $(P_1^{J^*}, P_2^{J^*} = P^J - P_1^{J^*})$ of the jammer corresponds to the solution of the quadratic equation,*

$$a(P_1^J)^2 + b(P_1^J) + c = 0 \tag{15}$$

where, the coefficients of the equation are as follows.

$$a = \eta_1^J \eta_2^T (B_2 \eta_2^T P_2^T N_1 \eta_1^J - B_1 \eta_1^T P_1^T) \tag{16a}$$

$$b = [\eta_1^T B_2 (\eta_2^T)^2 P_2^T (2N_1 + \eta_1^T P_1^T) + B_1 \eta_1^J \eta_1^T P_1^T (N_2 \eta_2^T + N_2 \eta_2^J - 2\eta_2^T P^J + (\eta_2^T)^3 P_2^T)] \tag{16b}$$

$$c = N_1 B_2 (\eta_2^T)^2 P_2^T (N_1 + P_1^T \eta_1^T) - [P_1^T B_1 N_2 \eta_1^J \eta_1^T (N_2 + 2P^J \eta_2^T) + \eta_2^T B_1 \eta_1^J \eta_1^T P_1^T ((P^J)^2 + N_2 P_2^T + \eta_2^T P_2^T P^J)] \tag{16c}$$

Proof. Based on Lemma 1, since the utility of the jammer (9) is a convex function of P_1^J for a given (P_1^T, P_2^T), (10) can be minimized by solving $\frac{d(R_J)}{dP_1^J} = 0$, which yields (15). This proves the lemma. □

LEMMA 4. *Against the optimal strategy of the jammer (follower) characterized in Lemma 3, the optimal power allocation strategy $(P_1^{T^*}, P_2^{T^*} = P^T - P_1^{T^*})$ of the system (leader) corresponds to the solution of the following equation.*

$$(2aN_1 - b\eta_1^J \pm \eta_1^T \sqrt{b^2 - 4ac})\eta_1^T - P_1^T \eta_1^T \big[2N_1 a' - \eta_1^J b' \pm \frac{b b' \eta_1^J}{\sqrt{b^2 - 4ac}} \pm 4(ac' + ca')\big] = 0 \tag{17}$$

where, the $\pm$ coincides with the sign considered in the quadratic formula for solving the quadratic equation in (15), a, b, and c are the coefficients defined in (16a), (16b), and (16c), respectively (with $P_2^T = P^T - P_1^T$), and $a' = \frac{d(a)}{dP_1^T}$, $b' = \frac{d(b)}{dP_1^T}$ and $c' = \frac{d(c)}{dP_1^T}$.

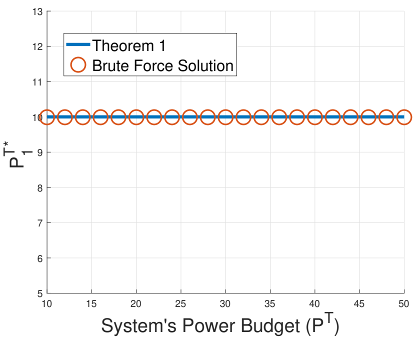
Proof. Since the utility function of the system (1) has been shown to be a concave function of P_1^T against the strategy of the jammer in Lemma 2, (8) can be solved by solving $\frac{dR_T(P_1^T, P_1^{J^*})}{dP_1^T} = 0$, which yields (17), where $P_1^{J^*}$ is the optimal power allocation strategy of the jammer found using Lemma 3. This proves the lemma. □

REMARK 1. Clearly, the equilibrium strategies of the system and the jammer presented in Lemma 4 and Lemma 3, respectively, comprise a SPNE of the leader-follower game. This is because the strategy characterized in Lemma 3 is a best response of the jammer to the power levels allocated by the system to T_1 and T_2. Again, the strategy characterized in Lemma 4 is a best response of the system to the jammer adopting the strategy given in Lemma 3. Thus, there exists no profitable unilateral deviations of the system and the jammer from their strategies presented in Lemma 4 and Lemma 3.

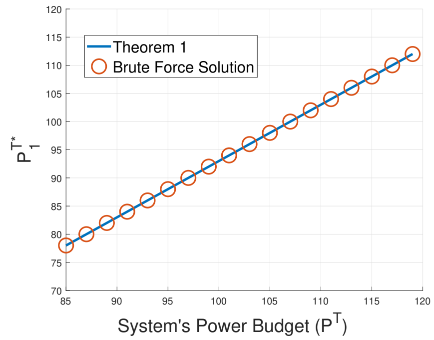
In the next section, we provide simulation results to gain insights into the designed deception strategies.

IV. SIMULATION RESULTS

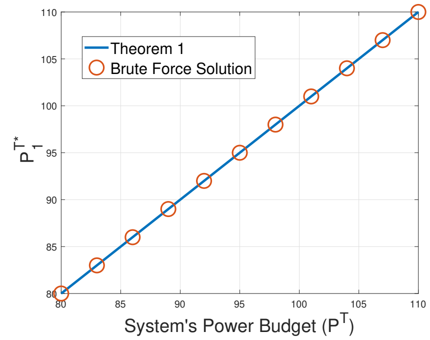
In this section, we provide simulation results to gain insights into the deception strategies presented in this paper. We first present simulation results to study the optimal strategy of the system presented in Theorem 1 in Section II for allocating transmission powers to T_1 and T_2 for deceiving a non-strategic jammer. In Fig. 2, with varying power budget of the system (P^T), we plot the optimal power allocation $P_1^{T^*}$ that should be used by the system for T_1 (with $P_2^{T^*} = P^T - P_1^{T^*}$) that solves the optimization problem in (2) against the jamming behavior



(a) Case I



(b) Case II



(c) Case III

Fig. 2: Optimal power allocation of the system against a non-strategic jammer.

given in (4). Fig. 2(a), Fig. 2(b) and Fig. 2(c) correspond to scenarios where the conditions in Case I, Case II, and Case III in Theorem 1 are satisfied, respectively. For all three figures, we consider $B_1 = B_2 = 1$, $N_1 = N_2 = 1$, $\eta_1^T = \eta_2^T = \eta_1^J = \eta_2^J = 1$, and decision making threshold of the jammer, $\tau = 7$. For Fig. 2(a), we consider $\eta_{1J} = \eta_{2J} = 0.7$, and $P^J = 30$, resulting in the satisfaction of the two conditions in Case I for the range of P^T considered in Fig 2(a). For Fig. 2(b), we consider $\eta_{1J} = \eta_{2J} = 1$, and $P^J = 20$, resulting in the satisfaction of the two conditions in Case II for the range of P^T considered in Fig 2(b). For Fig. 2(c), we consider $\eta_{1J} = 1$, $\eta_{2J} = 0.1$, and $P^J = 10$, resulting in the dissatisfaction of the conditions in Case I and Case II for the range of P^T considered in Fig 2(c). In each of the figures, we find the optimal power allocation (P_1^{T*}, P_2^{T*}) that solves (2) using the strategy provided in Theorem 1 as well as by using brute force search. As shown in the figures, the optimal power allocation strategy for the system found using Theorem 1 coincides with the optimal power allocation strategy for the system found using brute force search, thereby corroborating Theorem 1.

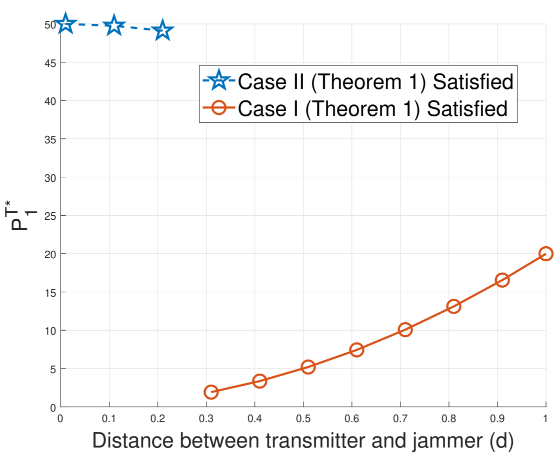


Fig. 3: Optimal $(P_1^{T^*})$ vs. distance (d) between transmitter and jammer.

In Fig. 3, to study the effect of the gain of the channel between transmitter T_i and the jammer J, we consider that the channel gain between them, $\eta_{iJ} = d^{-\gamma}$, with $\gamma = 2$, where d is the normalized distance between T_i and J based on a given reference distance (note, T_1 and T_2 are considered to be equidistant from J). In the figure, we consider $B_1 = B_2 = 1$, $N_1 = N_2 = 1$, $\eta_1^T = \eta_2^T = \eta_1^J = \eta_2^J = 1$, the decision making threshold of the jammer, $\tau = 20$, and $P^T = P^J = 50$. In the figure, for a given d between the transmitters and the jammer, the optimal power allocation strategy $(P_1^{T^*}, P_2^{T^*})$ of the system (against the jamming behavior in (4)) is found using Theorem 1. It should be noted that, based on the considered parameters, Case II of Theorem 1 is satisfied when $d \in [0, 0.3]$, so that the best power allocation strategy of the system in such a scenario is $(P_1^{T^*}, P_2^{T^*}) = (P^T - \frac{\tau}{\eta_{2J}}, \frac{\tau}{\eta_{2J}})$ to make the jammer jam both the real channel and the fake channel with a power of $P^J/2$. Thus, when $d \in [0, 0.3]$, as the jammer moves further away from the transmitters, $P_2^{T^*} = \frac{\tau}{\eta_{2J}}$ increases (since, η_{2J} decreases with increasing d), resulting in the decrease of $P_1^{T^*} = P^T - \frac{\tau}{\eta_{2J}}$ when $d \in [0, 0.3]$ as can be seen from the figure. Again, when $d \in (0.3, 1]$, it should be noted that Case I of Theorem 1 is satisfied, so that the best power allocation strategy of the system becomes $(P_1^{T^*}, P_2^{T^*}) = (\frac{\tau-\delta}{\eta_{1J}}, P^T - \frac{\tau-\delta}{\eta_{1J}})$ to make the jammer not jam Channel 1 (that carries the real information). Thus, when $d \in (0.3, 1]$, as the jammer moves further away from the transmitters, $P_1^{T^*} = \frac{\tau-\delta}{\eta_{1J}}$ increases (since η_{1J} decreases as d increases), as can be seen from the figure. In summary, as can be observed from the figure, when the jammer is relatively close to the transmitters, it becomes optimal for the system to allocate powers so that the jammer jams both the channel carrying real information and the channel carrying fake information with a power of $\frac{P^J}{2}$. However, when the jammer is relatively further away, in which case it becomes more difficult for the jammer to detect communication activities on the channels, it becomes optimal for the system to allocate powers so that the jammer does not jam the channel carrying the real information.

Next, we study the power allocation strategies presented in Section III for the case where both the system and the jammer are strategic in nature. In Fig. 4, we plot the rate between $T_1 - R_1$ (that carries the real information using Channel 1) with varying amount of transmission power P_1^T allocated to T_1 (with $P_2^T = P^T - P_1^T$). In the figure, we consider $B_1 = B_2 = 1$, $N_1 = N_2 = 1$, $\eta_1^T = \eta_2^T = \eta_1^J = \eta_2^J = 1$, and $P^T = P^J = 10$. For every power allocation strategy P_1^T in the figure, we consider the jammer to sense the two channels to determine the

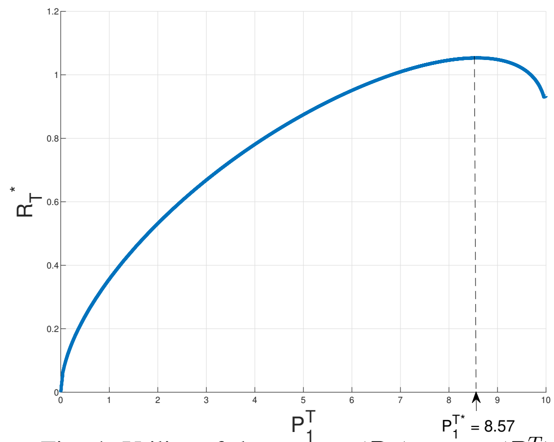


Fig. 4: Utility of the system (R_T) versus (P_1^T)

transmission powers of T_1 and T_2 and then choose its optimal power allocation strategy based on Lemma 3. As can be seen from the figure, the optimal power allocation strategy of the system is to allocate $P_1^{T^*} = 8.57$, which can be shown to coincide with the power allocation strategy of the system found using Lemma 4. Moreover, it is worth emphasizing that, as can be noted from the figure, instead of allocating the entire power budget of the system to transmit between $T_1 - R_1$ in the presence of a jammer capable of performing sensing to optimize the jamming strategy, the system can enhance the rate between $T_1 - R_1$ by investing some of the power budget of the system to transmit fake information between a second transmitter-receiver pair to deceive the jammer.

In Fig. 5, we plot the utility of the system R^{T^*} (1) at SPNE with varying power budget of the system (P^T) and the jammer (P^J) with the jammer and the system adopting their SPNE strategies based on Lemma 3 and Lemma 4, respectively. In the figure, we consider $B_1 = B_2 = 3$, $N_1 = N_2 = 1$, and $\eta_1^T = \eta_2^T = \eta_1^J = \eta_2^J = 1$. As can be seen from the figure, for any given P^T, R^{T^*} decreases as P^J increases as the jammer can avail more power for optimizing the attack. Again, for any given P^J, the figure shows that, the utility of the system increases as P^T increases showing that, at SPNE, the system is able to strategically exploit an increase in power budget to defend against the jammer by employing deception.

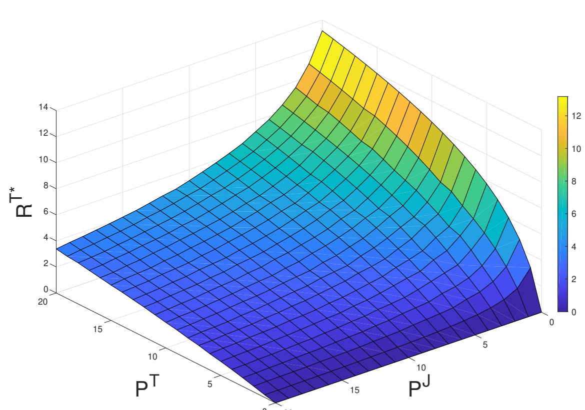


Fig. 5: Utility of the system (R^{T^*}) at SPNE versus varying power budget of the system (P^T) and the jammer (P^J).

V. Conclusion

This paper considered the problem of mitigating jamming attacks by deceiving the jammer. Specifically, to mitigate jamming attacks, the paper proposed the novel concept of defending a transmitter-receiver pair sending real information by having a second transmitter-receiver pair send fake information to deceive a jammer. The paper considered the jammer to be capable of sensing the communication activity on the real and fake channels to determine its jamming strategy, and analyzed the problem using a leader-follower model, with the system acting as the leader, and the jammer acting as the follower. The paper characterized the optimal power allocation strategy of the system considering the jammer to be non-strategic in nature, as well as the SPNE for the scenario where both the system and the jammer act strategically. From the optimal power allocation strategy of the system in both scenarios, it can be observed that the system can benefit by investing some of its power budget to deceive the jammer. The paper provided extensive simulation results to gain insights into the deception-based mitigation techniques presented. In the future, we will seek to design deception-based techniques to defend multiple transmitter-receiver pairs in a network against a jammer.

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