Equilibrium Outcomes of Dynamic Games in MIMO Channels with Active Eavesdroppers

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Abstract—This paper investigates transmission strategies in a MIMO wiretap channel with a transmitter, receiver and wiretapper, each equipped with multiple antennas. The secrecy rate between the transmitter and the legitimate receiver is chosen as the performance metric. In a departure from existing work, the wiretapper is able to act either as a passive eavesdropper or as an active jammer, under a half-duplex constraint. The transmitter therefore faces a choice between allocating all of its power for data; or broadcasting artificial noise along with the information signal in order to selectively degrade the eavesdropper's channel. We model the network as a dynamic zero-sum game in extensive form with the secrecy rate as the payoff function. We first examine subgame-perfect equilibrium strategies in the extensive form of the game with perfect information. We then discuss sequential and trembling hand perfect equilibria for the case of imperfect information. Finally, numerical simulations are presented to corroborate the analytical results.

I. INTRODUCTION

The two fundamental characteristics of the wireless medium, namely *broadcast* and *superposition*, present different challenges in ensuring secure communications in the presence of adversaries. The broadcast nature of wireless communications makes it difficult to shield transmitted signals from unintended recipients, while superposition can lead to the overlapping of multiple signals at the receiver. As a result, adversarial users are commonly modeled either as (1) a passive *eavesdropper* that tries to listen in on an ongoing transmission without being detected, or (2) a malicious transmitter (*jammer*) that tries to degrade the signal at the intended receiver. Two distinct lines of research have developed to analyze networks compromised by either type of adversary, as summarized below.

A network consisting of a transmitter-receiver pair and a passive eavesdropper is commonly referred to as the *wiretap* channel. The information-theoretic aspects of this scenario have been explored in some detail [1], [2]. In particular, this work led to the development of the notion of *secrecy capacity*, which quantifies the rate at which a transmitter can reliably send a secret message to the receiver, without the eavesdropper being able to decode it. Ultimately, it was shown that a non-zero secrecy capacity can only be obtained

if the eavesdropper's channel is of lower quality than that of the intended recipient. The work cited above assumes single antenna nodes; secrecy capacity for the multiple-input multiple-output (MIMO) wiretap channel, where all nodes may possess multiple antennas, has been studied in [3]-[5], for example.

The impact of malicious jammers on the quality of a communication link is another problem of long-standing interest, especially in mission-critical and military networks. A common approach is to model the transmitter and the jammer as players in a game-theoretic formulation with the mutual information as the payoff function, and to identify the optimal strategies for both parties [6], [7]. Recent work has extended this technique to MIMO and relay channels with various levels of channel state information (CSI) available to the transmitters [8]-[12].

In this paper, we consider a MIMO communication link in the presence of a more sophisticated adversary: a wiretapper with the dual capability of either eavesdropping passively or jamming any ongoing transmission, also referred to as an active eavesdropper. A dynamic game formulation of the system where one of the nodes moves first is investigated. However, in a departure from the previous work referenced above, the game payoff function is now chosen to be the *secrecy rate* between the legitimate transmitter-receiver pair. [13] independently considered the active eavesdropper scenario with single-antenna nodes and proposed robust transmission and secrecy encoding schemes.

The paper is organized as follows. In the next section, the assumed mathematical and active eavesdropper model is presented. The dynamic game framework with perfect and imperfect information is described in Sections III and IV, respectively. The resulting system performance is studied via simulation in Section V, and we conclude in Section VI.

Notation: $\mathcal{E}\{\cdot\}$ denotes expectation, $(\cdot)^T$ the transpose, $(\cdot)^H$ the Hermitian transpose, $(\cdot)^{-1}$ the matrix inverse, $\text{Tr}(\cdot)$ is the trace operator, $[\mathbf{A}]_{p,q}$ denotes the (p, q) entry of matrix $\mathbf{A}$, $|\cdot|$ is the matrix determinant, and $\mathbf{I}$ is an identity matrix of appropriate dimension.

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II. MATHEMATICAL MODEL

We study the MIMO wiretap problem in which three multiple-antenna nodes are present: a transmitter (Alice), a receiver (Bob), and a malicious user (Eve). Alice does not have knowledge of the instantaneous CSI of the eavesdropper, but she knows its distribution. Therefore, Alice has the option of utilizing all her power for transmitting data to Bob, regardless of channel conditions or potential eavesdroppers. Alternatively, she can split her power and simultaneously transmit the information vector and an 'artificial noise' signal that jams any unintended receivers other than Bob. The artificial noise scheme does not require knowledge of Eve's instantaneous CSI and is therefore suitable for deployment against passive eavesdroppers [5], [14]–[17]. Eve seeks to disrupt the information rate between Alice and Bob by either eavesdropping or jamming Bob.

A. MIMO Wiretap Channel

Assuming Eve jams Bob, the signals received by Bob and Eve can be represented as follows:

$$\mathbf{y}_b = \mathbf{H}_{ba}\mathbf{x}_a + \mathbf{H}_{be}\mathbf{x}_e + \mathbf{n}_b \quad (1)$$

$$\mathbf{y}_e = \mathbf{H}_{ea}\mathbf{x}_a + \mathbf{n}_e, \quad (2)$$

where $\mathbf{x}_a$ is the signal vector transmitted by Alice, $\mathbf{x}_e$ is the Gaussian, spatially white jamming signal from Eve, $\mathbf{n}_b, \mathbf{n}_e$ are the naturally occurring additive noise at Bob and Eve, respectively, and $\mathbf{H}_{ba}, \mathbf{H}_{be}, \mathbf{H}_{ea}$ are the corresponding $N_b \times N_a, N_b \times N_e, N_e \times N_a$ complex Gaussian channel matrices with standard normal elements. Alice is assumed to have perfect knowledge of the realization of $\mathbf{H}_{ba}$ and the statistics of $\mathbf{H}_{be}, \mathbf{H}_{ea}$. On the other hand, Eve knows the instantaneous value of $\mathbf{H}_{ea}$ and the statistics of $\mathbf{H}_{be}, \mathbf{H}_{ba}$.

The background noise at all receivers is assumed to be spatially white and zero-mean complex Gaussian:

$$\mathcal{E}\{\mathbf{n}_k \mathbf{n}_k^H\} = \sigma_k^2 \mathbf{I}; \quad k = b, e.$$

Alice's transmit power is assumed to be bounded,

$$\mathcal{E}\{\mathbf{x}_a \mathbf{x}_a^H\} = \mathbf{Q}_a \quad \text{Tr}(\mathbf{Q}_a) \leq P_a.$$

Similarly, Eve has a power constraint of P_e when in jamming mode.

In the most general scenario where Alice jams Eve, we have

$$\mathbf{x}_a = \mathbf{T}\mathbf{z} + \mathbf{T}'\mathbf{z}', \quad (3)$$

where $\mathbf{T}, \mathbf{T}'$ are the $N_a \times d, N_a \times (N_a - d)$ beamforming matrices for the $d \times 1$ information vector $\mathbf{z}$ and uncorrelated $(N_a - d) \times 1$ jamming signal $\mathbf{z}'$, respectively. To ensure the orthogonality of the information and artificial noise signals when received by Bob, $\mathbf{T}$ and $\mathbf{T}'$ can be formed from the columns of the right singular vectors of $\mathbf{H}_{ba}$, for example. Thus, $\mathbf{Q}_a$ may be expressed as

$$\mathbf{Q}_a = \mathbf{T}\mathbf{Q}_z\mathbf{T}^H + \mathbf{T}'\mathbf{Q}_{z'}\mathbf{T}'^H, \quad (4)$$

where $\mathbf{Q}_z, \mathbf{Q}_{z'}$ are covariance matrices associated with $\mathbf{z}$ and $\mathbf{z}'$, respectively, $\text{Tr}(\mathbf{T}\mathbf{Q}_z\mathbf{T}^H) \leq \rho P_a$, and $\text{Tr}(\mathbf{T}'\mathbf{Q}_{z'}\mathbf{T}'^H) \leq (1 - \rho)P_a$.

Note that Alice must decide how many spatial dimensions are to be used for artificial noise, and what is the optimal fraction ρP_a of transmit power distributed over them. An exhaustive search for the above was used in [14], while the authors proposed a low-complexity suboptimal approach in [16]. For the MISO wiretap channel, it was shown in [17] that an equal power allocation ($\rho = 0.5$) is close to optimal. The game-theoretic results obtained in this paper hold for either an optimal or a pre-determined power and data stream allocation.

B. Rate Thresholds

Define the payoff to Alice as the achievable *secrecy rate* between her and Bob. Modeling the strategic interactions between Alice and Eve as a strictly competitive game leads to a zero-sum formulation, where Alice tries to maximize her payoff and Eve attempts to minimize it. We can define the following strategy sets X, Y for the players: Alice chooses between transmitting with full power for data (F) or devoting some power to jam Eve (A), described as $X = \{F, A\}$. On the other hand, Eve must decide between eavesdropping (E) or jamming Bob (J) at every channel use, represented by $Y = \{E, J\}$.

We focus on the achievable MIMO secrecy rate instead of maximizing the mutual information to compute the secrecy capacity. The lack of instantaneous knowledge of $\mathbf{H}_{be}$ and the half-duplex constraint prevents Eve from detecting the transmitted signal $\mathbf{z}$ and then applying correlated jamming. Let the joint channel distribution $\mathbf{H} = (\mathbf{H}_{ba}, \mathbf{H}_{ea}, \mathbf{H}_{be})$ be jointly Gaussian and uncorrelated. The secrecy rate between Alice and Bob when Eve is in eavesdropping mode is

$$R_{i,E} = \mathcal{E}_H \left\{ \log |\mathbf{I} + \mathbf{H}_{ba} \mathbf{T} \mathbf{Q}_z \mathbf{T}^H \mathbf{H}_{ba}^H| \right\} - \mathcal{E}_H \left\{ \log |\mathbf{I} + \mathbf{H}_{ea} \mathbf{T} \mathbf{Q}_z \mathbf{T}^H \mathbf{H}_{ea}^H \mathbf{Q}_e^{-1}| \right\}; \quad (5)$$

whereas the transmission rate of the main channel while being jammed by Eve is

$$R_{i,J} = \mathcal{E}_H \left\{ \log |\mathbf{I} + \mathbf{H}_{ba} \mathbf{T} \mathbf{Q}_z \mathbf{T}^H \mathbf{H}_{ba}^H \mathbf{Q}_b^{-1}| \right\}, \quad (6)$$

where $i \in X$ denotes the transmission strategies available to Alice, and the interference-plus-noise covariance matrices for Bob and Eve are

$$\mathbf{Q}_b = \frac{P_e}{N_e} \mathbf{H}_{be} \mathbf{H}_{be}^H + \sigma_b^2 \mathbf{I} \quad (7)$$

$$\mathbf{Q}_e = \mathbf{H}_{ea} \mathbf{T}' \mathbf{Q}_{z'} \mathbf{T}'^H \mathbf{H}_{ea}^H + \sigma_e^2 \mathbf{I}. \quad (8)$$

The magnitude of $R_{A,E}$ relative to $R_{A,J}$ for a fixed set of array sizes is determined by the jamming power of Eve with respect to Alice's transmission power, as shown in the following lemma.

Lemma 1 [18]: For a given set of antenna array sizes, $R_{A,E} \leq R_{A,J}$ if

$$\log \left(\frac{P_e}{N_e} \right) \leq \frac{1}{d} \left[\Omega + (N_a - d) \log \left(\frac{(N_a - d) \rho}{d(1 - \rho)} \right) \right], \quad (9)$$

where Ω is an integral function of eigenvalues independent of P_e .

A comparison of the predicted and experimental jamming power thresholds was shown to be accurate for a range of antenna array sizes in [18].

In this paper we examine the dynamic or *extensive form* of the wiretap game, where one of the players moves first followed by the opponent's response. The strategic or simultaneous move version of this game and the resulting Nash equilibrium outcomes were studied in [18]. We consider the dynamic scenario where Alice moves first by either playing F or A , which is observed by Eve who responds accordingly, as shown in Fig. 1. All games considered in this work are assumed to have *perfect recall*, i.e., all players 'remember' all past moves made by them.

III. PERFECT INFORMATION GAME

Fig. 1. Extensive form game tree with perfect information where Alice moves first and Eve moves last.

Next, we introduce some game-theoretic terminology pertinent to the rest of the paper. If we assume that Eve can distinguish which move was adopted by Alice, and furthermore determine the exact jamming power $(1 - \rho)P_a$ if she is being jammed by Alice, then the extensive game is classified as one of perfect information. For each player, we can define an *information state* as a collection H_i of non-terminal nodes among which the player cannot distinguish a-priori. A vector that specifies a valid probability for every possible move at every possible information state of player i is called a *behavioral strategy* for player i .

In this section we analyze *subgame-perfect equilibria* of the extensive game with perfect information, which are a more refined form of NE that eliminate irrational choices. A *subgame* of Γ^e is any game that can be derived from Γ^e by deleting all nodes and branches that do not follow some subroot x ; and making that node x the root of the subgame. By definition, a subgame-perfect equilibrium is a Nash equilibrium for the entire game, and its relevant action rules are a Nash equilibrium for every subgame as well.

It is well known that in extensive games with perfect information, a subgame perfect equilibrium in pure strategies is guaranteed to exist by Zermelo's theorem [20, Ch. 4]. The equilibrium strategies can be obtained by a process of *backward induction* on the extensive game tree.

Proposition 1: In the extensive form game where Alice and Eve have antenna arrays of comparable size, the subgame-

perfect equilibrium in pure strategies is also determined by the jamming power available to Eve.

Proof: The extensive game tree comprises of three subgames: the two subgames at Eve's decision nodes (*information states*), and the game itself with Alice's decision node as the root. Eve always plays E in the lower-left subgame, whereas Eve picks either J or E in the lower-right subgame depending on P_e/P_a . By backward induction, Alice always plays A in her subgame regardless of P_e/P_a . Therefore, by a slight abuse of notation, the (unique) pure strategy subgame-perfect equilibrium is either (A, J) or (A, E) , depending on the direction of the inequality in (9).

Corollary: The extensive form game with perfect information where Eve moves first and Alice moves second has a subgame-perfect equilibrium either in the strategy pair (F, J) or (A, E) , depending on Eve's jamming power.

IV. IMPERFECT INFORMATION GAME

Fig. 2. Extensive form game tree with imperfect information where Alice moves first and Eve moves last.

We now consider the extensive game Γ_f^e of imperfect information between Alice and Eve. In particular, we assume that Alice moves first, but Eve is uncertain of the exact strategy adopted by Alice. This scenario is plausible for example if Eve is closer to Bob, or experiences a poor channel between herself and Alice, and therefore receives an unreliable signal $\mathbf{y}_e$.

The game tree representation of Γ_f^e is shown in Fig. 2. In contrast to Fig. 1, the dotted line connecting the decision nodes of Eve indicate her inability to determine Alice's move in the initial phase of the game, i.e., Eve now possesses a single information state.

While no player has an incentive to randomize in the game with perfect information in Section III, mixed strategies enter the discussion when the game is changed to one of imperfect information. The subgame perfect equilibrium solution is generally unsatisfactory for such games, since the only valid subgame in this case is the entire game Γ_f^e itself. *Sequential equilibrium* is a stronger solution concept eminently suited for games of imperfect information. Next, we introduce the background needed to define a sequential equilibrium.

Definition 1 [19]: An assessment is a pair (σ, β) where σ is a global behavioral strategy profile and β is a belief system. The beliefs vector specifies the players' a priori probabilities for their information states.

Definition 2: An assessment is *sequentially rational* if for every player i , every information state $h \in H_i$, and every behavioral strategy β_i , we have $v_i(\sigma, \beta|h) \geq v_i(\sigma, \beta_i, \beta_{-i}|h) \forall h$, where $v_i(\cdot)$ is the payoff function. An assessment for Γ_f^e is *fully consistent* if there is a sequence of completely mixed behavioral strategies β^n , converging to β , such that the associated sequence of beliefs σ^n converges to σ while being consistent with Bayes' rule.

Informally, sequential rationality requires that at every information state players maximize their expected utility over the subsequent equilibrium path of play described by β . Any sequential equilibrium is described by the pair (σ, β) , where β is a (behavioral) strategy profile that is sequentially rational, and a beliefs vector σ that is fully consistent with β .

We now compute the sequential equilibrium of Γ_f^e using a probabilistic version of backward induction. Assume $R_{A,E} \geq R_{A,J}$. Let Eve assign the a priori probabilities $(\alpha, 1 - \alpha)$ to Alice's moves over $\{F, A\}$. Therefore, Eve's left and right decision nodes are reached with probability α and $(1 - \alpha)$, respectively. There are three possible supports for Eve's moves at her information state: pure strategies $\{E\}$ or $\{J\}$ exclusively, or randomizing over $\{E, J\}$. Consider the scenario where Eve plays $\{E\}$ with probability one. Therefore, it is sequentially rational for Alice to always play $\{A\}$ in this case, i.e., $\alpha = 0$. However, sequential rationality for Eve requires that her expected payoff under $\{E\}$ be at least as large as that under $\{J\}$. This implies that $\alpha(R_{A,J} - R_{F,J}) - R_{A,J} \geq \alpha(R_{A,E} - R_{F,E}) - R_{A,E}$, which contradicts the earlier condition of $\alpha = 0$. Therefore, all candidate beliefs vectors σ are inconsistent and no sequential equilibrium exists if Eve plays the pure strategy $\{E\}$. An argument against Eve playing only $\{J\}$ can be constructed along similar lines.

Finally, we investigate the scenario where Eve randomizes over $\{E, J\}$ with probabilities $(\gamma, 1 - \gamma)$. Eve's expected payoff is now

$$-\alpha[\gamma R_{F,E} + (1 - \gamma) R_{F,J}] + (\alpha - 1)[\gamma R_{A,E} + (1 - \gamma) R_{A,J}].$$

Optimizing over γ leads to the following optimal move probabilities and equilibrium outcome v :

$$\begin{aligned} (\alpha^*, 1 - \alpha^*) &= (R_{A,J} - R_{A,E}, R_{F,E} - R_{F,J})/D \\ (\gamma^*, 1 - \gamma^*) &= (R_{A,J} - R_{F,J}, R_{F,E} - R_{A,E})/D \\ v(\alpha^*, \gamma^*) &= (R_{F,E}R_{A,J} - R_{F,J}R_{A,E})/D, \end{aligned} \quad (10)$$

where $D = R_{F,E} + R_{A,J} - R_{F,J} - R_{A,E}$.

For the particular extensive game with imperfect information considered here, the sequential equilibrium computed above can be corroborated using an alternative procedure. Observe that Γ_f^e is equivalent to a strategic game where Alice and Eve move simultaneously; since Eve cannot discern Alice's move the advantage of moving second is nullified. The equivalent strategic and agent-normal form is shown in Fig. 3, but note that this representation does not hold for the extensive game with perfect information in Section III. Solving for the Nash equilibrium in mixed strategies, we obtain the optimal strategies and equilibrium outcome exactly as shown in (10).

		Eve	
		Eavesdrop (E)	Jam Bob (J)
Alice	Full Power (F)	$R_{F,E}$	$R_{F,J}$
	Artificial Noise (A)	$R_{A,E}$	$R_{A,J}$

Fig. 3. Strategic and agent-normal form representation of the extensive game Γ_f^e with imperfect information.

We conclude this section by describing a refinement to the sequential equilibrium solution, which takes into account the possibility of opponents making small errors while executing their equilibrium strategies. These random perturbations are called 'trembles', and a stronger version of sequential equilibria that are robust to these trembles are known as *trembling hand perfect equilibria*.

Proposition 2: If $R_{A,E} \leq R_{A,J}$, the trembling hand perfect equilibrium outcome of the extensive game Γ_f^e with imperfect information is $R_{A,E}$.

Proof: A sketch of the proof is outlined next. For the case $R_{A,E} \leq R_{A,J}$, a pure equilibrium in behavioral strategies (A, E) exists for the agent-normal representation in Fig. 3. It can be shown that this equilibrium is robust to trembles by Alice, and is therefore also trembling hand perfect for the agent-normal form. Then using [20, Theorem 5.2], (A, E) is also the trembling hand perfect equilibrium of the extensive form of the game.

V. SIMULATION RESULTS

We present some examples that show the achieved secrecy rates for various array sizes and target performance levels. All displayed results are calculated based on an average of 1000 independent trials. The background noise power was assumed to be the same for both Bob and Eve: $\sigma_b^2 = \sigma_e^2 = 1$. Since $R_{A,J}$ and $R_{F,J}$ approach zero as Eve's jamming power increases asymptotically, we constrain the ratio of the transmit powers as $0 < P_e/P_a \leq 10$ to avoid the trivial solution of Eve choosing to jam all the time.

The subgame perfect equilibrium outcomes of the two extensive-form games with perfect information over a range of transmit power ratios P_e/P_a are shown in Fig. 4. For simplicity, the number of data streams is fixed as $d = 2$. The bold black and red dashed lines represent the subgame-perfect outcomes of the game when Alice moves first or second, respectively. We see that it is always beneficial for Alice to move second especially as Eve's jamming power increases, which agrees with intuition.

The sequential equilibrium outcomes of extensive games with imperfect information where Alice moves first for a range of array sizes is shown in Fig. 5. As described in Section IV, these are also the mixed-strategy Nash equilibrium outcomes for the strategic form of the MIMO wiretap game.

VI. CONCLUSION

This paper formulated the interactions between a transmitter and a dual eavesdropper/jammer as a zero-sum game with the secrecy rate as the payoff. We investigated subgame perfect

Fig. 4. Extensive-form games with perfect information, $N_a = N_b = N_e = 4$. The predicted crossover point for $R_{A,E}$ vs. $R_{A,J}$ is close to the actual threshold.

Fig. 5. Sequential equilibrium outcomes in terms of secrecy rate for the extensive game with imperfect information.

equilibria in the extensive form of the game with perfect information. We also examined the sequential and trembling hand perfect equilibrium outcomes of the extensive game with imperfect information. It was shown that the jamming power or number of antennas available to the eavesdropper relative to the legitimate transmitter determines the eventual equilibrium outcome of all versions of the game.

REFERENCES

- [1] A. D. Wyner, "The wire-tap channel," *The Bell Systems Technical Journal*, vol. 54, pp. 1355-1387, 1975.
- [2] S. L. Y. Cheong and M. Hellman, "The gaussian wire-tap channel," *IEEE Trans. Inf. Theory*, vol. 24, no. 4, pp. 451-456, July 1978.
- [3] F. Oggier and B. Hassibi, "The secrecy capacity of the MIMO wiretap channel," in *Proc. IEEE Intl Symp. on Inf. Theory*, pp. 524-528, July 2008.
- [4] T. Liu and S. Shamai, "A note on the secrecy capacity of the multiple-antenna wiretap channel," *IEEE Trans. Inf. Theory*, vol. 55, no. 6, pp. 2547-2553, June 2009.
- [5] A. Khisti and G. Wornell, "Secure transmission with multiple antennas II: the MIMOME wiretap channel," submitted to *IEEE Trans. Inf. Theory*, Aug. 2008. [Online]. Available: <http://www.rle.mit.edu/sia/>.
- [6] W. E. Stark and R. J. McEliece, "On the capacity of channels with block memory," *IEEE Trans. Inf. Theory*, vol. 34, no. 3, pp. 322-324, Mar. 1988.
- [7] M. Medard, "Capacity of correlated jamming channels," in *Proc. 35th Allerton Conf.*, pp. 1043-1052, 1997.
- [8] A. Kashyap, T. Basar, and R. Srikant, "Correlated jamming on MIMO gaussian fading channels," *IEEE Trans. Inf. Theory*, vol. 50, no. 9, pp. 2119-2123, Sep. 2004.
- [9] A. Bayesteh, M. Ansari, and A. K. Khandani, "Effect of jamming on the capacity of MIMO channels," in *Proc. 42nd Allerton Conf.*, pp. 401-410, Oct. 2004.
- [10] S. Shafiee and S. Ulukus, "Mutual information games in multi-user channels with correlated jamming," submitted for publication, 2006. [Online]. Available: <http://arxiv.org/abs/cs.IT/0601110>.
- [11] T. Wang and G. B. Giannakis, "Mutual information jammer-relay games," *IEEE Trans. Inform. Forensics Security*, vol. 3, no. 2, pp. 290-303, June 2008.
- [12] S. Wei and R. Kannan, "Jamming and counter-measure strategies in parallel gaussian fading channels with channel state information," in *Proc. IEEE MILCOM*, San Diego, Nov. 2008.
- [13] G. T. Amariuca, "Physical security in wireless networks: Intelligent jamming and eavesdropping," Ph.D. dissertation, LSU, 2009.
- [14] S. Goel and R. Negi, "Guaranteeing secrecy using artificial noise," *IEEE Trans. Wireless Commun.*, vol. 7, no. 6, pp. 2180-2189, June 2008.
- [15] A. L. Swindlehurst, "Fixed SINR solutions for the MIMO wiretap channel," in *Proc. IEEE ICASSP*, pp. 2437-2440, Taipei, Apr. 2009.
- [16] A. Mukherjee and A. L. Swindlehurst, "Fixed-rate power allocation strategies for enhanced secrecy in MIMO wiretap channels," in *Proc. IEEE SPAWC*, pp. 344-348, Perugia, June 2009.
- [17] X. Zhou and M. R. McKay, "Physical layer security with artificial noise: Secrecy capacity and optimal power allocation," in *Proc. Int. Conf. on Sig. Proc. and Commun. Syst.*, Omaha, NE, Sept. 2009.
- [18] A. Mukherjee and A. L. Swindlehurst, "To jam or not to jam: The MIMO wiretap game," submitted to *IEEE Trans. Wireless Commun.*, May 2010 [Online]. Available: arXiv.org.
- [19] D. Fudenberg and J. Tirole, *Game Theory*. MIT Press, 1991.
- [20] R. Myerson, *Game Theory: Analysis of Conflict*. Harvard University Press, 1997.
- [21] A. M. Tulino and S. Verdú, "Random matrix theory and wireless communications," *Foundations and Trends in Communications and Information Theory*, vol. 1, no. 1, pp. 1-163, 2004.