Artificial-Noise-Aided Secure Channel with a Full-duplex Source

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Abstract—This paper consider a new secure communication scene where a full-duplex transmitter (Alan) need to transmit confidential information to a half-duplex receiver (Bob), with a silent eavesdropper (Eve) that tries to eavesdrop the confidential information. For realizing secure communication between Alan and Bob, a novel two phases communication scheme is proposed: in Phase 1, Alan and Bob send artificial noises (AN) simultaneously, while in Phase 2, Alan superimposes the AN received in Phase 1 with its confidential signal and sends the mixed signal to Bob. Since the mixed AN could degrade the SINR (Signal to Interference and Noise Ratio) of Eve, but does not affect the SINR of Bob, a secrecy capacity can be achieved. We also derive the conditions that the secrecy capacity of the proposed scheme exists, and analyze the secrecy outage probability under Rayleigh fading channel. Numerical results show that the secrecy capacity is about two times higher than without AN, even though in the proposed scheme half of the time is used to transmit ANs, and the outage probability is about five times lower than that without AN.

Index Terms—Physical-layer Security, Artificial Noise, Full-duplex, Secrecy Capacity, Outage Probability

I. INTRODUCTION

Due to the broadcast nature of wireless channels, wireless security is an important concern that is attracting increasing interests from the community. Traditionally, the security problem in wireless networks was mainly studied at higher layers using key-based cryptographic methods. However, as the computational capability of wireless devices grows rapidly, perfect security can be hardly guaranteed with the key-based solutions. Physical-layer communication security that was first introduced by Shannon [1] emerges as an effective solution for secure communications by exploiting the physical characteristics of wireless channels. In [2], Wyner showed that a transmitter can communicate to its receiver with perfect secrecy from an information theoretic perspective, when the eavesdropper channel (between the transmitter and the eavesdropper) is degraded with respect to the main channel (between the transmitter and the receiver). Based on this result, various methods have been proposed to improve secrecy capacity by means of degrading the eavesdropper channel, and one important direction is to inject artificial noises (AN) to degrade the eavesdropper channel, such as [3]–[10]. Specifically, the confidential information is superimposed with some specially-designed artificial noises, which can be canceled by the receiver while remains an interference to the eavesdropper.

More specifically, in [3]–[6], the AN is a special signal designed in the null space of the main channel, and is emitted to interfere with the eavesdropper. That is, in [3]–[6], the MIMO (Multiple-Input Multiple-Output) equipment and the beamforming technology are needed, further, for playing beamforming, CSI (Channel State Information must be known by the node who playing beamforming. In [7], [8], the AN generated by transmitter of friendly jammer is assumed pre-known by the receiver but unknown by the eavesdropper. Its means in [7], [8] the risk that the selected AN may be eavesdropped by the eavesdropper is existing. Recently, full-duplex technology has been incorporated to realize physical-layer secrecy communication [9], [10], in which the authors considered a scenario in which either the relay node or the receiver has full-duplex communication ability. Thus, the relay or receiver can receive the information signal and transmit AN simultaneously to puzzle the eavesdropper, thus the AN-leakage problem in [9], [10] can be avoided.

Different from [9], [10], this paper consider a new secure communication scene where a full-duplex transmitter (Alan) need to transmit confidential information to a half-duplex receiver (Bob), with a silent eavesdropper (Eve) that tries to eavesdrop the confidential information, and to the best of our knowledge, there are no works have solved the problem that how to realize the secrecy transmission from a full-duplex transmitter to a half-duplex receiver without the help of relays. It is worth noting that the above problem is based on practical scene, for example, a full-duplex base station (BS) wants to transmit confidential information to a user while prevents other users from eavesdropping. To counter the above problem, a novel two-phase communication scheme that utilizes the advantages of full-duplex technology and AN is proposed: In phase 1, the transmitter and receiver send artificial noise $n_A$ and $n_B$ simultaneously ($n_A$ and $n_B$ are only known by Alan and Bob respectively), while in phase 2, Alan mixes the received signal with the confidential signal and sends it to Bob, thanks for full-duplex, the received signal in phase 1 at Alan is mainly constituted by $n_B$. After phase 2, because $n_B$ is known by Bob, so Bob could cancel the AN from the received signal, but the eavesdropper (Eve) only knows $n_B$ polluted by $n_A$ from phase 1, so Eve could not cancel the AN from received signal, then Eve must suffer more interference than Bob. We note that throughout the whole transmission process, both CSI and the artificial noise sent by Bob in phase 1 are not required by Alan, Alan also does not need the assistance of helpers or relays and does not need to perform beamforming, what Alan need to do, is just only mix and forward. Although this scheme only uses half times to transmission, but it still can prominent improve the secrecy capacity and reduce the secrecy outage probability than that without AN and full-duplex.

The contributions of this paper are summarized as follows:

• We propose a new transmission scheme to realize secure

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I. INTRODUCTION

Due to the broadcast nature of wireless channels, wireless security is an important concern that is attracting increasing interests from the community. Traditionally, the security problem in wireless networks was mainly studied at higher layers using key-based cryptographic methods. However, as the computational capability of wireless devices grows rapidly, perfect security can be hardly guaranteed with the key-based solutions. Physical-layer communication security that was first introduced by Shannon [1] emerges as an effective solution for secure communications by exploiting the physical characteristics of wireless channels. In [2], Wyner showed that a transmitter can communicate to its receiver with perfect secrecy from an information theoretic perspective, when the eavesdropper channel (between the transmitter and the eavesdropper) is degraded with respect to the main channel (between the transmitter and the receiver). Based on this result, various methods have been proposed to improve secrecy capacity by means of degrading the eavesdropper channel, and one important direction is to inject artificial noises (AN) to degrade the eavesdropper channel, such as [3]–[10]. Specifically, the confidential information is superimposed with some specially-designed artificial noises, which can be canceled by the receiver while remains an interference to the eavesdropper.

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The contributions of this paper are summarized as follows:

• We propose a new transmission scheme to realize secure
communication from full-duplex transmitter to half-duplex receiver. This scheme is simple to implement.

- We drive the conditions that positive secrecy capacity of the proposed scheme exists, analyze the secrecy outage probability and the ergodic secrecy capacity under Rayleigh fading channel.

The remainder of the letter is organized as follows: Section II describes the considered system model and introduces the proposed scheme. Section III analyzes the secrecy performance of the proposed scheme and gives the secrecy capacity and outage probability of the proposed scheme. Section IV presents the numerical results and finally Section V concludes the paper.

II. System Model and the Proposed Scheme

This section presents our system model and the proposed secure communication scheme.

A. System Model

As shown in Fig. 1, we consider a wireless communication system with three communication nodes: a full-duplex transmitter (Alan), an intended receiver (Bob) with single-antenna and a silent eavesdropper (Eve) with single-antenna. Alan need to send confidential information to Bob, and Eve tries to eavesdrop the information.

Fig. 1. The Considered Communication System.

Let $h_1$ and $h_3$ be the complex channel fading coefficient of the main channel and the eavesdropper channel, respectively, and $h_2$ be the complex channel fading coefficient between Bob and Eve. We assume that at the initial phase of secrecy communication, all the channel coefficients are unknown to Alan, Bob and Eve. Moreover, we assume the reciprocity of the forward and backward channels and a block-fading channel model where each channel coefficient remains unchanged for the time slot duration of $T$ seconds is assumed in this paper.\(^1\) Let the AWGN (Additive Gaussian White Noise) at each node has the same power $N_0$.

B. The Proposed Scheme

For guaranteeing the confidential information transmitted from Alan to Bob, a two-phase communication scheme is proposed.

Phase 1: In the first phase, which lasts for $T/2$ seconds, Bob sends an artificial Gaussian noise $\sqrt{P_B}n_B$, where $n_B$ is only known by Bob in which $n_B \sim CN(0,1)$ and $P_B$ is the transmit power of Bob. When Bob sends $\sqrt{P_B}n_B$, Alan synchronously sends another artificial Gaussian noise $\sqrt{P_A}n_A$ (note that $n_A$ is only known by Alan) in which $n_A \sim CN(0,1)$ and $P_A$ is the transmit power of Alan.

After Phase 1, denote the signal received by Alan (Thanks to the full-duplex ability, Allen can transmit and receive simultaneously) and Eve by $y_A$ and $y_{E1}$, respectively. We have:

$$y_A = h_1\sqrt{P_B}n_B + h_3\sqrt{P_A}n_A + n_{A1},$$

$$y_{E1} = h_2\sqrt{P_B}n_B + h_3\sqrt{P_A}n_A + n_{E1},$$

where $h_3\sqrt{P_A}$ is caused by the residual self-interference (RSI) in which $n_{A1}$ and $n_{E1}$ are AWGN satisfying $CN(0,N_0)$ respectively.

Note that, the residual self-interfering channel gain $\lambda$ is determined by the applied SI cancellation algorithm. Here, we consider the digital-domain cancellation, where $h_{SI}$ can be presented as $h_{SI} = 0$ is the RSI channel gain of Alan, and indicates the self-interference (SI) cancellation capability of Alan, where $h_{SI}$ is the RSI channel of Alan. Note that $R_{SI}=0$ denotes perfect cancellation capability.

Phase 2: In the second phase, which lasts for $T/2$ seconds, Alan superimposes the received signal $y_A$ with the information signal $\sqrt{P_s}s_A$, where $s_A \sim CN(0,1)$ is the confidential information signal and $P_s$ is the transmit power of $s_A$. The mixed signal is $x_A = \sqrt{P_s}s_A + y_A$. Alan then add a pilot signal ahead of $x_A$ and sent it to Bob(i.e., after Phase 2, $h_1$ and $h_3$ are known by Bob and Eve, respectively). Denote the received signal at Bob and Eve in Phase 2 by $y_B$ and $y_{E2}$, respectively. We have:

$$y_B = h_1\sqrt{P_s}s_A + h_1h_1\sqrt{P_B}n_B + h_1\sqrt{P_A}n_0 + h_1n_{A1} + n_{B2},$$

$$y_{E2} = h_3\sqrt{P_s}s_A + h_3h_1\sqrt{P_B}n_B + h_3\sqrt{P_A}n_0 + h_3n_{A1} + n_{E2},$$

where $n_{B2}$ and $n_{E2}$ are AWGN with variance $N_0$.

Since $\sqrt{P_B}n_B$ and $h_1$ are known by Bob, Bob could cancel the $h_1\sqrt{P_B}n_B$ term from $y_B$ easily. By contrast, it is difficult for Eve to detect $n_B$ from $y_{E1}$. Furthermore, $h_1$ is unknown to Eve. Thus, Eve could not cancel the $h_1h_3\sqrt{P_B}n_B$ term in $y_{E2}$. Thus, Eve suffers more interference from ANs than Bob, and the proposed two-phase transmission scheme achieves higher secrecy capacity.

III. Analysis on Secrecy Capacity and Outage Probability

We next analyze the secrecy capacity and outage probability of the assumed Rayleigh block fading channel.

A. Capacity of the Main Channel

Recall that a pilot signal is transmitted in Phase 2, Bob and Eve can estimate $h_1$ and $h_3$, respectively. For Bob, it knows $\sqrt{P_B}n_B$ and $h_1$. From $y_B$ in (3), it can cancel the interference caused by $h_1\sqrt{P_B}n_B$ and obtain $y_{BS}$:

$$y_{BS} = h_1\sqrt{P_s}s_A + h_1\sqrt{P_A}n_0 + h_1n_{A1} + n_{B2}.$$\(^2\)

For synchronizing, in phase 1, a pilot signal is added ahead $\sqrt{P_A}n_A$, so after phase 1, Alan knows $h_1$ and Eve knows $h_2$.\(^3\)

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\(^1\)Here we make this assumption for the purpose of easy analysis. In fact, the assumption of the reciprocity channel is not necessary. Bob could use the proposed method same as Eve (as in Lemma 1) to cancel the interference caused by the artificial generated by itself.

\(^2\)For synchronizing, in phase 1, a pilot signal is added ahead $\sqrt{P_A}n_A$, so after phase 1, Alan knows $h_1$ and Eve knows $h_2$.\(^3\)
Define \( g_1 = |h_1|^2, g_2 = |h_2|^2 \) and \( g_3 = |h_3|^2 \) as the gain of the three channels, respectively. The SINR of the main channel is:
\[
SINR_B = \frac{g_1 P_s}{g_1 P_A + g_1 N_0 + N_0},
\]
and the channel capacity of Bob, \( C_B \), is:
\[
C_B = \log_2(1 + SINR_B).
\]

B. Capacity of the Eavesdropper Channel

The signals received by Eve in two phases are (2) and (4), respectively. We assume Eve is smart enough and could use \( y_{E1} \) in (2) to reduce the interference in \( y_{E2} \) as much as possible.

For cancelling the interference, Eve multiplies \( y_{E1} \) with a complex coefficient \( h_s \), then obtains \( h_s y_{E1} \), and minus it from \( y_{E2} \). After cancel the interference, the signal obtained by Eve is:
\[
y_{ES} = h_3 \sqrt{P_s A} + h_3 \sqrt{P_B n_B} + h_3 \sqrt{P_A n_0} + h_3 n_{A1} + n_{E2}
\]
\[
- h_x \left( h_2 \sqrt{P_B n_B} + h_3 \sqrt{P_A n_0} + n_{E1} \right),
\]
\[h_{s,yE1}\]

As regarding to how \( h_x \) is determined to maximize the SINR of Eve, we have the following lemma:

**Lemma 1:** To achieve the highest SINR, Eve can select
\[
h_x^* = \frac{P_B |h_1 h_2 h_3|}{g_2 P_B + g_3 P_A + N_0} e^{i(\theta_1 + \theta_2 - \theta_3)}
\]
in which \( \theta_1, \theta_2 \) and \( \theta_3 \) are the phases of \( h_1, h_2, \) and \( h_3 \), respectively.

**Proof:** For achieving the highest SINR, \( h_x^* \) must be:
\[
h_x^* = \arg \max_{h_x} \left( SINR_{y_{ES}} \right),
\]
in which
\[
SINR_{y_{ES}} = \frac{g_3 P_s}{Var(N - h_{s,yE1})},
\]
and we have
\[
EN = |h_3 h_1 - h_x h_2|^2 P_B + |h_x|^2 g_3 P_A + |h_x|^2 N_0
\]
\[+ g_3 P_A + g_3 N_0 + N_0.\]

From (11), we have \( h_x^* = \arg \min(EN) \). From (12), it is easy to see that when the phase of \( h_3 h_1 \) is equal to that of \( h_x h_2 \), \( |h_3 h_1 - h_x h_2| \) is the smallest. That is, \( \theta_x^* = \theta_1 + \theta_2 - \theta_3 \).

After \( \theta_x^* \) is determined, we can write EN as:
\[
EN = \left( g_2 P_B + g_3 P_A + N_0 \right) |h_x|^2 - 2 \left( |h_1| |h_2| |h_3| P_B |h_x| + g_1 g_3 P_B + g_3 P_A + g_3 N_0 + N_0,\right)
\]
which is a convex function of \( |h_x| \) and it is easy to verify that
\[
|h_x|^2 = \frac{g_2 P_B |h_1 h_2 h_3|}{g_2 P_B + g_3 P_A + N_0}.
\]

Lemma 1 above gives out the value of \( h_x \) to make the SINR of Eve highest, but in our system, \( h_1 \) (correspondingly \( g_1 \)) is unknown for Eve, so Eve could not compute \( h_x^* \) directly. Eve could approximate achieve \( h_x^* \) by using exhaust method: firstly, Eve could set \( |h_x| = 1 \) and exhaust \( \theta_x \) to achieve \( \theta_x = \theta_x^* = \theta_1 + \theta_3 - \theta_2 \) makes \( EN \) smallest, secondly, Eve fixes \( \theta_x = \theta_x^* = \theta_1 + \theta_3 - \theta_2 \) and exhausts \( |h_x| \) to achieve \( |h_x|^2 = \frac{g_2 P_B |h_1 h_2 h_3|}{g_2 P_B + g_3 P_A + N_0} \) makes \( EN \) smallest. From the above exhaust method, we can see that, if \( T \) is long enough and the exhaust step length is small enough, Eve could achieve exact \( h_x^* \), because if \( T \) is long enough, the sample variance of the received signal at Eve will be almost equal to the real variance of the received signal, and if the exhaust step length is small enough, Eve could achieve the exact \( h_x^* \) obviously. In the remainder of this letter, we think the exact \( h_x^* \) can be achieved by Eve.

To ease expression, we define \( M \) as:
\[
M = \frac{P^2_2 g_2 g_3}{g_2 P_B + g_3 P_A + N_0},
\]

By submitting \( h_x^* \) into (8), we get can the SINR of Eve:
\[
SINR_E = \frac{g_3 P_s}{g_3 P_A + g_3 N_0 + N_0 + g_1 g_3 P_B - g_1 M^*}
\]
and the channel capacity is:
\[
C_E = \log_2(1 + SINR_E).
\]

C. Secrecy Capacity and Outage Probability

According to [2], the instantaneous secrecy capacity is:
\[
C_S = [C_B - C_E]^+ = \left[ \log_2 \left( 1 + SINR_B \right) - \log_2 \left( 1 + SINR_E \right) \right]^+.
\]

For expressing clearly, we define \( Y = P_B - M/g_3 \) and \( Z = AP_A + N_0 \). To achieve a expected secrecy rate \( R_s \) (i.e., \( C_S - C_E \geq R_s \)), we require
\[
1 + \frac{g_1 P_s |h_x|^2}{g_2 P_B + g_3 P_A + N_0} \geq 2^{R_s},
\]

After mathematical derivation, we can obtain:
\[
g_1 \geq g_1 L \left( g_2, g_3, R_s \right) = \frac{B + \lambda N^2 - 4AC}{2A},
\]
where \( A = \left( 1 - 2^{R_s} \right) YZ + XP_s, B = \left( 1 - 2^{R_s} \right) (Z^2 + ZN_0 / g_3 + YN_0 + ZP_s) + P_s N_0 / g_3 \) and \( C = \left( 1 - 2^{R_s} \right) (Z N_0 / g_3^2) - 2^{R_s} P_s N_0 \). The above inequation is the condition that the proposed scheme could achieve the target secrecy rate \( R_s \).

We assume the channels are Rayleigh fading then calculate the secrecy outage probability and ergodic secrecy capacity. We write \( h_j \sim C_N(0, \sigma^2) \), \( j \in \{1, 2, 3\} \), the PDF(Probability Density Function) of \( g_j, j \in \{1, 2, 3\} \) is:
\[
P(g_j) = \frac{1}{\sigma^2 \Gamma(1)} e^{-\frac{g_j}{\sigma^2}}, j \in \{1, 2, 3\}.
\]

The secrecy outage probability of the proposed scheme, \( P_{out}(R_s) = P(g_1 < g_1 L \left( g_2, g_3, R_s \right)) \), can be computed by:
\[
P_{out}(R_s) = \int_0^\infty \int_{g_1 L \left( g_2, g_3, R_s \right)}^{\infty} e^{-\frac{g_1}{\sigma^2} e^{-\frac{Z_1}{\sigma^2}} e^{-\frac{Z_2}{\sigma^2}} e^{-\frac{Z_3}{\sigma^2}}} d g_1 d g_2 d g_3,
\]
and the ergodic secrecy capacity is:
\[
E(C_S) = \int_0^\infty \int_{g_1 L \left( g_2, g_3, R_s \right)}^{\infty} e^{-\frac{Z_1}{\sigma^2} e^{-\frac{Z_2}{\sigma^2}} e^{-\frac{Z_3}{\sigma^2}}} \cdot \frac{1}{\sigma^2 \Gamma(1)} d g_1 d g_2 d g_3.
\]
where $C_S(g_1, g_2, g_3)$ is a function of $C_S$ about $g_1$, $g_2$, and $g_3$ given in (17).

IV. NUMERICAL RESULTS

This section presents numerical results to evaluate the performance of the proposed scheme. Fig. 2 shows the numerical results of secrecy capacity with different $P_s$, where $P_A = P_B = 200$, $g_1 = 0.4$, $g_3 = 0.6$, and $\lambda = 0.0001$. Since the channel fading is given and $g_1 < g_3$, the secrecy capacity with no full-duplex and AN is always zero. By contrast, our proposed scheme can achieve positive secrecy capacity and the outage probability is zero. As shown in Fig. 2, the secrecy capacity of the proposed scheme increases as $P_s$ increases. As $g_2$ increases, the achieved secrecy capacity decreases. That is because as $g_2$ increases, Eve could obtain more accurate $n_B$ from (2), then could cancel the noise term $h_3 h_1 \sqrt{P_B n_B}$ in (4) more effectively.

Fig. 3 presents the numerical results of secrecy capacity with different $P_A$ and $P_B$, where $P_s = 200$, $g_1 = 0.4$, $g_2 = 0.7$, $g_3 = 0.6$, $N_0 = 1$ and $\lambda = 0.0001$. As can be seen, as $P_A$ and $P_B$ increase, the secrecy capacity increases. That is because as the power of AN increases, Eve suffers from more interference.

For fading channels, we assume $h_j \sim CN(0, 1), j \in \{1, 2, 3\}$ and the other parameters are same as Fig. 2. Fig. 4 presents the secrecy capacities of the proposed scheme. Note that the ergodic secrecy capacity given by (22) is multiplied with 0.5 because half of the time is used to transmit ANs. As shown in Fig. 4, the proposed scheme achieves much higher secrecy capacity than the scheme without AN, even though in the proposed scheme half of the time is used to transmit random signals. On the other hand, as $\lambda$ increases, the ergodic secrecy capacity decreases, since a larger $\lambda$ corresponds to a severe residual noise caused by $P_A$ in Alan’s full-duplex transmission. It is natural to see that more effective SI cancellation gives higher ergodic secrecy capacity. Also, in Fig. 4 if SI cancellation is bad, and the $P_s$ is small, the proposed scheme is worse than without AN, that is because the ratio of the noise caused by SI to $P_s$ is much bigger, but as long as the $P_s$ is not to small, the proposed scheme is still batter then without AN.

Fig. 5 shows the outage probability, where $P_s = 400$, $P_A = P_B = P_{AN}$ and the other parameters are same as Fig. 3 used. As the target secrecy rate $R_s$ increases, the outage probability increases, but in our scheme, the outage probability is still lower than without AN. Also as the power of AN, $P_{AN}$, increases, the outage probability decreases, that is because the interference caused by AN at Eve become more effective.

V. CONCLUSIONS

We proposed a two-phase transmission scheme to guarantee secrecy information transmission from a full-duplex source to a half-duplex destination. We analyzed the secrecy capacity of the proposed scheme, and presented the conditions for the proposed scheme to achieve positive secrecy capacity. Numerical results showed that the proposed scheme can obtain good performance in terms of both secrecy capacity and outage probability. In this paper, we assume all the ANs are transmitted with the same power. As a future work, we will investigate the power allocation algorithm of ANs and the secrecy performance of the proposed scheme could be further improved.

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