Research Article

Securing Communication via Transmission of Artificial Noise by Both Sides: Bipolar-Beamforming Optimization

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The paper considers the secure transmission in a wireless environment in which both the transmitter (Alice) and the legitimate receiver (Bob) send artificial noise (AN) to interfere with the eavesdropper (Eve). Optimal design is analyzed in detail for this AN-by-both-side model to deal with Eve's stochastic channel condition and random spatial distribution. Bipolar-beamforming is first proposed to jointly design Alice and Bob's transmitting signals. By optimally assigning the transmitting antenna for Bob and allocating the power ratio between Alice's information and the AN signal, maximum secrecy capacity can be achieved. Simulation is done to illustrate the process of bipolar-beamforming optimization. Results show that the AN-by-both-side model has good secrecy performance on both average and extreme conditions as Eve approaches Alice or Bob.

1. Introduction

In wireless communication, a malicious intruder can easily overhear messages transmitted between two nodes. Traditional security problems involve three parties: transmitter (Alice), legitimate receiver (Bob), and a passive eavesdropper (Eve). Wyner [1] first studied the wiretap channel and introduced the notion of secrecy capacity. After that, Csiszár and Körner [2] extended this work to the nondegraded discrete memoryless broadcast channel. Their work showed that if Bob's channel is more capable than Eve's, perfect secrecy can be achieved. Secrecy capacity in MIMO (multiple-input and multiple-output) wiretap channel and fading channel is studied in [3, 4]. Recently, the problem of stochastic system modeling has also been considered in [5–11].

The method of adopting artificial noise (AN) to increase secrecy capacity was first proposed by Goel and Negi [12, 13]. In their model, Alice uses multiple transmitting antennas or cooperates with the helper nodes to generate the AN, shown in Figure 1(a). This degrades Eve's channel, without affecting Bob, by projecting the AN into the null space of Bob's channel. Authors in [14–17] adopted an iterative waterfilling algorithm

to allocate the power ratio between AN and the information signal, thus solving the optimal design problem of this model.

Li et al. proposed another AN based approach [18], in which AN is generated by Bob, shown in Figure 1(b). Such a kind of AN impairs Eve's channel but can be cancelled by Bob himself by applying the self-interference cancellation techniques [19–21]. In their model, Bob adopts one antenna for receiving information and another for transmitting AN. Outage secrecy capacity region (OSR) is analyzed for such a configuration. Li et al. also mentioned a model in the discussion part of their paper in which both Alice and Bob send AN. As shown in Figure 1(c), this is a combination of the above two models. However, no detailed optimization analysis is available yet for this AN-by-both-side model.

In this paper, we will generalize the above AN-by-both-side model from Alice equipped with 2 antennas, Bob with 2 antennas, and Eve with 1 antenna to a model that all of them are equipped with multiple antennas. Optimal design will be studied for such a configuration to best utilize Alice and Bob's antenna and power resources. In order to achieve optimal secrecy performance, many design-specific issues need to be addressed to deal with a stochastic Eve with random channel condition and spatial distribution. These

FIGURE 1: Illustration to compare 3 different kinds of AN models.

include the assignment of Bob's antennas, the optimal power allocation ratio for Alice, and the beamforming design. In this work, we will propose an efficient scheme, called "bipolar-beamforming optimization," to design Alice and Bob's transmitting signals and allocate their antenna and power resources so that maximum secrecy capacity can be achieved.

The paper is organized as follows. The system model will be described in Section 2. Sections 3–5 will then focus on the efficient computation of secrecy capacity and optimal parameter design for the proposed model. Simulation results will be presented in Section 6, and the conclusion will be given in Section 7.

Throughout this paper, the following notations will be used: bold symbols (e.g., $\mathbf{G}$ and $\mathbf{g}$) in capital letter and small letter denote matrices and vectors, respectively. $\mathbb{C}^N$ is the N -dimension vector space over the complex field. $(\cdot)^\dagger$ denotes the conjugate transpose and $(x)^+ = \max\{0, x\}$. $|\cdot|$ is the determinant of a square matrix while $\|\cdot\|$ is the norm of a vector. $E_G(\cdot)$ stands for the expectation over the random variate $\mathbf{G}$.

2. System Model

Suppose Alice is equipped with N_A ($N_A \geq 2$) antennas. Bob has N_B ($N_B \geq 2$) antennas. He will choose the i th ($1 \leq i \leq N_B$) antenna as receiving antenna, and the remaining ones as

AN-emitting antennas. Eve will have N_E ($N_E \geq 1$) antennas for eavesdropping on the transmission signal between Alice and Bob. It is assumed that the channel between Alice and Bob is known to all parties, but they do not hold channel state information (CSI) of Eve.

As shown in Figure 1(c), when both Alice and Bob send AN, the signal received by Bob can be expressed as

$$y_b = \mathbf{h}_{ab}^{(i)} \cdot \mathbf{x} + \mathbf{h}_{bb}^{(i)} \cdot \mathbf{n} + n_b, \quad (1)$$

where $\mathbf{h}_{ab}^{(i)}$ denotes the channel between Alice and the i th receiving antenna of Bob, which is a $1 \times N_A$ vector. $\mathbf{h}_{bb}^{(i)}$ is the channel between the receiving and the transmitting antennas of Bob, with size $1 \times (N_B - 1)$. n_b is the Gaussian noise at Bob, with noise power $\sigma_{n_b}^2$. The signal transmitted by Alice is $\mathbf{x}$, while $\mathbf{n}$ stands for the artificial noise emitted by Bob.

Similarly, the signal received by a stochastic Eve is given by

$$y_e = \mathbf{G}_{ae} \cdot \mathbf{x} + \mathbf{G}_{be}^{(i)} \cdot \mathbf{n} + n_e, \quad (2)$$

where n_e is the Gaussian noise at Eve. $\mathbf{G}_{ae}$ is the random channel between Alice's transmitting antennas and Eve. $\mathbf{G}_{be}^{(i)}$ is the random channel between Bob's transmitting antenna set and Eve. The elements of $\mathbf{G}_{ae}$ and $\mathbf{G}_{be}^{(i)}$ are modeled as i.i.d. zero-mean circularly symmetric complex Gaussian (ZMCSCG) random variables.

The total transmission power of Alice and Bob are P_A and P_B , respectively. For P_A , a proportion of ϕ ($0 \leq \phi \leq 1$) is allocated to the information signal, with others left for AN. Therefore, the power used for transmitting information and emitting AN is

$$\begin{aligned} P_{\text{info}} &= \phi \cdot P_A, \\ P_{\text{AN}} &= (1 - \phi) \cdot P_A. \end{aligned} \quad (3)$$

3. Beamforming and Secrecy Capacity

In this section, the beamforming of Alice and Bob's transmission signal is first studied. Secrecy capacity of the proposed AN-by-both-side model can therefore be obtained based on the signals received by Bob and Eve.

3.1. Bipolar Beamforming. For Bob, since the location and channel condition of Eve is unknown to him, the beamforming of $\mathbf{n}$ is just to generate random Gaussian noise. Therefore, $\mathbf{n}$ becomes an $(N_B - 1) \times 1$ complex random Gaussian vector with covariance matrix $E(\mathbf{nn}^\dagger) = P_B/(N_B - 1) \cdot \mathbf{I}_{N_B-1}$.

For Alice, the transmitted signal $\mathbf{x}$ can be decomposed into the information part, $\mathbf{s}$, and the AN part, $\mathbf{w}$ as follows:

$$\mathbf{x} = \mathbf{s} + \mathbf{w} = \mathbf{w}_1 \cdot u + \mathbf{W}_2 \cdot \mathbf{v}. \quad (4)$$

According to the beamforming scheme by [13], $(\mathbf{w}_1, \mathbf{W}_2)$ forms an orthogonal basis of $\mathbb{C}^{N_A}$, and $\mathbf{w}_1 = \mathbf{h}_{\text{ab}}^{(i)\dagger} / \|\mathbf{h}_{\text{ab}}^{(i)}\|$. $\mathbf{W}_2$ spans the null space of $\mathbf{h}_{\text{ab}}^{(i)\dagger}$. u stands for the information symbol with power $E(uu^\dagger) = \sigma_u^2 = P_{\text{info}}$; and $\mathbf{v}$ is a complex Gaussian vector with zero mean and covariance matrix $E(\mathbf{vv}^\dagger) = P_{\text{AN}}/(N_A - 1) \cdot \mathbf{I}_{N_A-1}$. Thus, (1) and (2) can be further expanded as

$$\begin{aligned} y_b(k) &= \mathbf{h}_{\text{ab}}^{(i)} \cdot (\mathbf{w}_1 \cdot u + \mathbf{W}_2 \cdot \mathbf{v}) + \mathbf{h}_{\text{bb}}^{(i)} \cdot \mathbf{n} + n_b \\ &= \|\mathbf{h}_{\text{ab}}^{(i)}\| \cdot u + \mathbf{h}_{\text{bb}}^{(i)} \cdot \mathbf{n} + n_b, \\ y_e(k) &= \mathbf{G}_{\text{ae}} \cdot (\mathbf{w}_1 \cdot u + \mathbf{W}_2 \cdot \mathbf{v}) + \mathbf{G}_{\text{be}}^{(i)} \cdot \mathbf{n} + \mathbf{n}_e \\ &= \mathbf{g} \cdot u + \mathbf{G} \cdot \mathbf{v} + \mathbf{G}_{\text{be}}^{(i)} \cdot \mathbf{n} + \mathbf{n}_e, \end{aligned} \quad (5)$$

where we denote $\mathbf{g} = \mathbf{G}_{\text{ae}} \cdot \mathbf{w}_1$ and $\mathbf{G} = \mathbf{G}_{\text{ae}} \cdot \mathbf{W}_2$ for simplicity. Note that due to the orthonormality of $(\mathbf{w}_1, \mathbf{W}_2)$, $\mathbf{g}$ and $\mathbf{G}$ also have i.i.d. ZMCSCG entries as $\mathbf{G}_{\text{ae}}$.

3.2. Secrecy Capacity. Based on the work of [4, 13], the lower bound of the secrecy capacity can be calculated in terms of (5), as follows:

$$\begin{aligned} Cs &= (Cs_1 - \overline{Cs_2})^+, \\ Cs_1 &= \log_2 \left(1 + \mathbf{h}_{\text{ab}}^{(i)} \cdot E(uu^\dagger) \cdot \frac{\mathbf{h}_{\text{ab}}^{(i)\dagger}}{\sigma_{n_b}^2} \right) \\ &= \log_2 \left(1 + \mathbf{h}_{\text{ab}}^{(i)} \cdot P_{\text{info}} \cdot \frac{\mathbf{h}_{\text{ab}}^{(i)\dagger}}{\sigma_{n_b}^2} \right) \\ &= \log_2 \left(1 + \phi \cdot P_A \cdot \frac{\|\mathbf{h}_{\text{ab}}^{(i)}\|^2}{\sigma_{n_b}^2} \right), \\ \overline{Cs_2} &= E_{\mathbf{G}_{\text{be}}^{(i)}, \mathbf{g}, \mathbf{G}} \log_2 \left| \mathbf{I}_{N_E} + \frac{\mathbf{g} \cdot E(uu^\dagger) \cdot \mathbf{g}^\dagger}{\mathbf{G} E(\mathbf{vv}^\dagger) \mathbf{G}^\dagger + \mathbf{G}_{\text{be}}^{(i)} E(\mathbf{nn}^\dagger) \mathbf{G}_{\text{be}}^{(i)\dagger}} \right| \\ &= E_{\mathbf{G}_{\text{be}}^{(i)}, \mathbf{g}, \mathbf{G}} \log_2 \left| \mathbf{I}_{N_E} + \frac{P_{\text{info}} \cdot \mathbf{g} \mathbf{g}^\dagger}{(P_{\text{AN}}/(N_A - 1)) \mathbf{G} \mathbf{G}^\dagger + (P_B/(N_B - 1)) \mathbf{G}_{\text{be}}^{(i)} \mathbf{G}_{\text{be}}^{(i)\dagger}} \right| \\ &= E_{\mathbf{G}_{\text{be}}^{(i)}, \mathbf{g}, \mathbf{G}} \log_2 \left| \mathbf{I}_{N_E} + \frac{\phi \cdot P_A \cdot \mathbf{g} \mathbf{g}^\dagger}{((1 - \phi) P_A/(N_A - 1)) \mathbf{G} \mathbf{G}^\dagger + (P_B/(N_B - 1)) \mathbf{G}_{\text{be}}^{(i)} \mathbf{G}_{\text{be}}^{(i)\dagger}} \right| \\ &= E_{\mathbf{G}_{\text{be}}^{(i)}, \mathbf{g}, \mathbf{G}} \log_2 \left| \mathbf{I}_{N_E} + \phi \cdot \mathbf{g} \left[\frac{1 - \phi}{N_A - 1} \mathbf{G} \mathbf{G}^\dagger + \frac{P_B}{P_A \cdot (N_B - 1)} \mathbf{G}_{\text{be}}^{(i)} \mathbf{G}_{\text{be}}^{(i)\dagger} \right]^{-1} \right| \\ &\stackrel{(a)}{=} E_{\mathbf{G}_{\text{be}}^{(i)}, \mathbf{g}, \mathbf{G}} \log_2 \left| 1 + \phi \cdot \mathbf{g}^\dagger (\alpha \mathbf{G} \mathbf{G}^\dagger + \beta \mathbf{G}_{\text{be}}^{(i)} \mathbf{G}_{\text{be}}^{(i)\dagger})^{-1} \mathbf{g} \right|, \end{aligned} \quad (6)$$

where $\alpha = (1 - \phi)/(N_A - 1)$ and $\beta = P_B/(P_A \cdot (N_B - 1))$. (a) holds due to the determinant identity $|\mathbf{I} + \mathbf{AB}| = |\mathbf{I} + \mathbf{BA}|$.

Note that in (7), there is no $\mathbf{h}_{\text{bb}}^{(i)} \cdot \mathbf{n}$ item in the calculation of Cs_1 because it is possible for Bob to cancel the AN exerted

on himself by adopting full duplex wireless communication techniques [20], and the problem of self-interference cancellation has also been discussed in depth in [18, 21].

In (8), the worst case situation, $\mathbf{n}_e \rightarrow \mathbf{0}$, is considered. Therefore, $\overline{Cs}_2$ is the upper bound of the information tapped by Eve; and Cs in (6) is the minimum guaranteed secrecy capacity that can be ensured in this scenario.

4. Optimization for Secrecy Capacity

Through the secrecy capacity (Cs) analyzed in (6)–(8), the optimization problem can be formalized as

$$\begin{aligned} \max_{\phi, i} \quad & Cs(\phi, i) \\ \text{s.t.} \quad & \phi \in (0, 1), \quad 1 \leq i \leq N_B. \end{aligned} \quad (9)$$

In order to maximize this secrecy capacity, the following 2 key parameters need to be optimized:

- (1) i , with the i th antenna selected as Bob's receiving antenna, and the others left as AN transmitting antennas;
- (2) ϕ , the power allocation ratio between Alice's information signal and AN.

As it can be seen from (6)–(8), it is hard to analyze Cs due to the existence of 3 random matrices in $\overline{Cs}_2$: $\mathbf{g}$, $\mathbf{G}$ and $\mathbf{G}_{be}^{(i)}$. In the following part, we will exploit the random characteristics of Eve to optimize the above 2 parameters.

4.1. Antenna Assignment for Bob. We first exam $\overline{Cs}_2$. In (8), the item related to i is $\beta \mathbf{G}_{be}^{(i)} \mathbf{G}_{be}^{(i)\dagger}$. Because the channel between Bob and Eve is unknown to Bob and considered to be randomized, any combination of Bob's AN transmitting antennas will result, on average, in the same effect. Hence, $\overline{Cs}_2$ is irrelevant to the selection of antenna i .

On the other hand, for (7), it is simple to check that Cs_1 is monotonically increasing with $\|\mathbf{h}_{ab}^{(i)}\|$. Therefore, this item needs to be maximized.

Finally; the assignment of Bob's antenna resources has a relatively simple solution, that is,

$$i = \arg \max_i \left\{ \|\mathbf{h}_{ab}^{(i)}\| \right\}. \quad (10)$$

4.2. Power Allocation Ratio for Alice. The form of Cs in (6)–(8) is hard to be computed due to the existence of 3 random matrices in $\overline{Cs}_2$: $\mathbf{g}$, $\mathbf{G}$ and $\mathbf{G}_{be}^{(i)}$. In fact, they are related to Eve's stochastic channel condition and spatial distribution. In the following section, we will first derive and explore an efficient method to compute the secrecy capacity based on Eve's random characteristics. The optimal power allocation ratio, ϕ^* , can be obtained thereafter.

4.2.1. Eve's Stochastic Channel Condition. As it can be seen in (8), $\overline{Cs}_2$ is the expectation over the channel condition of Eve; that is, $\mathbf{G}_{ae}$ and $\mathbf{G}_{be}$. When taking into account the path-loss effect, $\mathbf{G}_{ae}$ can be expanded as the product of a path-loss

component, σ_{ae} , and a Gaussian fading component, $\widetilde{\mathbf{G}}_{ae}$ as follows:

$$\mathbf{G}_{ae} = \sigma_{ae} \cdot \widetilde{\mathbf{G}}_{ae} = (\lambda_0 \cdot r_{ae}^{-\kappa})^{1/2} \cdot \widetilde{\mathbf{G}}_{ae}. \quad (11)$$

In (11), λ_0 is a coefficient and r_{ae} is the distance between Alice and Eve. κ stands for the pass-loss exponent. The Gaussian fading component, $\widetilde{\mathbf{G}}_{ae}$, is a unit random Gaussian matrix, and the elements of $\widetilde{\mathbf{G}}_{ae}$ are normalized to be i.i.d. zero-mean unit-covariance circularly symmetric complex Gaussian random variables.

This is similar for $\mathbf{G}_{be}^{(i)}$, $\mathbf{g}$, and $\mathbf{G}$; that is,

$$\begin{aligned} \mathbf{G}_{be}^{(i)} &= (\lambda_0 \cdot r_{be}^{-\kappa/2}) \cdot \widetilde{\mathbf{G}}_{be}^{(i)}, \\ \mathbf{G} &= (\lambda_0 \cdot r_{ae}^{-\kappa/2}) \cdot \widetilde{\mathbf{G}}, \\ \mathbf{g} &= (\lambda_0 \cdot r_{ae}^{-\kappa/2}) \cdot \widetilde{\mathbf{g}}, \end{aligned} \quad (12)$$

where $\widetilde{\mathbf{G}}_{be}^{(i)}$, $\widetilde{\mathbf{g}}$, and $\widetilde{\mathbf{G}}$ are all normalized random Gaussian matrices, the same as $\widetilde{\mathbf{G}}_{ae}$.

Therefore, by substituting (11)–(12), (8) can be further derived as (13) consider the following:

$$\begin{aligned} \overline{Cs}_2 &= E_{\left[\begin{smallmatrix} r_{ae}, r_{be} \\ \widetilde{\mathbf{g}}, \widetilde{\mathbf{G}}, \widetilde{\mathbf{G}}_{be}^{(i)} \end{smallmatrix} \right]} \log_2 \left\{ 1 + \phi \cdot \widetilde{\mathbf{g}}^\dagger \right. \\ &\quad \cdot \left(\alpha \widetilde{\mathbf{G}} \widetilde{\mathbf{G}}^\dagger + \beta \left(\frac{r_{ae}}{r_{be}} \right)^\kappa \widetilde{\mathbf{G}}_{be}^{(i)} \widetilde{\mathbf{G}}_{be}^{(i)\dagger} \right)^{-1} \widetilde{\mathbf{g}} \left. \right\} \\ &= E_{\left[\begin{smallmatrix} r_{ae}, r_{be} \\ \widetilde{\mathbf{g}}, \widetilde{\mathbf{G}}, \widetilde{\mathbf{G}}_{be}^{(i)} \end{smallmatrix} \right]} \log_2 \left\{ + \sum_{m=1}^{N_B-1} \beta \left(\frac{r_{ae}}{r_{be}} \right)^\kappa \widetilde{\mathbf{g}}_m \widetilde{\mathbf{g}}_m^\dagger \right\}^{-1} 1 + \phi \cdot \widetilde{\mathbf{g}}^\dagger \\ &\quad \cdot \left(\sum_{l=1}^{N_A-1} \alpha \cdot \widetilde{\mathbf{g}}_l \widetilde{\mathbf{g}}_l^\dagger \right. \\ &\quad \left. + \sum_{m=1}^{N_B-1} \beta \left(\frac{r_{ae}}{r_{be}} \right)^\kappa \widetilde{\mathbf{g}}_m \widetilde{\mathbf{g}}_m^\dagger \right)^{-1} \widetilde{\mathbf{g}} \left. \right\} \\ &\stackrel{(b)}{=} E_{\left[\begin{smallmatrix} r_{ae}, r_{be} \\ \widetilde{\mathbf{g}}, \widetilde{\mathbf{G}}_k \end{smallmatrix} \right]} \log_2 \left\{ 1 + \phi \cdot \widetilde{\mathbf{g}}^\dagger \right. \\ &\quad \cdot \left(\sum_{k=1}^{N_A-1+N_B-1} \Gamma_k \widetilde{\mathbf{g}}_k \widetilde{\mathbf{g}}_k^\dagger \right)^{-1} \widetilde{\mathbf{g}} \left. \right\}. \end{aligned} \quad (13)$$

In (13), the normalized Gaussian vector, $\widetilde{\mathbf{g}}_l$ ($1 \leq l \leq N_A - 1$), $\widetilde{\mathbf{g}}_m$ ($1 \leq m \leq N_B - 1$), and $\widetilde{\mathbf{g}}_k$ ($1 \leq k \leq N_A + N_B - 2$) are the column vectors of $\widetilde{\mathbf{G}}$, $\widetilde{\mathbf{G}}_{be}^{(i)}$, and $[\widetilde{\mathbf{G}}, \widetilde{\mathbf{G}}_{be}^{(i)}]$, with the following coefficients:

$$\Gamma_k = \begin{cases} \Gamma_1 = \alpha, & 1 \leq k \leq N_A - 1, \\ \Gamma_{N_A} = \beta \left(\frac{r_{ae}}{r_{be}} \right)^\kappa, & k \geq N_A. \end{cases} \quad (14)$$

As a result, the item $X = \tilde{\mathbf{g}}^\dagger (\sum_{k=1}^{N_A-N_B-2} \Gamma_k \cdot \tilde{\mathbf{g}}_k \tilde{\mathbf{g}}_k^\dagger)^{-1} \tilde{\mathbf{g}}$ in (13) is equivalent to the signal-to-interference ratio of an N_E -branch MMSE diversity combiner having $(N_A - 1) + (N_B - 1)$ interferers with covariance matrix $\text{diag}\{\Gamma_1, \dots, \Gamma_{N_A-N_B-2}\}$. The complementary cumulative distribution function of X is given in [22] (Equation (18) in that paper), as

$$\begin{aligned} R(x) &= \text{Prob}\{X \geq x\} = \frac{1 + \sum_{m=1}^{N_E-1} C_m x^m}{\prod_{k=1}^{N_A+N_B-2} (1 + \Gamma_k x)} \\ &= \frac{\sum_{m=0}^{N_E-1} C_m x^m}{\prod_{k=1}^{N_A+N_B-2} (1 + \Gamma_k x)} \\ &= \frac{\sum_{m=0}^{N_E-1} C_m x^m}{(1 + \Gamma_1 x)^{N_A-1} (1 + \Gamma_{N_A} x)^{N_B-1}}, \end{aligned} \quad (15)$$

where C_m is the coefficient of x^m in the polynomial, $\prod_{k=1}^{N_A+N_B-2} (1 + \Gamma_k x)$. Hence, the probability density function of X is $f_X(x) = d(-R(x))$. We can rewrite the expectation in (13) into integral form as

$$\begin{aligned} \overline{Cs_2} &= E_{r_{ae}, r_{be}} \int_0^\infty \log_2(1 + \phi x) \cdot d(-R(x)) \\ &\stackrel{(c)}{=} E_{r_{ae}, r_{be}} \frac{1}{\ln 2} \int_0^\infty \frac{\phi}{1 + \phi x} R(x) dx \\ &\quad + [\log_2(1 + \phi x) R(x)]_{x=\infty}^{x=0} \\ &= E_{r_{ae}, r_{be}} \frac{1}{\ln 2} \int_0^\infty \frac{\phi}{1 + \phi x} R(x) dx + (0 - 0) \\ &\stackrel{(d)}{=} E_{r_{ae}, r_{be}} \frac{1}{\ln 2} \sum_{m=0}^{N_E-1} \int_0^\infty \frac{C_m \cdot \phi \cdot x^m \cdot (1 + \phi x)^{-1} dx}{(1 + \Gamma_1 x)^{N_A-1} (1 + \Gamma_{N_A} x)^{N_B-1}}, \end{aligned} \quad (16)$$

(c) is obtained using integration by parts. Note that for a given r_{ae} and r_{be} , the integrand in (16) corresponds to a rational function. The improper integral, therefore, can be easily computed by adopting partial fraction decomposition.

Also, note that the second term in (c) equals 0, because $\lim_{x \rightarrow 0} \log_2(1 + \phi x) R(x) = 0$. If the size constraint in Section 5.1 is fulfilled; that is, $(N_A - 1) + (N_B - 1) \geq N_E$,

$$\lim_{x \rightarrow \infty} \log_2(1 + \phi x) R(x) \sim \lim_{x \rightarrow \infty} \frac{\log_2(x)}{x^{N_A+N_B-N_E-1}} = 0. \quad (17)$$

4.2.2. Spatial Distribution of Eve. In (16), $\overline{Cs_2}$ is still the expectation over r_{ae} and r_{be} , which is in turn related to the spatial location of Eve. Therefore, some geometry distribution could be prespecified for this imaginary attacker. For example, in [16, 23], the location of Eve follows a Poisson point process.

In our simulation (see Section 6, Figure 4), however, a certain region of area within a radius of $2 \cdot r_{ab}$ is delimited

around Alice and Bob. The probability density function of Eve's location can be expressed as

$$p(E_{x,y}) = \begin{cases} \frac{1}{S(\mathcal{D})}, & E_{x,y} \in \mathcal{D}, \\ 0, & E_{x,y} \notin \mathcal{D}, \end{cases} \quad (18)$$

where $E_{x,y}$ is the coordinate of Eve's location and $\mathcal{D} = \{E_{x,y} \mid r_{ae}, r_{be} < 2 \cdot r_{ab}\}$. We refer to $\mathcal{D}$ as the "Protected Zone," and $S(\mathcal{D})$ is the area of such a region. 25 points are sampled uniformly and symmetrically in this region to approximately compute the expectation in (16). Outside this region, Eve is considered to have little impact on the secure communication because the relatively high pass-loss and low-SNR makes it difficult to decode the information signal.

4.2.3. Searching for Optimal ϕ^* . Through the above derivation, C_s can be computed efficiently given a specified ϕ . Therefore, the optimal power allocation ratio, ϕ^* , can be obtained by some searching techniques.

Analytically, it is hard to prove the concavity of C_s in the form of (16). However, it can be checked from Figure 2 that the resulted curve is concave. Although not strict, it can still be empirically treated as a concave problem in practical engineering. Therefore, one-dimension search technique such as binary search can be applied to find the optimal ϕ^* .

5. Discussion and Extension

5.1. Constraints on Antenna Numbers. There are some size constraints on the number of antennas for Alice, Bob, and Eve in the proposed AN-by-both-side scenario.

First, as can be seen from (8), to avoid $\alpha \mathbf{G} \mathbf{G}^\dagger + \beta \mathbf{G}_{be}^{(i)} \mathbf{G}_{be}^{(i)\dagger}$ being singular, $(N_A - 1) + (N_B - 1) \geq N_E$ has to be ensured.

Second, for Eve's antenna number, N_E , it is related to an assumption on the capability of Eve. $N_E = N_B$ is typically assumed to mean that Eve has the same capability as Bob. N_E can also be considered as the number of colluding eavesdroppers, each equipped with one antenna.

5.2. Multiple Receiving Antennas for Bob. In this paper, the transmission between Alice and Bob adopts the MISO strategy; that is, Bob only uses one antenna for information receiving. In fact, Bob can use more than one antenna to receive information signals, because he has N_B antennas. Although authors in [13] have pointed out that the secrecy capacity, C_s , does not necessarily grow linearly with the number of receive dimensions, it still might result in a better performance than the MISO strategy. For such MIMO cases, it tends to be more difficult to analyze the statistical expectation of $\overline{Cs_2}$. Furthermore, the antenna selection problem becomes combinatorial NP hard for Bob with multiple receiving antennas. In future work, further efforts need to be made to solve these problems.

TABLE 1: Comparison results for Bob's antennas.

i	1	2	3	4
$\ h_{ab}^{(i)}\ $	2.16	3.03	2.67	2.79

FIGURE 2: Secrecy capacity versus power allocation ratio ϕ .

6. Simulation Results

In the simulation scenario (see Figure 4), topology is set as $(-2, 2) \text{ km} \times (-2, 2) \text{ km}$. Alice and Bob are located at $(-0.5, 0)$ and $(0.5, 0)$, respectively, with $N_A = 8$ and $N_B = 4$. Simulation parameters are set to the following values: $P_A = P_B = 0.1 \text{ W}$, $\lambda = 10^{-12.81}$, and $\kappa = 3.76$. The noise power density is -180 dBm/Hz , which gives a noise power of $\sigma_{n_b}^2 = 5 \times 10^{-15} \text{ W}$ within a bandwidth of 5 MHz . Such configurations result in an SNR of 4.77 dB at Bob. The channel fading between Alice and Bob is generated randomly.

Optimal design of this scenario is analyzed first. According to the antenna assignment method in Section 4.1, $\mathbf{h}_{ab}^{(i)}$ ($1 \leq n \leq N_B$) is computed for each of Bob's antennas, shown in Table 1.

Bob will therefore assign the 2nd antenna as the receiving antenna, and the remaining 3 ones for AN emission.

Figure 2 shows the power allocation ratio ϕ and the corresponding secrecy capacity computed according to Section 4.2. Eve's antenna number, N_E , varies from 1 to 4, and the optimal power allocation ratio, ϕ^* , is obtained for each condition. Secrecy capacity drops drastically with the increase of N_E . ϕ^* also decreases so that a greater proportion of the power should be assigned to AN in order to resist a more powerful eavesdropper. For $N_E = 4$, the dashed-line also shows the secrecy capacity when AN is sent only by Alice, and ϕ^o is the optimal power allocation ratio for this condition.

Figure 3 compares the secrecy capacity for 3 AN strategies at different SNR levels. To be fair, model (b) and model (c) are configured under the same resource condition as follows: $N_A = 6$, $N_B = 4$, $N_E = 2$, and $P_B = P_A$. As it can be seen from Figure 3, the strategy of model (c) has better performance. In addition, positive secrecy capacity can be achieved even when SNR is fairly low. For model (a), only Alice sends AN, therefore, $P_B = 0$, and the secrecy capacity is still taken under the optimal power allocation ratio, denoted as ϕ^o in Figure 3.

FIGURE 3: Comparison of 3 strategies in terms of secrecy capacity.

FIGURE 4: Impact of Eve's location on the secrecy capacity.

The achieved secrecy capacity of model (c) still outperforms that of model (a), but at the cost of extra AN power emitted by Bob.

In Figure 4, rather than the average secrecy capacity, we turn to see the distribution details of secrecy capacity when the attacker appears at various locations of the topology. When the eavesdropper approaches Alice, the secrecy capacity is degraded greatly due to Eve's superior channel condition compared with Bob. With the help of AN emitted by Alice, however, positive secrecy capacity is still possible. When Eve is located near Bob, high secrecy capacity is achieved, disregarding the fact that channel conditions for Eve and Bob are similar. This is a result of the strong interfering signal emitted by Bob, making it difficult for Eve to cancel the randomized AN.

7. Conclusion

In this paper, artificial noise sent by both Alice and Bob was studied. We proposed an efficient scheme, called "bipolar-beamforming optimization," to optimally configure the proposed model. Secrecy capacity was analyzed based on Eve's stochastic channel condition and spatial distribution. Maximum secrecy capacity can be achieved by adopting the proposed optimization technique to allocate their antenna and power resources. Research work of this paper can be extended to a more general configuration where Bob adopts more than one antennas for receiving the information signals.

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