A Novel Covert Communication Method using Ambient Backscatter Communications

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Abstract—This paper introduces a novel solution to enable covert communication in wireless systems by using ambient backscatter communication technology. In the considered system, the original message at the transmitter is first divided into two parts: (i) active transmit message and (ii) backscatter message. Then, the active transmit message is transmitted by using the conventional wireless transmission method while the backscatter message is transmitted by backscattering the active transmit signals via an ambient backscatter tag. As the backscatter tag does not generate any active signals, it is intractable for the adversary to detect the backscatter message. Therefore, secret information, e.g., secret key for decryption, can be carried by the backscattered message, making the adversary unable to decode the original message. Simulation results demonstrate that our proposed solution can help to significantly enhance security protection for communication systems.

Index Terms—Covert communications, ambient backscatter communications, signal detection, and physical layer security.

I. INTRODUCTION

The provisioning of security and privacy has been emerging as a critical issue in future wireless communication networks as a huge amount of private information is transmitted over the wireless environments. Therefore, ensuring security and reliability when sharing information in the presence of adversaries (e.g., eavesdroppers) is extremely important. To secure the data transmissions, traditional approaches mostly focus on encryption at application and transportation layers [1]. However, the encrypted data can be decrypted if the adversary has sufficient computational capacities. In addition, distributing and managing cryptographic keys is a difficult task, especially in decentralized systems with random access and mobility [3]. To overcome these issues, covert communication has been introduced as a promising approach. Specifically, covert communications, as known as low probability of detection communication, aim to guarantee wireless transmissions between two users while minimizing the detection probability of these transmissions at the adversary (e.g., an eavesdropper). Compared with conventional encryption approaches, covert communication offers several advantages. First, covert communication can significantly increase the security level of the wireless system by hiding transmissions from the adversary. Second, covert communication can be easily deployed as an alternative or complementary solution for traditional security methods [3]. Finally, growing computational power of the adversary does not compromise the performance of covert communication as in encryption techniques.

The earliest type of covert communication is steganography in which sensitive information is hidden in innocuous objects such as images or text [2]. An example of steganography for wireless communications is proposed in [4]. In this work, the authors aim to secure the communication of IoT networks by hiding secret information into images. Another kind of covert communication is spread spectrum [2]. Nevertheless, these two approaches require additional data and resources to hide the actual information. Recently, another type of physical-layer covert communication that uses noise to hide sensitive information is proposed. In [5], the authors propose a strategy in which a friendly node (closest to the adversary) generates artificial noise to disrupting the reception at the adversary. However, this solution requires friendly nodes placed near the adversary, which may not be feasible to deploy in practice [6]. To improve the performance of covert communication, the authors in [6] consider the uncertainty of interference when optimizing the system performance. Nevertheless, all these works and others in the literature assume that the adversary is passive and static. Moreover, its location is usually considered to be fixed and known in advance, that might not be feasible in practice.

In this paper, we propose a novel solution to address all the drawbacks of existing studies by deploying an ambient backscatter tag to assist the communication of the transmitter. Specifically, the original message is first divided into two parts: (i) active transmit message and (ii) backscatter message. The active transmit message is sent to the receiver based on active transmission signals from the transmitter. At the same time, the backscatter message is backscattered based on the active transmission signals to the receiver through the ambient backscatter tag. Note that the backscattered signals are different from the active transmission signals as they are backscattered from the active signals. But, they are transmitted at the same time on the same frequency, and thus the adversary is nearly impossible to detect backscatter signals. The backscatter signals can be considered as the pseudo noise in this case. For the sake of security, the backscatter message may contains secret information, e.g., secret key for decryption. In this case, even the adversary can obtain the information from the active signals, it still cannot decode the original message (due to missing the important information sent over the backscatter signals). Simulation results show that our proposed approach not only enables a novel covert communication method, but also provides a flexible framework
in trading-off between communication and security efficiency.

II. SYSTEM MODEL

![System Model Diagram]

Fig. 1: System model.

We consider a wireless network consisting of a transmitter, a receiver, and an ambient backscatter tag in the presence of an adversary (e.g., an eavesdropper), as illustrated in Fig. 1. The adversary aims to detect the transmitted signals and then derives the information sent from the transmitter. To deal with this problem, in this work, we propose a novel solution to protect the communication link between the transmitter and receiver. In particular, we first deploy a backscatter tag near the transmitter. The tag is equipped with a backscatter circuit and connected with the transmitter through a wired channel. When the transmitter wants to send a message to the receiver, it will first split this message into two parts as illustrated in Fig. 2. The first part will be transmitted to the receiver over the conventional communication channel \((d_{mn})\) based on the active RF component of the transmitter. The second part will be simultaneously transmitted to the receiver through the backscatter tag. It is important to note that, when the transmitter transmits signals over the conventional communication channel, the tag will backscatter such signals and transmit the data for the second part to the receiver. As a result, at the same time, we can transmit two data streams (one is over the conventional channel and another one is over a hidden channel, i.e., backscatter channel) to the receiver. It is also worth mentioning that the backscatter rate is lower than the active transmission rate. Thus, the size of the second part is usually smaller than the first part. As the backscatter tag does not generate any active signals, it is intractable for the adversary to detect the backscattered signals. As a result, the adversary may not be able to derive the original message, thereby securing the communication between the transmitter and the receiver.

Details of splitting the original message are illustrated in Fig. 2. In particular, we randomly take a number of bits from the original message to construct the backscatter message with a step of \(K\) symbols. The rest of the original message is conveyed to the receiver by the transmitter through active transmissions. The size of the active transmit message is usually larger than that of the backscatter message. In this letter, we assume that the backscatter frame has the size of \(I\) bits in which \(P\) bits are reserved for pilot signals and \(S\) bits are used for dividing information (i.e., the first bit’s ID and the step \(K\)) with \((P+S) < I\). In this way, we can significantly improve the security level of the system in the presence of the adversary as the eavesdropper cannot derive the backscatter message as well as the divided information.

III. CHANNEL MODEL

To successfully decode the backscattered signals from the tag at the receiver, the backscatter rate must be lower than the sampling rate of the transmitter’s signals \([7], [8]\). Thus, we assume that the backscatter rate is \(N\) times lower than the sampling rate of the transmitter’s signals. In particular, the tag will backscatter each information bit over \(N\) transmitter symbols. Denote \(y_{mn}\) as the \(n\)-th received sample at the \(m\)-th antenna of the receiver. In our system, \(y_{mn}\) is the combination of the backscattered signals from the tag, the direct link signals from the transmitter, and noise. We have

\[
y_{mn} = d_{mn} + b_{mn} + \sigma_{mn},
\]

where \(d_{mn}\) is the transmitter’s direct link signals, \(b_{mn}\) presents the backscattered signals, and \(\sigma_{mn}\) is the CSCG noise with zero mean and unit variance, i.e., \(\sigma_{mn} \sim CN(0, 1)\).

A. Direct Link

We denote \(s_{tn}\) as the transmitter’s signals at time instant \(n\). It is worth noting that the tag considers the transmitter’s signals as ambient signals to backscatter information to the receiver. Thus, we assume that \(s_{tn}\) is random and unknown at the backscatter tag. Without loss of generality, \(s_{tn}\) is assumed to follow the standard CSCG distribution, i.e., \(s_{tn} \sim CN(0, 1)\).

The direct link signals from the transmitter received at the \(m\)-th antenna of the receiver can be expressed as

\[
d_{mn} = f_{mn} \sqrt{P_{tr}} s_{tn},
\]

where \(f_{mn}\) is the Rayleigh fading \([10]\) from the transmitter to the receiver. Without loss of generality, let \(\mathbb{E}[[f_{mn}^2]] = 1\). \(P_{tr}\) is the average received power of the direct link from the transmitter to the receiver. \(P_{tr}\) can be calculated as follows:

\[
P_{tr} = \frac{k P_t G_t G_r}{L_r \nu},
\]

where \(k = \left(\frac{4}{\lambda^2}\right)^2\) with wavelength \(\lambda\). \(P_t\) denotes the transmitter’s transmit power. \(G_t\) and \(G_r\) are the antenna gains of the transmitter and the receiver, respectively. \(L_r\) is the transmitter-to-receiver distance. \(\nu\) is the path loss exponent.

B. Backscatter Link

The transmitter’s signals received at the backscatter tag can be expressed as

\[
c_n = g_r \sqrt{P_b} s_{tn},
\]

where \(g_r\) denotes the Rayleigh fading from the transmitter to the tag with \(\mathbb{E}[[g_r^2]] = 1\). \(P_b\) is the average power from the transmitter received at the tag. We have

\[
P_b = \frac{k P_t G_t G_b}{L_b \nu},
\]

where \(G_b\) is the antenna gain at the tag and \(L_b\) is the transmitter-to-tag distance. The tag backscatter information...
to the receiver by reflecting or absorbing the transmitter’s signals. We denote the reflecting state as \( e = 1 \) and the absorbing state as \( e = 0 \). As mentioned, each information bit will be backscattered over \( N \) transmitter symbols. Thus, state \( e \) remains unchanged during this period. We then can express the backscattered signals as \( s_{t,n} = \gamma c_n e \), where \( \gamma \) is the reflection coefficient. The backscattered signals received at the \( m \)-th antenna of the receiver can be expressed as follows:

\[
b_{mn} = f_{bm} \sqrt{\frac{G_b G_r \kappa}{L_e \delta}} \gamma e \left( g_r \sqrt{P_{Br} s_{t,n}} \right) e^{j \alpha_{dm} L_r s_{t,n}^\delta},
\]

\[
f_{bm} = f_{bm} \left( g_r \sqrt{\frac{\kappa |\gamma|^2 P_{Br} L_r L_p}{L_b L_r \delta}} s_{t,n} \right),
\]

where \( L_e \) is the tag-to-receiver distance, \( \delta \) denotes the path loss exponent, and \( f_{bm} \) is the Rayleigh fading of the tag-to-receiver link with \( \mathbb{E}[|f_{bm}|^2] = 1 \). Denote \( \alpha_r = \frac{\kappa |\gamma|^2 G_r G_a}{L_b L_r \delta} \), we can rewrite (4) as:

\[
\eta_{mn} = f_{bm} e \left( g_r \sqrt{\frac{\kappa |\gamma|^2 P_{Br} L_r L_p}{L_b L_r \delta}} s_{t,n} \right).
\]

C. Received Signals at the Receiver

The received signals at the \( m \)-th antenna can be expressed as:

\[
y_{mn} = f_{rm} \sqrt{P_{Ir} s_{t,n}} + f_{bm} e \left( g_r \sqrt{\frac{\kappa |\gamma|^2 P_{Br} L_r L_p}{L_b L_r \delta}} s_{t,n} \right) + \sigma_{mn}.
\]

where \( \alpha_{dt} \approx \sigma \), as the signal-to-noise ratio (SNR) of the transmitter-to-receiver link, \( \alpha_{dt} \approx \alpha_r P_{Ir} \) as the SNR of the backscatter link, \( \text{transmitter-tag-receiver link} \), we have:

\[
y_{mn} = f_{rm} \sqrt{P_{Ir} s_{t,n}} + f_{bm} e \left( g_r \sqrt{\frac{\kappa |\gamma|^2 P_{Br} L_r L_p}{L_b L_r \delta}} s_{t,n} \right) + \sigma_{mn}.
\]

Denote \( f_r = \left[ f_{r1}, \ldots, f_{rm}, \ldots, f_{rM} \right] \) as the backscatter link, \( f_b = \left[ f_{b1}, \ldots, f_{bm}, \ldots, f_{bM} \right] \), and \( \sigma_n = \left[ \sigma_{n1}, \ldots, \sigma_{mn}, \ldots, \sigma_{nM} \right] \), we can express the backscattered signals as:

\[
y_n = \left[ y_{1n}, \ldots, y_{mn}, \ldots, y_{Nn} \right] \in \mathbb{C}^N \approx \mathbb{R}^N \sim \mathbb{R}^N \sim \mathbb{R}^N \sim \mathbb{R}^N \sim \mathbb{R}^N \sim \mathbb{R}^N.
\]

In this paper, each backscatter frame \( b \) is assumed to contain \( I \) information bits, i.e., \( b = [b^{(i)}, \ldots, b^{(i)}] \). The channel is assumed to be invariant during one backscatter frame. Each information bit is encoded before backscattering with the modulo-2 operation, i.e., \( e^{(i)} = e^{(i-1)} \oplus b^{(i)} \), where \( \oplus \) is the modulo-2 operator and \( e = \left[ e^{(1)}, \ldots, e^{(i)}, \ldots, e^{(I)} \right] \) denotes the encoded symbol vector with \( e^{(0)} = 1 \). As mentioned, \( e^{(i)} \) will be backscattered on the receiver over \( N \) transmitter symbols. Thus, the received signals at the receiver during the \( i \)-th backscatter symbol period can be expressed by:

\[
y_n^{(i)} = f_r \sqrt{\alpha_{dt}} s_{t,n} + f_b e^{(i)} \left( g_r \sqrt{\alpha_{bt}} s_{t,n} \right) + \sigma_n^{(i)},
\]

where \( n = 1, 2, \ldots, N \) and \( i = 1, 2, \ldots, I \).

IV. DECODING BACKSCATTERED INFORMATION AT THE RECEIVER WITH MAXIMUM LIKELIHOOD DETECTOR

A. Maximum Likelihood Detector

The backscattered signals received at the receiver are usually weaker than those of the direct link signals from the transmitter. As such, it is very challenging to detect the backscattered signals. In this section, we provide details on decoding the backscattered signals by using the optimal ML detector.

When the tag backscatters bits “0”, i.e., \( e^{(i)} = 0 \), the received signals contain only the direct link signals. Differently, when the tag backscatters bits “1”, i.e., \( e^{(i)} = 1 \), the received signals are the combination of the direct link signals and the backscattered signals. As such, we first obtain the channel statistical covariance matrices corresponding to these cases as follows [9], [10]:

\[
K = (b_1 + b_2)(b_1 + b_3)^I + I_M, K_0 = b_1 b_3^I + I_M, \quad \text{where} \quad b_1 = f_r \sqrt{\alpha_{dt}}, b_2 = f_r \sqrt{\alpha_{bt}}, I_M = \text{the} \times M \text{identity matrix,}
\]

and \( \text{The conjugate transpose of matrix} \ A \), \( K_0 \) are the channel statistical covariance matrices when backscattering bits “1” and bits “0”, respectively. Given received signals \( y_n^{(i)} \) and backscatter symbol \( e^{(i)} \), the conditional probability density functions (PDFs) corresponding to \( e^{(i)} = 0 \) and \( e^{(i)} = 1 \) can be expressed as follows:

\[
p(y_n^{(i)} | e^{(i)} = 0) = \frac{1}{\pi^M |K_0|} e^{-y_n^{(i)} K_0^{-1} y_n^{(i)}},
\]

\[
p(y_n^{(i)} | e^{(i)} = 1) = \frac{1}{\pi^M |K_1|} e^{-y_n^{(i)} K_1^{-1} y_n^{(i)}}.
\]

From (8), the likelihood functions of \( Y^{(i)} = [y_1^{(i)}, \ldots, y_n^{(i)}, \ldots, y_N^{(i)}]^T \) can be expressed as follows [9], [10]:

\[
\mathcal{L}(Y^{(i)} | e^{(i)} = 0) = \prod_{n=1}^{N} \frac{1}{\pi^M |K_0|} e^{-y_n^{(i)} K_0^{-1} y_n^{(i)}},
\]

\[
\mathcal{L}(Y^{(i)} | e^{(i)} = 1) = \prod_{n=1}^{N} \frac{1}{\pi^M |K_1|} e^{-y_n^{(i)} K_1^{-1} y_n^{(i)}}.
\]

Then, we can derive the ML criterion (i.e., hypothesis) for backscattered symbol \( e^{(i)} \) as follows [9], [10]:

\[
\hat{e}^{(i)} = \begin{cases} 
0, & \mathcal{L}(Y^{(i)} | e^{(i)} = 0) > \mathcal{L}(Y^{(i)} | e^{(i)} = 1), \\
1, & \mathcal{L}(Y^{(i)} | e^{(i)} = 0) < \mathcal{L}(Y^{(i)} | e^{(i)} = 1), 
\end{cases}
\]

where \( \hat{e}^{(i)} \) is the decision result of \( e^{(i)} \). Using the logarithm operations, we have

\[
\hat{e}^{(i)} = \begin{cases} 
0, & \sum_{n=1}^{N} y_n^{(i) H} (K_0^{-1} - K_1^{-1}) y_n^{(i)} < N \ln \frac{|K_1|}{|K_0|}, \\
1, & \sum_{n=1}^{N} y_n^{(i) H} (K_0^{-1} - K_1^{-1}) y_n^{(i)} > N \ln \frac{|K_1|}{|K_0|}.
\end{cases}
\]

Based on \( \hat{e}^{(i)} \) we can derive the backscattered bit \( b^{(i)} \) and then recover the original bit \( b^{(i)} \).

B. SUCCESSFUL DECODED INFORMATION AT THE RECEIVER

Let \( \epsilon_d \) and \( \epsilon_b \) denote the bit error ratio (BER) of the signals transmitted over the direct link and backscatter link, respectively. Given \( \epsilon_d \) and \( \epsilon_b \), the number of successful decoded bits at the receiver, denoted as \( \hat{T} \), can be expressed as follows:

\[
\hat{T} = T(1 - \eta)(1 - \epsilon_d) + \eta(1 - \epsilon_b),
\]

where \( T \) is the total number of bits transmitted from the transmitter, \( \eta \in [0, 1] \) is the splitting ratio between backscatter bits and direct-transmission bits. For example, given \( T = 1,000 \) bits, \( \eta = 0.1 \) splits 1,000 bits into 900 bits and 100 bits to be transmitted over direct link and backscatter link, respectively. Here, \( \hat{T} \) is calculated as a sum of the
Successful decoded bits transmitted over the backscatter link, i.e., \( T \) decoded bits distribution with zero mean and unit variance \([10]\). We set

\[ T = \alpha N \]

where \( \alpha = \frac{1}{M} \) is varied from 1dB to 9dB and observe the BER of the system as well as the number of the successful received at the receiver can be enhanced. In Fig. 3(b), we observe that with \( \eta = 0 \), i.e., \( \epsilon_b = \epsilon_d \), the BER of the backscatter link is much higher than that of the direct link, i.e., \( \epsilon_b \gg \epsilon_d \). The results express the trade-off between the number of bits that can be hidden from the adversary and the number of successful received bits at the receiver. Given the above, our proposed solution is very promising in dealing with the adversary for the following reasons. First, backscatter communications are easy to implement in practice. Second, due to a new way of communication, it will make more difficulties for attacks in decoding the actual information.

VI. SIMULATION RESULTS

A. Parameter Setting

In our simulations, the Rayleigh fading follows the CSCG distribution with zero mean and unit variance \([10]\). We set \( N = 5 \) and \( \epsilon = 100 \). It is worth mentioning that the average signal-to-noise ratios of the direct link from the transmitter \( \alpha_{dl} \) to the receiver greatly depend on the environment parameters such as path loss, distances between the transmitter to the receiver, transmit power, and antenna gain. Therefore, we vary \( \alpha_{dl} \) from 1dB to 9dB in the simulations to evaluate the system performance in different scenarios. As mentioned, the backscatter link is usually weak. As such, we set \( \alpha_i = -10\)dB. Moreover, to evaluate the performance of our framework in different settings, \( M \) is varied from 1 to 10. To obtain robust and reliable results, all simulations in this section are averaged over \( 10^6 \) Monte Carlo runs.

B. Performance Evaluation

In Fig. 3 we vary \( \alpha_{dl} \) from 1dB to 9dB and observe the BER of the system as well as the number of the successful decoded bits. It is noted that we only consider the BER of the signals transmitted over the backscatter link, i.e., \( \epsilon_d \), since the value of \( \epsilon_d \) is approximate to 0. It can be observed from Fig. 3(a) that the BER performance increases with \( \alpha_{dl} \). The reason is that the backscattered signals received at the receiver can be improved when the tag backscatters strong signals from the transmitter. It can be also observed that the BER decreases with the number of antennas at the receiver. The reason is that with multiple antennas, the receiver can leverage the antenna gain to eliminate the effects of the fading and the direct link interference. As a result, the backscattered signals received at the receiver can be enhanced. In Fig. 3(b), we consider the scenario with \( M = 10 \) antennas at the receiver and vary the splitting ratio \( \eta \) to evaluate the effectiveness of the backscatter tag. We consider that the total number of \( T = 1,000 \) bits are transmitted over a period of time (e.g., a time frame). It is noted that the dashed lines express the number of successful decoded bits of the backscatter link (bs. link) and the solid lines express the total number of bits successfully transmitted from the transmitter. The dashed lines, in other words, illustrate the amount of covert information that can be securely transmitted without being detected by the eavesdropper. It can be observed that with \( \eta = 0 \), i.e., no information is transmitted over the backscatter link, the successful decoded signals achieve approximately 1,000 bits with the BER \( \epsilon_d \approx 0 \). When \( \eta \) increases to 0.1 and 0.4, the gap between the respective solid lines and dash lines shrinks. The reason is that the more signals are transmitted over the backscatter link, the more signals are lost because the BER of the backscatter link is much higher than that of the direct link, i.e., \( \epsilon_b \gg \epsilon_d \). The results express the trade-off between the number of bits that can be hidden from the adversary and the number of successful received bits at the receiver.

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