Hindawi
Complexity
Volume 2021, Article ID 8806874, 10 pages
https://doi.org/10.1155/2021/8806874

Research Article

Beamforming Design and Covert Performance Analysis for Full-Duplex Multiantenna System

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Received 25 May 2021; Accepted 6 September 2021; Published 7 October 2021

Academic Editor: Hou-Sheng Su

In this work, a wireless covert communication system with full-duplex (FD) multiantenna receiver is considered. In order to improve the convert performance of the wireless communication system in the FD mode, a scheme based on selection combining/zero forcing beamforming (SC/ZFB) is proposed. More specifically, a covert message receiver with a FD multiantenna uses the zero forcing beamforming method to transmit randomly varying noise power to the adversary while receiving covert information from the sender. Firstly, we derive the optimal detection threshold and the corresponding closed expression of the minimum detection error rate of the warden. Secondly, the transmission interruption probability is explored to measure the communication reliability between the sender and the receiver of the covert message. Finally, the throughput performance of the covert communication system is analyzed under random geometry. Our analysis shows that the proposed SC/ZFB scheme can achieve the positive effective convert rate while interfering with the detection of the warden as much as possible. It is worth noting that the increase of the number of antennas and the power of covert message transmission can improve the convert performance of the system.

1. Introduction

The confidentiality of network activities and the integrity of data transmission are the basic goals of wireless network system construction. Although the network system structure [1, 2] and network control protocol [3, 4] design determine the efficiency of data transmission to a certain extent, due to the wireless network uses the public electromagnetic wave as an open medium to transmit data signals, the risk of data transmission will be greatly increased. Therefore, how to ensure the security and privacy of information in wireless networks has been a hot research issue. The common methods include traditional information theory technology [5–7], encryption technology [8, 9], and emerging covert communication technology [10, 11]. Traditional methods [12, 13] focus on protecting information content from eavesdropping, while new methods focus on protecting information transmission process. The covert communication technology (also known as low probability detection communication (LPD)) appeared in the form of spread spectrum technology in the earliest stage. In recent years, the researchers have studied covert communication under additive white Gaussian noise (AWGN) channel [14, 15], binary symmetric channel (BSC) [16], and discrete memoryless channel (DMC) [17], respectively. At the same time, the basic limitations of covert communication under these channels have also been studied in these literatures, especially in the pioneering work of covert communication [14]; a pessimistic conclusion is put forward that when $n \longrightarrow \infty$, there is $O(\sqrt{n})/n \longrightarrow 0$, which means that when n is large enough, the covert rate is 0. Therefore, more and more people are devoting themselves to exploring the conditions that can ensure the positive covert rate and putting forward some new research methods; the main purpose is to create conditions for the warden to detect errors. The basic strategy is adopted to disturb the warden detection by uncertainties of noise [18, 19], channel [20], interference power [19, 21–23], and communication time [24]. In addition, covert communication schemes with relays [25] have also been proposed successively, and the literature [26] studies covert communication with finite block length in AWGN channels. Yan et al. [27] study delay-intolerant covert communications in AWGN channels with finite block length. Recently, some researchers consider covert communication in the network environment of unmanned aerial vehicle (UAV) [28]. However, the existing covert communication systems involve multiple antennas in addition to [29–31]; most of the existing research on covert communication focuses on single-antenna scenarios, while multi-antenna covert communication scenarios [32] have not been well developed.

Full-duplex (FD) technology in wireless communication scenarios has been effectively explored in [22, 33, 34]. Shu et al. [33] send artificial interference to the adversary through the FD receiver, so as to enhance the convert performance. Wang et al. [34] use channel uncertainty to explore covert communication in relay networks operating in the FD mode. Similarly, Shahzad et al. [22] also use FD technology; when the receiver of the covert message receives the signal, it will generate artificial noise with different power, resulting in uncertainty to the opponent.

As for beamforming technology, it is rarely used. In [35], the enhancement effect of multiantenna AN nodes on covert performance is studied, and it is pointed out that directional beamforming is the optimal AN strategy. In fact, how to use multiantenna technology to improve spectrum efficiency so as to bring more security gains in covert communication systems and how to design more appropriate multiantenna scenarios to make effective covert rate higher are necessary to be considered. Therefore, the potential of multiantenna technology for covert communication in fading channels remains to be tapped, which also stimulates the current research work.

In this work, we consider covert communication in the context of multiantenna receiver networks. Specifically, the full-duplex and multiantenna receiver generates artificial noise (AN) with a randomized transmit power to deliberately confusion and affect the detection of Willie. The covert transmission selection combining/zero forcing beamforming (SC/ZFB) schemes are proposed: the destination selects the best antenna to receive the information from the source and uses all the remaining antennas to send the jamming signal to warden according to the principle of ZFB. The main contributions of this paper are summarized as follows:

(i) We demonstrate the possibility that the proposed SC/ZFB scheme can achieve covert performance in wireless communication networks; the results show that the SC/ZFB schemes can achieve positive effective covert rate.

(ii) The closed-form expressions of the minimum detection error rate and transmission outage probability are derived, respectively, and the covertness and reliability of the system are described, respectively, on this basis.

(iii) Our analysis shows that increasing the number of antennas can improve the covert performance. In other words, with the increase of the number of antennas, the detection performance and covert performance of the covert communication system will also increase.

The remainder of this paper is organized as follows. The system model is introduced in Section 2. Sections 3 and 4 analyze the detection performance and the covert throughput for the SC/ZFB schemes, respectively. The theoretical analyzes are verified by numerical results in Section 5. Finally, Section 6 concludes the paper and summarizes the key findings.

Notation: throughout this paper, the boldface uppercase letters are used to denote matrices. † is denoted as the conjugate transpose operation. $\|\cdot\|$ is defined as the Frobenius norm. $F(\cdot)$ and $f(\cdot)$ represent the cumulative distribution function (CDF) and the probability density function (PDF) of random variable, respectively. $E(\cdot)$ denotes the expectation operation. A list of the fundamental variables is provided in Table 1.

2. System Model

2.1. Considered Scenario and Adopted Assumptions. As shown in Figure 1, considering a multiantenna wireless network consisting of a source Alice, a destination Bob, and a warden Willie, Warden Willie seeks to detect any transmission by Alice, and Alice desires to deliver messages to Bob reliably while guarantees a low probability of being detected by Willie; at the same time, they know each other's existence and location. Bob is equipped with N_B antennas, and all the other nodes, including Alice and Willie, are single-antenna devices. In addition to receiving covert messages, Bob uses additional antenna for transmission of AN in order to confuse Willie, and FD operations are assumed at Bob.

We assume that the wireless channels are subject to independent quasi-static Rayleigh fading, where the channel coefficient remains constant over one communication slot of n channel uses and changes independently from slot to slot. The channels from Alice-to-Bob, Alice-to-Willie, and Bob-to-Willie, are denoted by $\mathbf{h}_{AB}$, h_{AW}, and $\mathbf{h}_{BW}$, respectively, while the self-interference channel of Bob is denoted by $\mathbf{h}_{BB}$. We assume that Bob knows $\mathbf{h}_{AB}$, while Willie knows h_{AW} and $\mathbf{h}_{BW}$. Considering Bob knows about Willie, so it is assumed that Bob also knows $\mathbf{h}_{BW}$.

Based on FD operation, Bob first selects the best antenna based on the channel state information (CSI) of the channel between Alice and Bob to receive the covert messages and utilizes the remaining $N_B - 1$ antennas to send a weighted AN signal to disturb Willie's detection. We adopt the ZFB algorithm to avoid the undesirable AN signals at Alice. Thus, the optimal weight vector $\mathbf{W}_{ZF}$ is the solution of the following optimization problem:

Table 1: List of fundamental variables.

Symbol	Description
N_B	Antenna number of Bob
$h_{a,b}$	The channel between a and b who both consist a single antenna
$\mathbf{h}_{a,b}$	The channel vector between a and b consisting one and multiple antennas, respectively
$\mathbf{w}_{a,b}$	The received weighting vector on link $a-b$
$T^{\perp}$	The projection idempotent matrix with rank N_B-2
B_j	The jth antenna of Bob
P_z	The AN power of Bob
P_X	The power send by X, $X\in\{\text{Alice},\text{Bob},\text{Willie}\}$
σ_A^2	The variance of AWGN at node A, $A\in\{\text{Bob},\text{Willie}\}$
γ_A	The SNR on A, $A\in\{\text{Bob},\text{Willie}\}$
y_A	The received signal at A, $A\in\{\text{Bob},\text{Willie}\}$
n	The number of each channel use
$n_B[i]$	The complex additive Gaussian noise at A, $A\in\{\text{Bob},\text{Willie}\}$
T_W	The average power
τ	The predefined detection threshold
ξ	The detection error rate
ξ^*	The minimum detection error rate
P_{FA}	The false alarm rate
P_{MD}	The miss detection rate
R	The transmission rate
δ	The transmission outage probability
R_C	The effective covert rate
$\overline{R_C}$	The maximizing effective covert rate

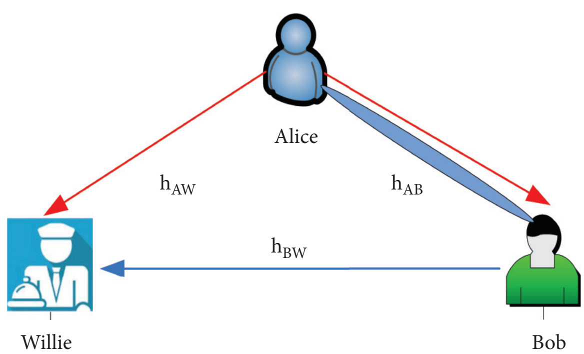

Figure 1: System model.

$$\begin{aligned}&\max_{\mathbf{W}_{ZF}} \quad \left|\mathbf{h}_{BW}^{\dagger}\mathbf{W}_{ZF}\right| \\ &\text{s.t.} \quad \left|\mathbf{h}_{BA}^{\dagger}\mathbf{W}_{ZF}\right| = 0\&\left\|\mathbf{W}_{ZF}\right\|_F = 1,\end{aligned} \tag{1}$$

where $\dagger$ is the conjugate transpose operator, $\|\cdot\|_F$ denotes the Frobenius norm, and $\mathbf{h}_{BW}$ and $\mathbf{h}_{BA}$ denote the $(N_B-1)\times 1$ channel vectors between the remaining N_B-1 antennas of the Bob and the Willie and the remaining N_B-1 antennas of the Bob and the Alice, respectively. According to the theorems in [36], the solution of the optimal weight vector in formula (1) can be obtained as

$$\mathbf{W}_{ZF} = \frac{T^{\perp}\mathbf{h}_{BW}}{\left\|T^{\perp}\mathbf{h}_{BW}\right\|}, \tag{2}$$

where $T^{\perp} = (\mathbf{I}-\mathbf{h}_{BA}(\mathbf{h}_{BA}^{\dagger}\mathbf{h}_{BA})^{-1}\mathbf{h}_{BA}^{\dagger})$ is the projection idempotent matrix with rank N_B-2.

Let us define $Z_1 \triangleq P_Z|\mathbf{h}_{BW}^{\dagger}\mathbf{W}_{ZF}|^2/\sigma_W^2$ and $Z \triangleq P_Z|\mathbf{h}_{BW}^{\dagger}\mathbf{W}_{ZF}|^2$; the corresponding probability density function (PDF) and the cumulative distribution function (CDF) can be expressed as

$$\begin{aligned} f_{Z_1}(Z) &= \frac{Z^{N_B-3}\exp\left(-\left(\sigma_W^2 Z/P_Z\right)\right)}{(N_B-3)!\left(P_Z/\sigma_W^2\right)^{N_B-2}}, \quad N_B\geq 3, Z\geq 0, \\ F_{Z_1}(Z) &= 1-\exp\left(-\frac{Z\sigma_W^2}{P_Z}\right)\sum_{l=0}^{N_B-3}\frac{1}{l!}\left(\frac{Z\sigma_W^2}{P_Z}\right)^l, \quad Z\geq 0, \end{aligned} \tag{3}$$

where P_Z denotes the power of the AN signal from Bob and the σ_W^2 is noise variance of Willie.

The instantaneous SINR at Bob is given by

$$\gamma_{\text{Bob}} = \frac{P_A\max_{1\leq i\leq N_B}\left(\left|h_{AB_i}\right|^2\right)}{\sigma_B^2}. \tag{4}$$

When Alice transmits, the received signal at Willie is given by

$$y_{\text{Bob}}[i] = \sqrt{P_A}\max_{1\leq i\leq N_B}\left(\left|h_{AB_i}\right|^2\right)x_A[i]+n_B[i], \tag{5}$$

where h_{AB_i} denotes the channel coefficient between Alice and the ith antenna of Bob, $x_A[i]$ is the transmitted signal by Alice satisfying $E[x_A[i]x_A^{\dagger}[i]]=1$, i is the index of each channel use, $i=1,2,\ldots,n$, and $n_B[i]$ is the complex additive Gaussian noise at Willie with σ_B^2 as its variance, i.e., $n_B[i]\sim \text{CN}(0,\sigma_B^2)$.

2.2. Detection Metrics at Willie. Warden Willie attempts to judge whether Alice is transmitting to Bob in a communication slot. To this end, Willies should distinguish two hypotheses, namely, the null hypothesis H_0 meaning that

Alice is not transmitting covert information and the alternate hypothesis H_1 indicating an ongoing communication. The two hypotheses are detailed as below:

$$y_{\text{willie}}[i] = \begin{cases} \sqrt{P_Z}\left|h_{BW}^{\dagger} W_{ZF}\right| V_B[i] + n_W[i], & H_0, \\ \sqrt{P_A}\, h_{AW} x_A[i] + \sqrt{P_Z}\left|\mathbf{h}_{BW}^{\dagger} \mathbf{W}_{ZF}\right| V_B[i] + n_W[i], & H_1, \end{cases} \tag{6}$$

where $n_W[i]$ is the AWGN at Willie with σ_W^2 as its variance, i.e., $n_W[i] \sim \mathrm{CN}(0, \sigma_W^2)$. Willie does not know P_{B_j} and P_Z in a communication slot, while P_A is fixed and known.

We focus on a communication slot, where Willie has to decide whether Alice transmitted covert information to Bob, or not. By applying Neyman-Pearson criterion [37] and likelihood ratio test, Willie can obtain the optimal decision rule to minimize his detection error; the rule is given by

$$T_W \gtrless_{D_0}^{D_1} \tau, \tag{7}$$

where $T_W = 1/n \sum_{i=1}^{n} y_{\text{Willie}}[i]$ is the average power received at Willie in the slot, τ is a predefined detection threshold, D_1 and D_0 are the binary decisions that infer whether the Alice transmits covert message to Bob or not, respectively, and decision D_0 is made if $T_W < \tau$, whereas decision D_1 is made otherwise. We consider an infinite number of channel uses, i.e., $n \longrightarrow \infty$.

The average received power is given by

$$T_W = \begin{cases} P_Z\left|h_{BW}^{\dagger} W_{ZF}\right|^2 + \sigma_W^2, & H_0, \\ P_A\left|h_{AW}\right|^2 + P_Z\left|\mathbf{h}_{BW}^{\dagger} \mathbf{W}_{ZF}\right|^2 + \sigma_W^2, & H_1. \end{cases} \tag{8}$$

At the end of the communication slot, Willie must make a decision. We define the false alarm rate as $P_{\text{FA}} = P(D_1 | H_0)$, and the miss detection rate is defined as $P_{\text{MD}} = P(D_0 | H_1)$. Under the assumption of equal a priori probabilities of hypotheses H_0 and H_1, the detection performance of Willie is normally measured by the detection error probability, which is defined as $\xi \triangleq P_{\text{FA}} + P_{\text{MD}}$.

3. Detection Performance at Willie

In this section, we derive Willie false alarm and miss detection rates and examine how Willie optimally sets the value of τ aiming to minimize the detection error rate ξ.

3.1. False Alarm and Miss Detection Rates. Considering Rayleigh fading, the cumulative distribution function (CDF) of the channel coefficient $|h_{B_jW}|^2$ between the jth antenna of Bob and the Willie is given by $F_{|h_{B_jW}|^2}(x) = 1 - \exp(-x)$.

Theorem 1. *For SC/ZBF scheme, the false alarm and miss detection rates at Willie are derived as (10) and (11), shown at the top of the next page, where*

$$\begin{aligned} k_1 &= \frac{\tau - \sigma_w^2}{(N_B - 1) P_{B_j}^{\max}}, \\ k_2 &= \frac{\tau - \sigma_w^2 - P_A\left|h_{AW}\right|^2}{(N_B - 1) P_{B_j}^{\max}}, \end{aligned} \tag{9}$$

$$P_{\text{FA}} = \begin{cases} 1, & \tau \le \sigma_W^2, \\ x Ei(-k_1) + \exp(-k_1), & \tau > \sigma_W^2, N_B = 3, \\ \exp(-k_1), & \tau > \sigma_W^2, N_B = 4, \\ \left\{1 + \sum_{l=2}^{N_B-3}\left[\frac{1}{l(l-1)} \sum_{k=0}^{l-2} \frac{(k_1)^{k+1}}{k!}\right]\right\}\exp(-k_1), & \tau > \sigma_W^2, N_B \ge 5, \end{cases} \tag{10}$$

$$P_{\text{MD}} = \begin{cases} 0, & \tau \le \sigma_W^2 + P_A\left|h_{AW}\right|^2, \\ 1 - \left[k_2 Ei(-k_2) + \exp(-k_2)\right], & \tau > \sigma_W^2 + P_A\left|h_{AW}\right|^2, N_B = 3, \\ 1 - \exp(-k_2), & \tau > \sigma_W^2 + P_A\left|h_{AW}\right|^2, N_B = 4, \\ 1 - \left\{1 + \sum_{l=2}^{N_B-3}\left[\frac{1}{l(l-1)} \sum_{k=0}^{l-2} \frac{(k_2)^{k+1}}{k!}\right]\right\}\exp(-k_2), & \tau > \sigma_W^2 + P_A\left|h_{AW}\right|^2, N_B \ge 5. \end{cases} \tag{11}$$

Proof. According to the optimal decision rule and (8), the false alarm rate is given by

$$P_{\mathrm{FA}} = P\left[P_Z\left|\mathbf{h}_{BW}^{\dagger}\mathbf{W}_{ZF}\right|^2 + \sigma_W^2 > \tau\right] = \begin{cases} 1, & \tau < \sigma_W^2, \\ 1 - P\left[\dfrac{P_Z\left|\mathbf{h}_{BW}^{\dagger}\mathbf{W}_{ZF}\right|^2}{\sigma_W^2} < \dfrac{\tau - \sigma_W^2}{\sigma_W^2}\right], & \tau \geq \sigma_W^2. \end{cases} \quad (12)$$

From (10), the P_{FA} can be obtained as

$$P_{\mathrm{FA}} = \begin{cases} 1, & \tau < \sigma_W^2, \\ 1 - \displaystyle\int_0^{(N_B-1)P_{B_j}^{\max}} \left[1 - \exp\left(-\frac{\tau - \sigma_w^2}{P_Z}\right)\sum_{l=0}^{N_B-3}\frac{1}{l!}\left(\frac{\tau - \sigma_w^2}{P_Z}\right)^l\right] \times \frac{1}{(N_B - 1)P_{B_j}^{\max}}\,\mathrm{d}P_Z & \tau \geq \sigma_W^2. \end{cases} \quad (13)$$

Then, we solve the integral in (13) with the aid of equation (3.351. 2.11) and equation (3.351.4) in [34], utilizing the variable substitution (i.e., setting $t = 1/P_Z$). Similarly, the miss detection rate is given by

$$P_{\mathrm{MD}} = P\left[P_A\left|h_{AW}\right|^2 + P_Z\left|\mathbf{h}_{BW}^{\dagger}\mathbf{W}_{ZF}\right|^2 + \sigma_W^2 < \tau\right] = \begin{cases} 0, & \tau < \sigma_W^2 + P_A\left|h_{AW}\right|^2, \\ \displaystyle\int_0^{(N_B-1)P_{B_j}^{\max}} \begin{bmatrix} 1 - \exp\left(-\dfrac{\tau - \sigma_w^2 - P_A\left|h_{AW}\right|^2}{P_Z}\right) \\ \times \displaystyle\sum_{l=0}^{N_B-3}\frac{1}{l!}\left(\dfrac{\tau - \sigma_w^2 - P_A\left|h_{AW}\right|^2}{P_Z}\right)^l \end{bmatrix} \times \frac{1}{(N_B - 1)P_{B_j}^{\max}}\,\mathrm{d}P_Z & \tau \geq \sigma_W^2 + P_A\left|h_{AW}\right|^2. \end{cases} \quad (14)$$

3.2. The Optimization of Detection Threshold and Detection Error Rate at Willie

Theorem 2. *For the SC/ZBF scheme, under the assumption of a radiometer at Willie, the optimal threshold that minimizes ξ is derived as*

$$\tau^* = P_A\left|h_{AW}\right|^2 + \sigma_W^2, \quad (15)$$

and the corresponding detection error rate is derived as

$$\xi^* = \begin{cases} x^* Ei(-x^*) + \exp(-x^*), & N_B = 3, \\ \exp(-x^*), & N_B = 4, \\ \left\{1 + \displaystyle\sum_{l=2}^{N_B-3}\left[\frac{1}{l(l-1)}\sum_{k=0}^{l-2}\frac{(x^*)^{k+1}}{k!}\right]\right\}\exp(-x^*), & N_B \geq 5, \end{cases} \quad (16)$$

$$\xi = \begin{cases} 1, & \tau \le \sigma_W^2, \\ k_1 Ei(-k_1) + \exp(-k_1), & \sigma_W^2 < \tau \le \sigma_W^2 + P_A |h_{AW}|^2, N_B = 3, \\ \exp(-k_1), & \sigma_W^2 < \tau \le \sigma_W^2 + P_A |h_{AW}|^2, N_B = 4, \\ \left\{ 1 + \sum_{l=2}^{N_B-3} \left[\frac{1}{l(l-1)} \sum_{k=0}^{l-2} \frac{(k_1)^{k+1}}{k!} \right] \right\} \exp(-k_1), & \sigma_W^2 < \tau \le \sigma_W^2 + P_A |h_{AW}|^2, N_B \ge 5, \\ 1 + k_1 Ei(-k_1) + \exp(-k_1) - k_2 Ei(-k_2) - \exp(-k_2), & \tau > \sigma_W^2 + P_A |h_{AW}|^2, N_B = 3, \\ 1 + \exp(-k_2) - \exp(-k_2), & \tau > \sigma_W^2 + P_A |h_{AW}|^2, N_B = 4, \\ 1 + \left\{ 1 + \sum_{l=2}^{N_B-3} \left[\frac{1}{l(l-1)} \sum_{k=0}^{l-2} \frac{(k_1)^{k+1}}{k!} \right] \right\} \exp(-k_1) - \left\{ 1 + \sum_{l=2}^{N_B-3} \left[\frac{1}{l(l-1)} \sum_{k=0}^{l-2} \frac{(k_2)^{k+1}}{k!} \right] \right\} \exp(-k_2), & \tau > \sigma_W^2 + P_A |h_{AW}|^2, N_B \ge 5, \end{cases} \tag{17}$$

where

$$x^* = \frac{P_A |h_{AW}|^2}{(N_B - 1) P_{B_j}^{\max}}. \tag{18}$$

Proof. Following (12) and (13), the detection error rate can be expressed as (17), shown at the top of the next page.

For $N_B = 3$, defining $f(x) = xEi(-x) + \exp(-x)$, we derive the first derivative of $f(x)$ as $f'(x) = Ei(-x) < 0$. Similarly, we can derive the second derivative as $f''(x) = e^{-x}/x > 0, x > 0$. When $\sigma_W^2 < \tau \le \sigma_W^2 + P_{B_k} |h_{B_k W}|^2$, the first derivative of ξ with respect to τ can be derived as

$$\frac{d\xi}{d\tau} = \frac{1}{(N_B - 1) P_{B_j}^{\max}} \frac{df(k_1)}{dk_1} < 0. \tag{19}$$

When $\tau > \sigma_W^2 + P_{B_k} |h_{B_k W}|^2$, the second derivative of ξ with respect to τ can be derived as

$$\frac{d\xi}{d\tau} = \frac{1}{(N_B - 1) P_{B_j}^{\max}} \left[\frac{df(k_1)}{dk_1} - \frac{df(k_2)}{dk_2} \right] > 0. \tag{20}$$

According to $k_1 > k_2$ and the monotonicity of function $f(x)$, the minimum detection error rate ξ^* at Willie is obtained at $\tau^* = \sigma_W^2 + P_A |h_{AW}|^2$.

Using the same method, we can obtained that the minimum detection threshold and the corresponding minimum detection error rate for $N_B = 4$ and $N_B \ge 5$ are the same as those for $N_B = 3$. Hence, the optimal threshold that minimizes ξ is $\tau^* = P_A |h_{AW}|^2 + \sigma_W^2$. Substituting into (17), the desired ξ^* can be obtained. □

Corollary 1. *For the SC/ZBF scheme, the minimum detection error rate ξ^* increases with the increase of $P_{B_j}^{\max}$ and N_B.*

Proof. From (16), for $N_B \ge 3$, ξ^* is monotonic decreasing function of x^* and x^* is monotonic decreasing function of $P_{B_j}^{\max}$ and N_B, so $P_{B_j}^{\max} \longrightarrow \infty$ or $N_B \longrightarrow \infty$, $\xi^* \longrightarrow 1$. □

Remark 1. The minimum detection error rate ξ^* is a monotonic decreasing function of P_A. This is because of ξ^* is monotonic decreasing function of x^*, and x^* is monotonic increasing function of P_A, so $P_A \longrightarrow \infty$ and $\xi^* \longrightarrow 0$.

4. Performance of Covert Communication

For the SC/ZBF scheme, the maximizing the effective covert rate subject to the constraint can be expressed as

$$\begin{aligned} &\max \overline{R_C} \\ &\text{s.t.} \quad \xi^* \ge 1 - \varepsilon, \end{aligned} \tag{21}$$

where $\overline{R_C} \triangleq R(1 - \delta)$.

4.1. Transmission Outage Probability from Alice to Bob

Theorem 3. *A closed-form expression for the exact transmission outage probability δ of SC/ZFB is provided below:*

$$\delta = \left[1 - \exp\left(-\frac{(2^R - 1)\sigma_B^2}{P_A} \right) \right]^{N_B}. \tag{22}$$

Proof. If the transmission outage probability from Alice to Bob incurs, following (4), the probability can be represented as

$$\delta = P\left\{ \frac{P_A \max_{1 \le i \le N_B} |h_{AB_i}|^2}{\sigma_B^2} < 2^R - 1 \right\} = P\left\{ \max_{1 \le i \le N_B} |h_{AB_i}|^2 < \frac{(2^R - 1)\sigma_B^2}{P_A} \right\}. \tag{23}$$

To this end, substituting the PDF of $\max_{1\le i\le N_B}(|h_{AB_i}|^2)$ into (23), the desired result can be derived. □

Corollary 2. *For the SC/ZBF scheme, the transmission outage probability δ decreases with the increase of P_A and the increase of N_B and increases with the increase of σ_B^2 and R.*

Proof. If P_A gets bigger, $1-\exp(-((2^R-1)\sigma_B^2)/P_A)$ gets smaller and $1-\exp(-((2^R-1)\sigma_B^2)/P_A)\ge 0$, so δ gets smaller. Similarly, if σ_B^2 gets bigger, δ gets smaller as R gets bigger.

Due to $1-\exp(-((2^R-1)\sigma_B^2)/P_A)<1$, δ gets smaller as N_B gets bigger. □

4.2. Optimal Transmission Power of Covert Information

Theorem 4. *For a given transmission rate R and the covertness constraint ε, the optimal value for Alice transmission power of SC/ZFB is given by*

$$P_A^* = \begin{cases} \dfrac{(N_B-1)P_{B_j}^{\max}t_{\varepsilon_1}}{|h_{AW}|^2}, & N_B=3, \\[2ex] \dfrac{(N_B-1)P_{B_j}^{\max}}{|h_{AW}|^2}\ln\left(\dfrac{1}{1-\varepsilon}\right), & N_B=4, \\[2ex] \dfrac{(N_B-1)P_{B_j}^{\max}t_{\varepsilon_2}}{|h_{AW}|^2}, & N_B\ge 5, \end{cases} \tag{24}$$

where t_{ε_1} is the solution of $xEi(-x)+\exp(-x)=1-\varepsilon$ and t_{ε_2} is the solution of $\{1+\sum_{l=2}^{N_B-3}[(1/l(l-1))\sum_{k=0}^{l-2}(x^{k+1}/k!)]\}\exp(-x)=1-\varepsilon$.

Proof. According to the minimum detection error rate and its proof process, it is easy to be obtained; for $N_B>3$, ξ^* is monotonically decreasing with respect to P_A. Therefore, the optimal Alice transmission power is determined by $\xi^*=1-\varepsilon$, and (24) can be obtained by jointing (16). □

4.3. Maximum Effective Covert Rate

Theorem 5. *For the SC/ZFB scheme, the achievable maximum effective covert rate $\overline{R_C^*}$ is given by*

$$\overline{R_C}^* = R - R\left\{1-\exp\left[-\frac{(2^R-1)\sigma_B^2}{P_A^*}\right]\right\}^{N_B}. \tag{25}$$

Proof. From (21), we have

$$\overline{R_C} = R(1-\delta) = R - R\left\{1-\exp\left[-\frac{(2^R-1)\sigma_B^2}{P_A}\right]\right\}^{N_B}. \tag{26}$$

Because δ decreases with the increase of P_A, so $\overline{R_C}$ gets bigger, that is, $\overline{R_C}$ is monotonic increasing function with respect to P_A. Therefore, the maximum value of P_A can maximize the value of $\overline{R_C}$, and $\xi^*\ge 1-\varepsilon$ should be satisfied. For $N_B>3$, ξ^* decreases with the increase of P_A, so the maximum value of P_A is determined by $\xi^*\ge 1-\varepsilon$, i.e., P_A^*. Substituting (24) into (26), (25) can be derived. □

Corollary 3. *For the SC/ZBF scheme, the maximum effective covert rate $\overline{R_C^*}$ increases with the increase of $P_{B_j}^{\max}$, P_A^*, N_B, and ε.*

Proof. From (24), for $N_B\ge 3$, P_A^* is the monotonic increasing function of $P_{B_j}^{\max}$, and from (25), $\overline{R_C^*}$ is the monotonic increasing function of P_A^*, so $\overline{R_C^*}$ is the monotonic increasing function of $P_{B_j}^{\max}$. Other contents can be proved similarly. □

Corollary 4. *For the SC/ZFB scheme, when the transmit power P_A at Alice increases, the maximum effective covert rate $\overline{R_{C_1}^*}$ approaches a fixed value R:*

$$\lim_{P_A^*\longrightarrow\infty}\overline{R_{C_2}^*}=R. \tag{27}$$

Proof. Following (25), $\exp\{-[(2^R-1)\sigma_B^2]/P_A^*\}\longrightarrow 1$ as $P_A\longrightarrow\infty$, and then, $\{1-\exp[-(2^R-1)\sigma_B^2/P_A^*]\}^{N_B}\longrightarrow 0$, so $\overline{R_C^*}\longrightarrow R$. □

Remark 2. The maximum effective covert rate $\overline{R_C^*}$ is the monotonic decreasing function of the channel noise σ_B^2. That is, the larger σ_B^2 is, the smaller $\overline{R_C^*}$ is.

5. Numerical Result

In this section, we present representative numerical results to verify the detection performance of Willie and the covert communication performance of the considered system. In our simulations, because the channel coefficients change independently from slot to slot, their values within a time slot remains constant; we set all the channel coefficients to 0 dB. Except for the necessary comparisons, channel noise values are also 0 dB, and set the number of antennas N_B to 3 and the transmission rate R to 1.5, respectively.

Figure 2 shows the detection error rate ξ^* at Willie versus $P_{B_j}^{\max}$ for different values of P_A and N_B for the SC/ZFB scheme. In this figure, we first observe that ξ^* is a monotonically increasing function of P_A, and it is easy to understand that ξ^* increases with N_B. This is because the increase of interference power and antenna number of single antenna makes the total interference of Willie transmission larger. The total interference directly hinders the detection of Willie, resulting in the higher error rate of Willie. We also observe that ξ^* is a monotonically decreasing function of P_A, since a higher transmission power used by Alice increases the probability of being detected by Willie. This observation is also consistent with our earlier comments in Corollary 1.

Figure 3 depicts the transmission outage probability δ with different P_A for the SC/ZFB scheme, δ decreases with the increase of P_A. This is because an increase in P_A will increase the SINR at Bob, making transmission more secure

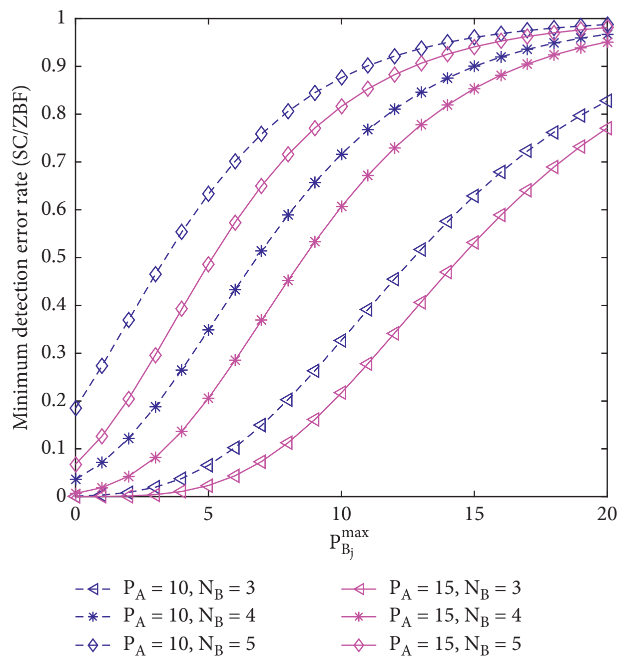

FIGURE 2: ξ^* versus $P_{B_j}^{max}$ with different values of P_A and N_B.

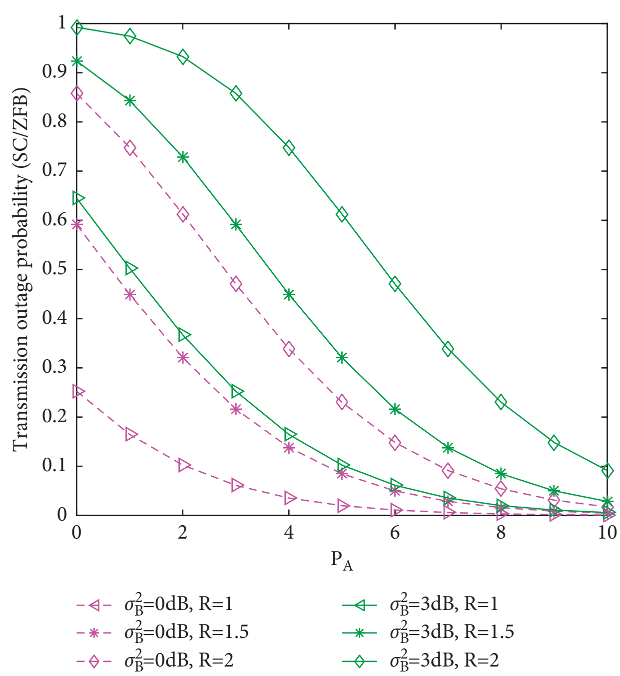

FIGURE 3: δ versus P_A with different values of σ_B^2 and R.

and less likely to interrupt. The relationship between δ and Bob's channel noise σ_B^2 is also described in Figure 3. δ increases with the increase of σ_B^2. This is because the SINR at Bob decreases with the increase of σ_B^2, which makes the transmission easy to interrupt. It can also be observed from Figure 3 that the higher the transmission rate, the easier the transmission to interrupt. These observations are consistent with those in Corollary 2.

It can be seen from Figure 4 that the maximum effective covert rate $\overline{R_C^*}$ increases with the increase of interference power $P_{B_j}^{max}$ transmitted by a single antenna based on the SC/ZFB scheme. This is because the greater the interference power transmitted, the more error-prone Willie detection, which makes the effective covert rate greater. $\overline{R_C^*}$ increases with the increase of N_B and ε in SC/ZFB schemes. These are consistent with Corollary 3. In

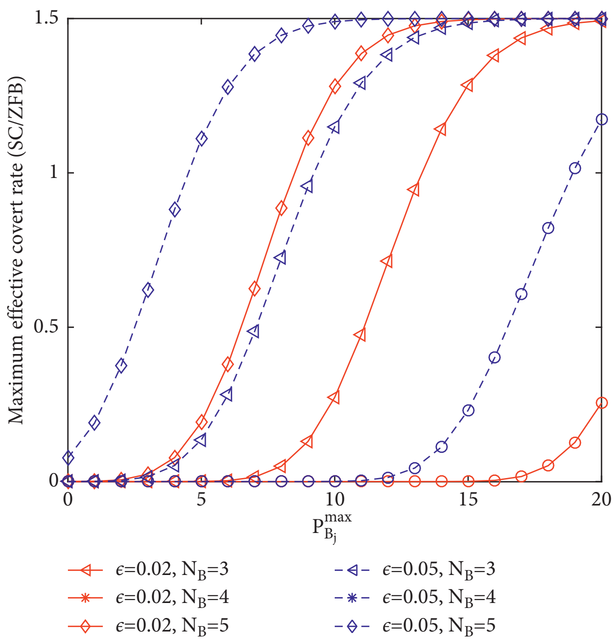

FIGURE 4: $\overline{R_C^*}$ versus $P_{B_j}^{\max}$ with different values of ε and N_B.

addition, Figure 4 shows that the maximum effective covert rate tends to a fixed value R, which verifies the correctness of Corollary 4.

6. Conclusion

In this paper, we have investigated the wireless covert communication network with the FD multiantenna receiver to achieve the convert performance by the generated randomly AN power of the selected antenna, and the analysis process of the covert performance was based on the detection performance of the warden. Our examinations showed that a higher positive effective covert rate can be ensured by controlling the number of antennas, and the AN power of the antenna is selected randomly by Bob. It can be expected that more multiantenna covert transmission schemes will be devised to achieve better covert performance in the future.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China, under Grant no. 62071486, the National Natural Science Foundation of Hunan Province, under Grant no. 2021JJ50051, and the Scientific Research Project of Education Department Hunan Province, China (nos. 19C0561 and 18C0531).

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