Secure Relay and Jammer Selection for Physical Layer Security

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Abstract—Secure relay and jammer selection for physical-layer security is studied in a wireless network with multiple intermediate nodes and eavesdroppers, where each intermediate node either helps to forward messages as a relay, or broadcasts noise as a jammer. We derive a closed-form expression for the secrecy outage probability (SOP), and we develop two relay and jammer selection methods for SOP minimization. In both methods a selection vector and a corresponding threshold are designed and broadcast by the destination to ensure each intermediate node knows its own role while knowledge of the relay and jammer set is kept secret from all eavesdroppers. Simulation results show the SOP of the proposed methods are very close to that obtained by an exhaustive search, and that maintaining the privacy of the selection result greatly improves the SOP performance.

Index Terms—Cooperative jamming, physical layer security, relay selection, secrecy outage probability.

I. INTRODUCTION

SECURITY and privacy are of great importance in modern wireless communications. Traditional cryptographic mechanisms [1] require private key exchange, which introduces additional complexities and redundancy. Physical-layer security, which ensures secure communication by taking advantage of the physical characteristics of wireless channels, has attracted increasing attention. Wyner revealed that when the channel of the legitimate user has better propagation conditions than that of the eavesdropper, secret data transmission is theoretically possible without sharing any key [2]. This conclusion was extended to Gaussian wire-tap channels in [3]. However, when channel conditions in wireless networks are not favorable for the legitimate user, the secrecy rate can be very low or even decline to zero.

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An efficient solution to meet this challenge is to enhance the legitimate transmission by cooperative relaying or confuse the eavesdroppers via cooperative jamming. In [4], several cooperative relaying schemes are proposed for improving the security of wireless communications, and the security benefits of cooperative jamming have also been extensively studied [5], [6], [7]. The combined use of relays and jamming has also been addressed in a number of papers, including [8]–[17]. More relevant to this paper is prior work that focuses on relay or jammer selection for amplify-and-forward (AF) and decode-and-forward (DF) protocols to improve security in terms of intercept probability, secrecy outage probability or achievable secrecy rate [11], [12], [13]. Selection for the two-way relay case has also been considered in [14] for one eavesdropper whose instantaneous CSI is known. These prior works either ignore the issue of how the selection results are made known to the relays, or they assume that the results are openly broadcast such that the eavesdroppers are aware of them. If the eavesdroppers are aware of the relay and jammer selection, they could cooperate to aggregate the signals of interest and cancel the jamming noise through coordinated beamforming such as interference zero-forcing, and this can dramatically reduce the secrecy of the network. To avoid this impairment, it is critical to keep information about the relay and jammer selection secret from the eavesdroppers.

In this letter, we study secret relay and jammer selection for physical-layer security. We assume a decode-and-forward (DF) relay system, in which a source communicates to a destination with the help of multiple intermediate nodes in the presence of multiple passive eavesdroppers. The intermediate nodes act as either conventional relays or as jammers to hinder the eavesdroppers from intercepting the signal of interest. A closed-form expression for the secrecy outage probability (SOP) is derived for this scenario, and two relay and jammer selection methods are proposed. In these methods, the destination, which is aware of the channel state information (CSI) for the legitimate channels but only the statistics of the eavesdroppers' links, chooses appropriate relay and jammer sets to minimize the SOP. Then, the destination broadcasts information that allows the intermediate nodes to determine whether they will serve as relays or jammers, but this information does not allow the eavesdroppers to know the selection result.

II. SYSTEM MODEL AND TRANSMISSION SCHEME

A. System Model

Consider a wireless network consisting of one source S , one destination D , and M intermediate nodes $T_1, T_2, \dots, T_M$, in the presence of K passive eavesdroppers $E_1, E_2, \dots, E_K$. The source, the intermediate nodes and the eavesdroppers are

equipped with a single antenna, while D has N antennas. We assume that direct links S -to- D and S -to- E_j are not available [12], so data transmission from S to D requires the help of the intermediate nodes. Each intermediate node can act as either a conventional relay to assist in message transmission, or as a jammer that transmits noise to interfere with the eavesdroppers. During each transmission, the intermediate nodes are to be divided into two sets - the relay set $\mathcal{R}$ and the jammer set $\mathcal{J}$.

Let $h_{i,j}$ and $g_{i,j}$ denote the channel coefficient from T_i to the j th antenna of the destination, and from T_i to E_j , respectively. All channel coefficients are assumed to be independent and $h_{i,j} \sim \mathcal{CN}(0, \lambda_{h_{i,j}})$, $g_{i,j} \sim \mathcal{CN}(0, \lambda_{g_{i,j}})$, where $\mathcal{CN}(\mu, \lambda)$ denotes a complex Gaussian distribution with mean μ and variance λ . For simplicity we assume that the intermediate nodes are close enough together so that $\lambda_{g_{i,j}} = \lambda_{g_j}$. We assume reciprocal channels and that each node has knowledge of the instantaneous CSI of its direct links; *i.e.*, the uplink and downlink channel coefficients from T_i to D are identical and available at both T_i and D . However, only statistical CSI for the eavesdroppers is available at D , and no information about the eavesdroppers is available to the intermediate nodes. While the eavesdroppers know $g_{i,j}$, we assume they are unaware of $h_{i,j}$; this is reasonable for time-division duplex scenarios with reciprocal channels, where channel feedback is unnecessary. Finally, we also assume additive white Gaussian noise of power N_0 is present at D as well.

B. Transmission Scheme

The transmission is divided into two phases. In phase I, the source transmits a signal s . As in [12], all intermediate nodes decode the message successfully in this phase, and the transmission is assumed to be secure in phase I due to the lack of direct links between the source S and the eavesdropper E_j .

For phase II, define the transmission matrix as $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \dots, \mathbf{h}_M]$, where each column of $\mathbf{H}$ is defined as $\mathbf{h}_i := [h_{i,1}, h_{i,2}, \dots, h_{i,N}]^T$, which denotes the transmission coefficients from T_i to every antenna of the destination. The nodes in $\mathcal{R}$ re-encode the message and forward it to D , and each node k in $\mathcal{J}$ attempts to confuse the eavesdroppers by injecting independent artificial noise z_k . We define the jammer and relay transmission matrices as $\mathbf{H}_J = \mathbf{H}\mathbf{\Lambda}$ and $\mathbf{H}_R = \mathbf{H}(\mathbf{I} - \mathbf{\Lambda})$, respectively, where $\mathbf{\Lambda} = \text{diag}(\mathbf{b})$, and $\mathbf{b} = [b_1, b_2, \dots, b_M]$. When T_i is selected as a jammer, $b_i = 1$, otherwise, $b_i = 0$. The number of relays and jammers are respectively defined as $|\mathcal{R}| = L_1 \geq 1$ and $|\mathcal{J}| = L_2$, where $L_2 = M - L_1$.

Both the relays and the jammers transmit with a power of P . Since there are N antennas at the destination and the CSI from all the intermediate nodes is available, beamforming can be performed at D . Assuming a beamformer $\mathbf{w} \in \mathbb{C}^{N \times 1}$ is used at D , the signal at the destination is expressed by

$$y_D = \sqrt{P}\mathbf{w}^H \mathbf{H}_R \mathbf{s} + \sqrt{P}\mathbf{w}^H \mathbf{H}_J \mathbf{z} + \mathbf{w}^H \mathbf{n}_D, \quad (1)$$

where $\mathbf{s} = [s, s, \dots, s]^T$, $\mathbf{z} = [z_1, z_2, \dots, z_M]^T$, $\mathbf{n}_D = [n_{D,1}, n_{D,2}, \dots, n_{D,N}]^T$, and $n_{D,i}$ is the noise at the i th antenna of D . If T_i is chosen as a relay, then $z_i = 0$; otherwise, the non-zero entries of $\mathbf{z}$ are assumed to have unit power. The received SNR at the destination is

$$\gamma_D = \frac{P\mathbf{w}^H \mathbf{H}_R \mathbf{e} \mathbf{e}^H \mathbf{H}_R^H \mathbf{w}}{P\mathbf{w}^H \mathbf{H}_J \mathbf{H}_J^H \mathbf{w} + N_0 \mathbf{w}^H \mathbf{w}}, \quad (2)$$

where $\mathbf{e} = [1, 1, \dots, 1]^T \in \mathbb{C}^{M \times 1}$. The achievable rate of the legitimate link is given by

$$R_D = \frac{1}{2} \log_2(1 + \gamma_D). \quad (3)$$

In the next section, we will present methods that prevent the eavesdroppers from identifying whether an intermediate node is a jammer or a relay. Thus, the eavesdroppers cannot perform coordinated beamforming, and must each attempt to individually intercept the transmitted signal. The SNR at E_j is no more than

$$\gamma_{E_j} = \frac{P(|g_{1,j} + g_{2,j} + \dots + g_{L_1,j}|^2)}{P(|g_{L_1+1,j}|^2 + \dots + |g_{M,j}|^2) + N_0}. \quad (4)$$

Define the maximum SNR among the eavesdroppers as $\gamma_E = \max_j \gamma_{E_j}$, so the worst-case achievable rate at any of the eavesdroppers is

$$R_E = \frac{1}{2} \log_2(1 + \gamma_E). \quad (5)$$

Thus the achievable secrecy rate is no less than

$$R_s = [R_D - R_E]^+ = \left[\frac{1}{2} \log_2 \left(\frac{1 + \gamma_D}{1 + \gamma_E} \right) \right]^+, \quad (6)$$

where $[z]^+ = \max(0, z)$, and the SOP is given by

$$P_{out} = \Pr(R_s < R), \quad (7)$$

where R is the required rate. Therefore, the relay and jammer selection problem for minimizing SOP can be written as

$$\min_{\mathbf{b}} P_{out}. \quad (8)$$

III. SECURE RELAY AND JAMMER SELECTION

In this section, we develop methods for relay and jammer selection that remain hidden from the eavesdroppers. The selection process consists of two steps. First, the destination determines appropriate relay and jammer sets using instantaneous CSI of the intermediate nodes and statistical CSI of the eavesdroppers. Second, the destination informs the intermediate nodes of the selection without giving away the information to the eavesdroppers. In the methods we present below, the destination broadcasts a vector and a corresponding selection threshold T_{hr} . Each node uses the vector to compute a channel-dependent quantity that is compared against the threshold; if it is above the threshold, then the node acts as a relay, otherwise it acts as a jammer. Note that knowledge of the vector and T_{hr} at the eavesdroppers does not provide them any knowledge of the node selection, since they are not aware of the channels $\mathbf{h}_j$.

A. Secrecy Outage Probability

The SOP for our scenario is quantified below.

Proposition 1: The c.d.f. of γ_{E_j} can be expressed by:

$$F_{\gamma_{E_j}}(z) = 1 - \frac{e^{\eta/\lambda_{g_j}}}{\lambda_{g_j}^{L_2} (L_2 - 1)!} \sum_{m=0}^{L_2-1} \binom{L_2-1}{m} (-\eta)^{L_2-1-m} \times \left(\frac{L_1 \lambda_{g_j}}{z + L_1} \right)^{(m+1)} \Gamma \left(m+1, \frac{\eta(z + L_1)}{L_1 \lambda_{g_j}} \right), z \geq 0 \quad (9)$$

for $L_2 > 0$ where $\eta = N_0/P$, and $\Gamma(s, x) = \int_x^\infty t^{s-1} e^{-t} dt$ is the Upper Incomplete Gamma Function. For $L_2 = 0$ the c.d.f is given by

$$F_{\gamma_{E_j}}(z) = 1 - e^{-\frac{z\eta}{M\lambda_{g_j}}}, z \geq 0. \quad (10)$$

Proof: See Appendix A.

Note that $Z_1, Z_2, \dots, Z_K$ are independent, so the c.d.f. of γ_E can be obtained as $F_{\gamma_E}(z) = \prod_{j=1}^K F_{\gamma_{E_j}}(z)$, and the SOP of the system can be expressed by

$$\begin{aligned} P_{out} &= \Pr(R_s < R) \\ &= \Pr\left\{\frac{1}{2} \log_2 \left(\frac{1 + \gamma_D}{1 + \gamma_E}\right) < R\right\} \\ &= 1 - \Pr\left\{\gamma_E \leq \frac{1 + \gamma_D}{2^{2R}} - 1\right\} \\ &= 1 - F_{\gamma_E}\left(\frac{1 + \gamma_D}{2^{2R}} - 1\right). \end{aligned} \quad (11)$$

Given (11), once the relays and jammers are determined, the exact SOP can be calculated. Note that the SOP in (11) is monotonically decreasing with increases in γ_D if L_1 (or equivalently L_2) is fixed. On the other hand, P_{out} will increase as K grows, approaching unity as $K \rightarrow \infty$.

B. Selection of Relay and Jammer Sets

It can be observed from (11) that P_{out} is a function of γ_D and L_2 when M and λ_{g_j} are known. Due to this fact, a joint optimization over γ_D and L_2 can minimize the SOP. Considering L_2 is a finite integer, in this work we separate this joint problem into two steps. The first step is to minimize P_{out} for any given L_2 , which is equivalent to maximizing γ_D for fixed L_2 . Then the second step is to find the optimal L_2 that achieves the minimum P_{out} .

According to (2), maximizing γ_D is equivalent to

$$\max_{\mathbf{w}} \frac{P\mathbf{w}^H \mathbf{H} \bar{\mathbf{b}} \bar{\mathbf{b}}^H \mathbf{H}^H \mathbf{w}}{\mathbf{w}^H (\mathbf{P} \mathbf{H} \mathbf{A} \mathbf{H}^H + N_0 \mathbf{I}) \mathbf{w}}, \quad (12)$$

where $\bar{\mathbf{b}}$ is defined as the logical complement of $\mathbf{b}$, i.e., $\bar{\mathbf{b}} := 1 - \mathbf{b}$. For a particular $\mathbf{A}$, (12) is a typical Rayleigh quotient problem, and the maximum value of γ_D is

$$\gamma_D^* = \zeta_{\max}(\mathbf{Q}), \quad (13)$$

where $\mathbf{Q} = (\mathbf{P} \mathbf{H} \mathbf{A} \mathbf{H}^H + N_0 \mathbf{I})^{-1} (\mathbf{P} \mathbf{H} \bar{\mathbf{b}} \bar{\mathbf{b}}^H \mathbf{H}^H)$, $\zeta_{\max}(\mathbf{Q})$ denotes the largest eigenvalue of matrix $\mathbf{Q}$, and $\mathbf{w}^*$ is given by

$$\mathbf{w}^* = u_{\max}(\mathbf{Q}), \quad (14)$$

where $u_{\max}(\mathbf{Q})$ denotes the eigenvector corresponding to $\zeta_{\max}(\mathbf{Q})$. Substituting γ_D^* into (11), the SOP corresponding to $\mathbf{A}$ can be calculated. Thus the SOP minimization problem of (8) can in principle be solved by an exhaustive search, although with a high computational complexity.

Selecting more nodes as relays may give a larger value of γ_D , but it also increases the risk that an eavesdropper succeeds in intercepting the source message through the wiretap link. Thus whether a node should be selected as a relay depends on its impact on both the destination and the eavesdroppers.

Assuming that we are in the more interesting situation where the jamming power dominates the background noise, then according to (12), maximizing γ_D can be simplified to

$$\begin{aligned} \max_{\mathbf{w}, \mathbf{A}} & \frac{\mathbf{w}^H \mathbf{H} \bar{\mathbf{b}} \bar{\mathbf{b}}^H \mathbf{H}^H \mathbf{w}}{\mathbf{w}^H \mathbf{H} \mathbf{A} \mathbf{H}^H \mathbf{w}} \\ \text{s.t.} & L_2 = c_0, \end{aligned} \quad (15)$$

where $c_0 \in \{1, \dots, M-1\}$ is fixed for the moment. With a given $\mathbf{w}$, it can be obtained from (15) that

$$\begin{aligned} \max \gamma_D &= \max \frac{\text{trace}(\bar{\mathbf{b}} \bar{\mathbf{b}}^H \mathbf{H}^H \mathbf{w} \mathbf{w}^H \mathbf{H})}{\text{trace}(\mathbf{A} \mathbf{H}^H \mathbf{w} \mathbf{w}^H \mathbf{H})} \\ &= \max \frac{\sum_{i=1}^M \bar{b}_i |\mathbf{w}^H \mathbf{h}_i|^2}{\sum_{i=1}^M b_i |\mathbf{w}^H \mathbf{h}_i|^2} \\ &\quad + \frac{\sum_{i,j=1, i \neq j}^M \bar{b}_i \bar{b}_j \text{Re}\left\{(\mathbf{w}^H \mathbf{h}_i)^H (\mathbf{w}^H \mathbf{h}_j)\right\}}{\sum_{i=1}^M b_i |\mathbf{w}^H \mathbf{h}_i|^2} \\ &\geq \max \frac{\sum_{i=1}^M \bar{b}_i |\mathbf{w}^H \mathbf{h}_i|^2}{\sum_{i=1}^M b_i |\mathbf{w}^H \mathbf{h}_i|^2}. \end{aligned} \quad (16)$$

Eq. (16) gives a lower bound for the maximum value of γ_D , which suggests that the intermediate nodes with the L_2 minimum values of $|\mathbf{w}^H \mathbf{h}_i|$ should be selected as jammers, and the rest selected as relays. Without loss of generality, reorder $|\mathbf{w}^H \mathbf{h}_i|$ in increasing order, set T_{hr} as any value between $|\mathbf{w}^H \mathbf{h}_{L_2}|$ and $|\mathbf{w}^H \mathbf{h}_{L_2+1}|$, and then the jammer set can be obtained as $\mathcal{J} = \{T_i : |\mathbf{w}^H \mathbf{h}_i| < T_{hr}\}$. To define the selection result $\mathbf{A}$, assign $b_i = 1$ when T_i is a jammer and $b_i = 0$ otherwise.

To solve the complete problem, the destination must not only find $\mathbf{w}$, but also the optimal value for L_2 that minimizes the SOP. Once this is done, it will feed back the vector $\mathbf{w}$ and the corresponding threshold T_{hr} to each intermediate node. Using its CSI to the destination, each node i then compares $|\mathbf{w}^H \mathbf{h}_i|$ to the threshold to determine its action. While an exhaustive search could be used to find globally optimal values for $\mathbf{w}$ and L_2 , we propose two simpler solutions below that perform nearly as well at a fraction of the computational cost.

1) *Greedy Method:* In the Greedy Method (GM), we begin by assuming no jammers, i.e., $\mathbf{b} = \mathbf{0}$, in which case $\mathbf{Q} = \mathbf{H} \mathbf{e} \mathbf{e}^H \mathbf{H}^H$ and $\mathbf{w} = u_{\max}(\mathbf{Q})$. We then set $L_2 = 1$, and find the node with the smallest value for $|\mathbf{w}^H \mathbf{h}_i|$. This node is placed in the jammer set, a new $\mathbf{w}$ is calculated, and the corresponding SOP is determined. Next we set $L_2 = 2$ and find the node in the relay set for which $|\mathbf{w}^H \mathbf{h}_i|$ is smallest, switch it to the jamming set and update $\mathbf{w}$ and the SOP. This process is repeated until only one relay is left, and the value for L_2 is chosen to be the one that results in the smallest SOP. Compared with the exhaustive search, which requires checking all $2^M - 1$ possible selection results, the GM only requires M SOP evaluations.

2) *Vector Alignment Method:* The basic idea of the Vector Alignment Method (VAM) is to group intermediate nodes together whose channel vectors are most aligned. For example, if T_i is selected as a relay since $|\mathbf{w}^H \mathbf{h}_i|$ is relatively large, then nodes with channel vectors $\mathbf{h}_j$ that are “aligned” or nearly parallel with $\mathbf{h}_i$ should also be chosen as relays. This method is implemented as follows. For every node T_i and every possible value of L_1 , we calculate the SOP assuming $T_i \in \mathcal{R}$ and the

Fig. 1. Secrecy outage probability for different selection methods.

other relays are chosen as the $L_1 - 1$ nodes whose channel vectors $\mathbf{h}_j$ maximize $c_{ij} = |\mathbf{h}_i^H \mathbf{h}_j| / (|\mathbf{h}_i| |\mathbf{h}_j|)$, the cosine of the angle between the vectors. The VAM method is somewhat more costly than GM, requiring that the SOP be calculated for $M(M - 1) + 1$ possible scenarios (including the case where $\mathbf{b} = 0$), but still significantly less costly than an exhaustive search when M is large.

IV. SIMULATION RESULTS

In this section, simulation results are presented to illustrate the SOP of the proposed methods. We set $\lambda_{h_{i,j}} = 1$, $\lambda_{g_{i,j}} = 1$, and $R = 1$ for all simulations. In Fig. 1, the SOP is plotted for a case where $M = 4$, $N = 3$, and $K = 2$. It is observed that the SOP achieved with all nodes acting as relays is close to 1, which shows that without jamming the “best” eavesdropper can on average achieve nearly the same SNR as the destination. While using a random node assignment provides an improvement over using no cooperative jamming, the GM and VAM methods perform significantly better, and their SOP performance is nearly as good as that achieved by an exhaustive search.

Fig. 2 shows the performance of the GM and VAM methods compared with “insecure” relay and jammer selection ($M = 3$, $N = 3$), where the eavesdroppers are aware of the relay/jammer status of the intermediate nodes and can cooperatively aggregate the signals of interest and cancel the jamming noise in a manner similar to the destination. We see that both GM and VAM have significantly lower SOP, even when they encounter twice as many eavesdroppers as in the case of an insecure selection.

V. CONCLUSIONS

This paper has studied secure relay and jammer selection for minimizing the secrecy outage probability in cooperative wireless networks. A closed-form expression for the SOP was derived, and methods were developed that allow for cooperative nodes to be assigned as either relays or jammers in an attempt to minimize the resulting SOP. Most importantly, the algorithms are implemented in such a way that the node assignment can not be determined by the eavesdroppers, preventing

Fig. 2. Secrecy outage probability for secure and insecure selections.

them from cooperatively using distributed multi-antenna techniques to null the interference. Besides an optimal method based on an exhaustive search for the best node assignment, reduced complexity methods were discussed that have SOP performance approaching that of the exhaustive search. Simulations results were presented to show the advantage of the proposed methods compared with a random assignment or with an assignment that was not kept secret from the eavesdroppers.

APPENDIX A

PROOF OF PROPOSITION 1

For $L_2 > 0$, let $X = |\sum_{i=1}^{L_1} g_{i,j}|^2$ and $U = \sum_{i=L_1+1}^M |g_{i,j}|^2$. It can be found that $X \sim \exp(1/(L_1 \lambda_{g_j}))$ and that U follows a central chi-square distribution with $2L_2$ degrees of freedom. Denoting $\gamma_{E_j} = \frac{X}{U + N_0/P}$ and $Y = U + \eta$, we have

$$F_{\gamma_{E_j}}(z) = \int_{\eta}^{\infty} f_Y(y) F_X(yz) dy. \quad (17)$$

According to the c.d.f. of X , we have

$$F_X(yz) = 1 - e^{-\frac{yz}{L_1 \lambda_{g_j}}}, \quad (18)$$

and using the p.d.f. of U , we obtain

$$f_Y(y) = \frac{dF_Y(y)}{dy} = f_U(y - \eta) = \frac{(y - \eta)^{L_2 - 1}}{\lambda_{g_j}^{L_2} (L_2 - 1)!} e^{-(y - \eta)/\lambda_{g_j}}. \quad (19)$$

Substituting (18) and (19) into (17), it can be seen that

$$F_{\gamma_{E_j}}(z) = 1 - \frac{e^{\eta/\lambda_{g_j}}}{\lambda_{g_j}^{L_2} (L_2 - 1)!} \times \int_{\eta}^{\infty} (y - \eta)^{L_2 - 1} e^{-(z + L_1)y/L_1/\lambda_{g_j}} dy. \quad (20)$$

Applying the Binomial Theorem and the Upper Incomplete Gamma Function, we finally obtain (9). For $L_2 = 0$, (10) can be derived similarly. ■

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