Energy-Efficient Covert Communications for Bistatic Backscatter Systems

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Abstract—In this paper, we consider covert communications for bistatic backscatter systems, where a tag transmits information passively to a reader by reflecting incident carrier signals with artificial noise (AN) generated from a dedicated carrier emitter (CE) under the supervision of a warden. By exploiting the channel uncertainty introduced by CE, we analytically derive the warden’s minimum sum of error probabilities to evaluate communication covertness. We find that communication covertness can be improved by reducing the tag’s reflection coefficient, but is not affected by the CE’s transmit power. Therefore, in order to achieve energy-efficient design, we optimize the tag’s reflection coefficient to minimize the CE’s transmit power under the constraints of communication covertness and reliability. Our analysis shows that the minimum CE’s transmit power can be further reduced with a minor loss of the achievable covert rate.

Index Terms—Bistatic backscatter, covert communication, reflection coefficient, transmit power minimization.

I. INTRODUCTION

Due to low cost and energy consumption, the backscatter technology has been supposed as a promising solution to meet the requirements of Internet of Things (IoT) [1]. A widely used application of this paradigm is the radio frequency identification (RFID) system, where an interrogator reads information from a device containing a tag by sending incident carrier signals and then collecting the modulated backscatter signals from the tag. However, this typical monostatic RFID system is difficult to meet higher application demands caused by the round-trip loss of the interrogator [2]. In contrast to the typical monostatic configuration, the bistatic backscatter replaces the interrogator by a dedicated carrier emitter (CE) and a dedicated reader. As such, bistatic backscatter systems can obtain higher transmission rate and better reliability [3].

Although the rapid extension of backscatter systems in IoT has greatly facilitated our daily life, the broadcast nature of backscatter systems poses a severe threat to security and privacy. Due to the size, cost and power constraints, the conventional cryptography is not suitable for such a paradigm. In some existing works, this problem was relieved by lightweight cryptography [4], tag selection [5], injecting artificial noise (AN) [6] and multi-antenna techniques [7]. However, to guarantee a strong security or privacy, it is not sufficient to protect the transmission content as aforementioned works, but also required to hide the transmission behavior itself, i.e., covert communications [8].

Following the pioneering work [9], the authors in [10] proved that covert communications can be achieved by randomly changing the transmit power of AN generated from a jammer. To the best of our knowledge, there is only one work about covert communications in backscatter system (i.e., [11]). Specifically, the authors in [11] extended above approach to a monostatic backscatter system, where a full-duplex interrogator continuously transmits AN with variable transmit power to confuse a warden’s detection on a tag’s backscatter communication behavior. Unfortunately, the way in the preliminary work has the following significant limitations when facing bistatic backscatter systems. 1) The influence of fading channels is overlooked. 2) Varying the transmit power across time slots is costly and energy-guzzling. 3) The tag’s reflection coefficient should be further optimized.

In this paper, we propose a new framework of energy-efficient covert communications for bistatic backscatter systems, where a CE generated carrier signals with AN to support a tag’s backscatter communication and confuse a warden’s detection on the communication behavior. The energy-efficient design is achieved by minimizing the CE’s transmit power, which is the main energy consumption for bistatic backscatter systems. The contributions of this paper are summarized as follows:

- We analytically derive the warden’s minimum sum of error probabilities and the backscatter communication outage probability to evaluate communication covertness and reliability, respectively. It is interesting to find that communication covertness is not affected by the CE’s transmit power, but can be improved by reducing the tag’s reflection coefficient. Therefore, there exists a maximum tag’s reflection coefficient for a given covertness requirement. On this basis, we can further determine the minimum CE’s transmit power to meet a reliability requirement.

- In order to achieve energy-efficient covert communications for bistatic backscatter systems, we formulate the tag’s reflection coefficient optimization problem to minimize the CE’s transmit power under the constraints of communication covertness and reliability. Then, we acquire the exact optimal tag’s reflection coefficient and find that the minimum CE’s transmit power can be further reduced at a small cost of the achievable covert rate.

II. SYSTEM MODEL

A. Communications and Adopted Assumptions

As shown in Fig. 1, we consider a bistatic backscatter system consisting of a tag (Tag), a reader (Reader) and a CE, where Tag has a backscatter circuit such that it can transmit information passively to Reader by reflecting incident signals or keep silent by absorbing incident signals. In addition, CE generates the incident signals with AN based on a secret key pre-distributed between CE and Reader, which can be eliminated at Reader by the successive interference cancellation [12], [13]. In this context, a warden (Willie) is present as an adversary, trying to detect whether there is a transmission from Tag to Reader. Each node is equipped with a single antenna. We note that each time slot contains...
From a conservative point of view, we consider that Willie still knows the instantaneous CSI of $f_{tw}$, as well as the statistical CSI of $h_{cw}$ and $h_{ct}$. It is noted that varying the transmit power across time slots is costly and hard to achieve [21]. Thus, we assume that CE’s transmit power is fixed and public, i.e., $P$ is known to Willie. In addition, we consider that Willie can acquire the synchronization information about backscatter communication, which is normally operated based on time slots. Thus, we focus on Willie’s detection within a time slot in this work, when the backscatter communication either exists or not [22], [23]. In other words, Willie adopts a binary hypothesis detection based on observation vector $y_w$ within a time slot, in which Tag absorbs incident carrier signals in the null hypothesis $H_0$ while it reflects incident carrier signals in the alternative hypothesis $H_1$. It is noted that Willie can adopt a sequential change-point detection as an alternative choice in the case without the synchronization information [24], which serves as future work for further examination.

In this context, the composite received signal at Willie of observation vector $y_w$ for the $i$-th channel use is given by

$$y_w(i) = \begin{cases} \sqrt{P}h_{cw}c(i)+n_w(i), & H_0, \\ f_{tw}x(i)+\sqrt{P}h_{cw}c(i)+n_w(i), & H_1, \end{cases}$$

(4)

where $n_w(i)$ is the AWGN at Willie with zero mean and the variance of $\sigma_w^2$.

Consider equal prior probability of $H_0$ and $H_1$. In this case, the binary hypothesis detection performance of Willie can be measured by the sum of error probabilities [25], which is defined as

$$\xi = P_{FA} + P_{MD},$$

(5)

where $P_{FA} = \Pr(D_1|H_0)$ is the false alarm probability and $P_{MD} = \Pr(D_0|H_1)$ is the miss detection probability, while $D_1$ and $D_0$ are the binary decisions that infer whether Tag reflects or not, respectively.

As per the Neyman-Pearson criterion, the optimal approach for Willie to minimize his detection error is to adopt the likelihood ratio test (LRT) [25]. With the aid of the Neyman-Fisher factorization theorem [26] and the likelihood ratio order concept [27], the LRT in the considered system can be proved to be equivalent to the test of the average received power within a time slot, which is given by

$$P_w = \frac{D_1}{D_0} \tau,$$

(6)

where $P_w = \frac{1}{n} \sum_{i=1}^{n} |y_w(i)|^2$ is the average received power at Willie within a time slot, and $\tau$ is Willie’s detection threshold. Since $c(i)$ is circularly Gaussian with unit variance, as per (4), we have $y_w(i) \sim \mathcal{CN}(0, P|h_{cw}|^2 + \sigma_w^2)$ under $H_0$. As such, the corresponding $P_w$ converges to the variance of $y_w(i)$ when $n$ is sufficiently large, due to the strong law of large numbers [28]. Similar properties hold under $H_1$. Thus, as $n \to \infty$, $P_w$ is given by

$$P_w = \begin{cases} P|h_{cw}|^2 + \sigma_w^2, & H_0, \\ \beta P|h_{ct}|^2 g_{cw} + P|h_{cw}|^2 + \sigma_w^2, & H_1, \end{cases}$$

(7)

### III. PERFORMANCE OF COVERT COMMUNICATIONS

In this section, we first analyze the Willie’s minimum sum of error probabilities to evaluate communication covertness. Then, we derive the backscatter communication outage probability to evaluate communication reliability.

#### A. Minimum Sum of Error Probabilities

Following the analysis in Section II, $P_{FA}$ and $P_{MD}$ are given in the following lemma.

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**Fig. 1. Covert communications model for bistatic backscatter systems.**

$n$ channel uses, i.e., $n$ symbols are transmitted within each time slot, and the channel gain is assumed unchanged within one time slot but varies independently from one time slot to another.

The channels of Tag-Reader and Tag-Willie, CE-Tag, CE-Reader and CE-Willie are denoted by $f_{tr}$, $f_{tw}$, $h_{ct}$, $h_{cr}$ and $h_{cw}$, respectively. In this work, to guarantee communication reliability, we consider that Tag is deployed close to Reader and hence, the LoS path of the channel is not blocked. Under this consideration, $f_{tr}$ is assumed to follow Rician fading and is consisted of a deterministic LoS component and a Rayleigh fading component. From a worst case perspective, we also consider that Willie is close to Tag and thus $f_{tw}$ follows the same model.

As such, $f_{tr}$ and $f_{tw}$ can be represented as

$$f_{ij} = \sqrt{\frac{\kappa}{1 + \kappa}} f_{ij}^{\text{LoS}} + \sqrt{\frac{1}{1 + \kappa}} f_{ij}^{\text{NLoS}},$$

(1)

where $ij \in \{tr, tw\}$, $\kappa$ is the Rician factor, $f_{ij}^{\text{LoS}}$ and $f_{ij}^{\text{NLoS}}$ represent the deterministic LoS component and the Rayleigh fading component, respectively [14]. In addition, the channel gain of Tag-Reader or Tag-Willie can be denoted as $g_{ij} = |f_{ij}|^2$. In contrast to Willie, we consider that CE can be with a relatively long distance away from other terminals, thus $h_{ct}$, $h_{cr}$ and $h_{cw}$ are assumed to follow Rayleigh fading and the corresponding average channel gains are $1/k_{pq}$, where $pq \in \{ct, cr, cw\}$ [15].

When Tag reflects the incident carrier signal within a time slot, the backscatter signal is given by

$$x(i) = \sqrt{P}h_{ct}c(i),$$

(2)

where $i = 1, 2, \ldots, n$ is the index of each channel use, $\beta$ is Tag’s reflection coefficient and $P$ is CE’s transmit power; $c(i)$ and $\phi$, the $i$-th elements of vector $s$ and $\phi$, are the signals generated at Tag and CE for the $i$-th channel use, respectively, satisfying $\mathbb{E}[s(i)s^*(i)] = 1$ and $\mathbb{E}[c(i)c^*(i)] = 1$. As such, the received signal at Reader is given by

$$y_r(i) = \sqrt{\phi}h_{cr}c(i) + f_{tw}x(i) + n_r(i),$$

(3)

where $n_r(i)$ is the additive white Gaussian noise (AWGN) at Reader with zero mean and the variance of $\sigma_r^2$, $\phi = 0$ means the perfect interference cancellation [16]. In addition, $c(i)$ and $x(i)$ are assumed to be circularly symmetric complex Gaussian (CSCG) random variables [17], [18].

### B. Detection of Covert Communications

In the considered system, CE, Tag and Reader work cooperatively to hide the communication behavior between Tag and Reader from Willie. As such, we assume that Reader can acquire the estimated channel state information (CSI) based on secure feedback links, whereas it is impossible for Willie to obtain the estimated CSI without such feedback links [19], [20]. Therefore, Willie has its uncertainty on the instantaneous CSI of $h_{cw}$ and $h_{ct}$.
Lemma 1: When \( n \to \infty \), the false alarm probability and miss detection probability at Willie for arbitrary detection threshold \( \tau \) are given by

\[
P_{FA} = \begin{cases} 1, & \tau \leq \sigma_w^2, \\ \exp \left\{-\lambda_{cw} \varphi \right\}, & \tau > \sigma_w^2, \end{cases}
\]

(8)

\[
P_{MD} = \begin{cases} 0, & \lambda_{cw} \exp(-\lambda_{cw} \varphi) - \lambda_0 \exp(-\lambda_{cw} \varphi), \\ 1 - \lambda_{cw} \exp(-\lambda_{cw} \varphi), & \tau > \sigma_w^2, \end{cases}
\]

(9)

respectively, where \( \varphi = \frac{\tau - \sigma_w^2}{\lambda_{cw}} \) and \( \lambda_0 = \frac{\lambda_{cw}}{\gamma_0} \).

Proof: The detailed proof is presented in Appendix A.

From a worst case perspective, we consider that Willie has the ability to adopt an optimal detection threshold to achieve the minimum sum of error probabilities, which is used to measure communication covertness [29], [30]. In the considered system, the minimum sum of error probabilities is given in the following theorem.

Theorem 1: Willie’s optimal detection threshold is given by

\[
\tau^* = \left\{ \begin{array}{ll}
\frac{\ln \lambda_{cw} - \ln \lambda_0}{\lambda_{cw} + \lambda_0}, & \lambda_0 \neq \lambda_{cw}, \\
\frac{1}{\lambda_{cw} + \lambda_0}, & \lambda_0 = \lambda_{cw},
\end{array} \right. 
\]

(10)

and the corresponding minimum sum of error probabilities is

\[
\xi^* = \left\{ \begin{array}{ll}
1 - \exp \left(\frac{\ln \lambda_0}{\lambda_{cw} + \lambda_0}\right), & \theta 
eq 1, \\
1 - \exp (-1), & \theta = 1,
\end{array} \right.
\]

(11)

where \( \theta = \frac{\lambda_{cw}}{\lambda_{cw} + \lambda_0} \).

Proof: The detailed proof is presented in Appendix B.

Intuitively, increasing CE’s transmit power leads to the weakens of communication covertness due to the increase of the information leakage power. However, we find that \( P \) has no impact on \( \xi^* \) as per (11), which means that CE's transmit power in the considered system does not affect communication covertness. It is due to the fact that increasing CE’s transmit power not only expands the information leakage power at Willie but also enhances the received interference power at Willie, and thus their impacts on communication covertness are counteracted.

B. Backscatter Communication Outage Probability

As per (3), the signal-to-interference-plus-noise ratio (SINR) at Reader is given by

\[
\gamma_r = \frac{\beta h_{cr}^2 g_{cr} \gamma_0}{\phi h_{cr}^2 \gamma_0 + 1},
\]

(12)

where \( \gamma_0 = P/\sigma_t^2 \) is the transmit signal-to-noise ratio (SNR). We assume \( R_0 \) is the predetermined transmission rate from Tag to Reader [31], [32]. Due to the random nature of \( h_{ct} \) and \( h_{cr} \), an outage event of backscatter communication occurs when \( R < R_0 \), where \( R = \log_2(1 + \gamma_r) \) denotes the achievable transmission rate from Tag to Reader [33]–[35]. As such, the expression of the backscatter communication outage probability is derived in the following theorem.

Theorem 2: The backscatter communication outage probability is given by

\[
P_{out} = \frac{\lambda_{cr}}{\phi \lambda_{cr} + \lambda_{cr}} \exp \left( \frac{\mu \lambda_{cr}}{\gamma_0} \right),
\]

(13)

where \( \mu = \frac{2 R_0 - 1}{3 h_{cr}} \).

Proof: Based on the definition of the backscatter communication outage probability, we have

\[
P_{out} = \Pr \left\{ \beta h_{ct}^2 g_{cr} \gamma_0 < 2 R_0 - 1 \right\} = \int_{0}^{\infty} f_{\gamma_r}^* (x) \int_{0}^{\infty} f_{\gamma_c}^* (x) dx dy.
\]

(14)

Then, (13) can be acquired by solving the above integral.

IV. ACHIEVING ENERGY-EFFICIENT COVERT COMMUNICATIONS

From (11) and (13), we find that Tag’s reflection coefficient can simultaneously affect communication covertness and reliability. Since energy consumption is a key concerning factor in bistatic backscatter systems, in this section we optimize Tag’s reflection coefficient to minimize CE’s transmit power under the constraints of communication covertness and reliability.

Specifically, we formulate CE’s transmit power minimization problem under the constraints of the backscatter communication outage probability and the minimum sum of error probabilities, which is given by

\[
(P1): \minimize \quad P \\
\text{s.t.} \quad P_{out} \leq \delta, \\
\xi^* \geq 1 - \epsilon, \\
0 \leq \beta \leq 1, \\
0 < P \leq P_{max},
\]

where the constraint (15b) is to ensure communication reliability, where \( \delta \in [0, 1] \) denotes a tolerance of the backscatter communication outage probability. The constraint (15c) is to ensure communication covertness, where \( \epsilon \in [0, 1] \) denotes a covertness requirement. In addition, (15d) is the constraint of Tag’s reflection coefficient and (15e) is the constraint of CE’s transmit power, where \( P_{max} \) is the maximum CE’s transmit power.

Theorem 3: The achievable covert rate of the optimization problem (15) is \( R_{max} \), which is the solution to

\[
f(R) = \frac{\lambda_{cr}}{\phi \mu \lambda_{cr} + \lambda_{cr}} \exp \left( -\frac{\mu \lambda_{cr}}{\gamma_0} \right) = 1 - \delta,
\]

(16)

where \( \mu_0 = \frac{2 R_0 - 1}{h_{cr}}, \beta_0 = \min(1, \frac{\lambda_{cr}}{\phi h_{cr} \gamma_0 + 1}), \) and \( (1 - \epsilon) \lambda_{cr} + \lambda_{cr} \phi \mu_0 \).

When \( R_0 \leq R_{max} \) holds, the optimal Tag’s reflection coefficient and optimal CE’s transmit power in the optimization problem (15) are given by

\[
\beta^* = \beta_0,
\]

(17)

\[
P^* = \frac{\lambda_{cr}}{\ln (\lambda_{cr}) - \ln ((1 - \delta) \lambda_{cr} + \lambda_{cr} \phi \mu_0)),
\]

(18)

respectively.

Proof: From (13), we find that \( P_{out} \) is a monotonically decreasing function of \( P \). Then, we determine the monotonicity of \( P_{out} \) with respect to (w.r.t.) \( \mu = \frac{2 R_0 - 1}{3 h_{cr}} \). The corresponding first derivative is given by

\[
\frac{\partial P_{out}}{\partial \mu} = \left( \frac{\lambda_{cr} \mu \lambda_{cr} + \lambda_{cr} + \phi \gamma_0}{(\phi \mu \lambda_{cr} + \lambda_{cr})^2} \right) \exp \left( -\frac{\mu \lambda_{cr}}{\gamma_0} \right) \geq 0.
\]

(19)
Since $\mu$ is inversely proportional to $\beta$, $P_{\text{out}}$ is a monotonically decreasing function of $\beta$. Based on the analysis in Section III-A, there is no impact of $P$ on $\xi^*$. In addition, $P$ and $\beta$ are independent. Thus, $P$ can be reduced with the increase of $\beta$ to meet the constraint (15b). Then, the optimization problem (23) can be rewritten as follows,

\[
\begin{align*}
\text{(P2.1)} & \text{: minimize } P \\
& \text{s.t. } P_{\text{out}}(\beta = \beta_0) \leq \delta, \quad 0 < P \leq P_{\text{max}},
\end{align*}
\]

(20a)

(20b)

(20c)

where $\beta_0$ is the solution to the following optimization problem.

\[
\begin{align*}
\text{(P2.2)} & \text{: maximize } \beta \\
& \text{s.t. } \xi^* \geq 1 - \epsilon, \quad 0 \leq \beta \leq 1.
\end{align*}
\]

(21a)

(21b)

(21c)

We note that $P$ and $R_0$ are independent in $P_{\text{out}}(\beta = \beta_0)$. Thus, we can analyze the monotonicity of $P_{\text{out}}(\beta = \beta_0)$ w.r.t. $P$ and $R_0$, separately. As per (13), $P_{\text{out}}(\beta = \beta_0)$ is still a monotonically decreasing function of $P$. As per (19) and the proportional relation between $\mu$ and $R_0$, $P_{\text{out}}(\beta = \beta_0)$ is a monotonically increasing function of $R_0$. As such, we can obtain $R_{\text{max}}$ by solving $P_{\text{out}}(R, \beta = \beta_0, P = P_{\text{max}}) = \delta$, which is given by (16). When $R_0 > R_{\text{max}}$, there is no feasible region in the optimization problem (20).

When $R_0 \leq R_{\text{max}}$ holds, we then derive the optimal solutions of the optimization problems (21) and (20), respectively. Firstly, we need to determine the monotonicity of $\xi^*$ w.r.t. $\theta = \frac{1}{\mu_{\text{out}}^\beta}$. The corresponding first derivative is given by

\[
\frac{\partial \xi^*}{\partial \theta} = \left(\frac{-\ln \theta - 1}{(\theta - 1)^2}\right) \theta^{-\theta}. \tag{22}
\]

Since $\theta \in (0, +\infty)$, the monotonicity of $\xi^*$ w.r.t. $\theta$ only depends on $\nu = \theta - \ln \theta - 1$. We further derive the first derivative of $\nu$ w.r.t. $\theta$ as

\[
\frac{\partial \nu}{\partial \theta} = 1 - \frac{1}{\theta}. \tag{23}
\]

We find that $\nu$ is a monotonically decreasing function of $\theta$ for $\theta \in [0, 1]$, while $\nu$ is a monotonically increasing function of $\theta$ for $\theta \in (1, +\infty)$. It means that the minimum value of $\nu(\theta) = 0$ for $\theta \in (0, +\infty)$, hence $\frac{\partial \xi^*}{\partial \nu} \geq 0$ for $\theta \in (0, +\infty)$. Since $\theta$ is inversely proportional to $\beta$, $\xi^*$ is a monotonically decreasing function of $\beta$. Then, the optimal value of $\beta$ in the optimization problem (21) is the solution to $\xi^*(\beta) = 1 - \epsilon$, which is given by (17). Finally, we can acquire the optimal value of $P^*$ in the optimization problem (20) by solving $P_{\text{out}}(P^*, \beta = \beta_0) = \delta$, which is given by (18).

As per (22) and (23), we find that $\xi^*$ is a monotonically decreasing function of $\beta$. As such, relaxing the constraint (15c) leads to a larger feasible region of $\beta$, which raises $R_{\text{max}}$. Furthermore, as per (18), we rewrite the expression of $P^*$ as

\[
P^* = \frac{\lambda_{\text{ct}} \sigma_b^2 \mu_0}{U}, \tag{24}
\]

where $U = \ln(\frac{1}{\nu}) - \ln(1 + \Theta \mu_0)$, $\Theta = \frac{1}{\kappa^*}$. Then, we derive the first derivative of $P^*$ w.r.t. $\mu_0$ as

\[
\frac{\partial P^*}{\partial \mu_0} = \frac{\lambda_{\text{ct}} \sigma_b^2}{U^2} \left(\frac{\Theta \mu_0}{\Theta \mu_0 + 1} + U\right) > 0. \tag{25}
\]

As such, $P^*$ is a monotonically increasing function of $\mu_0$. Since $\mu_0$ monotonically increases with $R_0$, $P^*$ is a monotonically increasing function of $R_0$. Furthermore, the second derivative of $P^*$ w.r.t. $\mu_0$ is given by

\[
\frac{\partial^2 P^*}{\partial (\mu_0)^2} = \lambda_{\text{ct}} \sigma_b^2 \left(\frac{\Theta \mu_0}{(1 + \Theta \mu_0)^2} U\right). \tag{26}
\]

After some algebra calculations, we find that $\frac{\partial^2 P^*}{\partial (\mu_0)^2} > 0$ when $\Theta < 1 - 1/\exp(2)$. It means that the slope of $P^*$ to $\mu_0$ increases as $\mu_0$ increases if $\Theta < 1 - 1/\exp(2)$. As a result, $P^*$ increases faster w.r.t. $R_0$ when $R_0$ is larger and $\Theta < 1 - 1/\exp(2)$. Since $1 - 1/\exp(2) \approx 0.86$ and a reasonable outage probability target should have $\Theta < 0.86$, $R_0$ should be chosen with care to reduce the CE’s transmit power. As we will show in Section V, setting $R_0$ slightly lower than the achievable covert rate can significantly reduce the CE’s transmit power.

It is noted that when performing the analysis above, we have used the Shannon formula to characterize the channel capacity. In practice, since finite-alphabet modulated signals are adopted, the achievable transmission rate is lower than the Shannon rate. To more accurately reflect the covertness and power consumption in such circumstances, a scale coefficient can be introduced to the Shannon formula to approximate the actual achievable transmission rate, i.e., $R = \rho \log_2(1 + \gamma_t)$ [36], [37]. With this approximation, the analysis above can be readily applied.

V. NUMERICAL RESULTS

We consider large scale channel fading model as $|f_{ij}^{\text{LoS}}|^2 = G_{ij} K d_{ij}^{-\alpha_{\text{LoS}}}$ and $1/\lambda_{ab} = G_{ab} K d_{ab}^{-\alpha_{\text{NLoS}}}$, where $ab \in \{ij, pq\}$, $|f_{ij}^{\text{LoS}}| \sim \exp(\lambda_{ij})$, $K = \lambda/4\pi$ is a constant dependent upon the carrier wavelength $\lambda$, $\alpha_{\text{LoS}}$ is the path loss exponent of LoS link, $\alpha_{\text{NLoS}}$ is the path loss exponent of non-LoS link, $G_{ab}$ and $d_{ab}$ are the combined transmitter-receiver antenna gain and the distance between node $a$ and node $b$, respectively. In our simulations, we set the carrier frequency as 915 MHz, the interference cancellation coefficient as $\phi = 0.01$, the maximum transmit power as $P_{\text{max}} = 10$ dB, $\alpha_{\text{LoS}} = 2$, $\alpha_{\text{NLoS}} = 3.5$, and $d_{ct} = d_{cr} = d_{cw} = 100$ m.

In Fig. 2, we plot the CE’s transmit power $P$ versus the minimum sum of error probabilities $\xi^*$ with $\beta = 1$ and $d_{cw} = 3$ m.

![Fig. 2. The CE’s transmit power $P$ versus the minimum sum of error probabilities $\xi^*$ with $\beta = 1$ and $d_{cw} = 3$ m.](image-url)
communication covertness decreases as $\kappa$ increases. This is due to the fact the average Rician fading channel gain increases as the proportion of the LoS components increases, which leads to a larger information leakage power.

In Fig. 3, we plot Tag’s reflection coefficient $\beta$ versus the exposed probability $p_e = 1 - \xi^*$ with $\kappa = 30$ dB. We observe that $\xi^*$ decreases as $\beta$ increases. This observation demonstrates that there exists a maximum Tag’s reflection coefficient for a given covertness requirement. Meanwhile, we find that $\xi^*$ decreases as $d_{tw}$ decreases. Thus, when Willie is closer to Tag, Tag’s reflection coefficient should be set smaller to guarantee communication covertness.

In Fig. 4, we plot the predetermined transmission rate $R_0$ (bps/Hz) versus the minimum CE’s transmit power $P^\star$ with $d_{tr} = d_{tw} = 3$ m, $\kappa = 30$ dB and $\delta = 0.1$. We note that $\xi^*$ decreases as $d_{tw}$ decreases. Thus, when Willie is closer to Tag, Tag’s reflection coefficient should be set smaller to guarantee communication covertness.

In this paper, we investigated covert communications for bistatic backscatter systems with the help of the channel uncertainty introduced by CE. To evaluate communication covertness, we derived Willie’s minimum sum of error probabilities. Surprisingly, we found that CE’s transmit power did not affect communication covertness. Then, we optimized Tag’s reflection coefficient to achieve the target of energy-efficient covert communications, i.e., minimizing the CE’s transmit power under the constraints of communication covertness and reliability. Furthermore, our analysis demonstrated that setting the predetermined transmission rate slightly below the achievable covert rate was an effective way to save considerable energy consumption in covert communications for bistatic backscatter systems.

**APPENDIX A**

**PROOF OF LEMMA 1**

As per (6) and (7), the false alarm probability is given by

$$P_{FA} = \begin{cases} 1, & \tau \leq \sigma_w^2, \\ \Pr \left( \left| h_{cw} \right|^2 > \varphi \right), & \tau > \sigma_w^2, \end{cases}$$

(27)

where the probability density function (pdf) of $\left| h_{cw} \right|^2$ is $f_{\left| h_{cw} \right|^2}(x) = \lambda_{cw} \exp(-\lambda_{cw} x)$ if $x \geq 0$. By substituting the pdf of $\left| h_{cw} \right|^2$ into (27), we derive the result of (8).

Similarly, the miss detection probability is given by

$$P_{MD} = \begin{cases} 0, & \tau \leq \sigma_w^2, \\ \Pr \left( \beta g_{tw} \left| h_{ct} \right|^2 + \left| h_{cw} \right|^2 < \varphi \right), & \tau > \sigma_w^2. \end{cases}$$

(28)

In order to derive the closed-form expression of (28), we denote $Z = \beta \left| h_{ct} \right|^2 g_{tw}^2 + \left| h_{cw} \right|^2$. We note that $Z$ follows generalized chi-squared distribution with 4 degrees of freedom. Based on the general pdf of generalized chi-squared distribution given in [38], we derive the pdf of $Z$ as follows

$$f_Z(z) = \begin{cases} \frac{\lambda_{cw}^2}{\lambda_{cw}\lambda_0} \exp\left(-\lambda_{cw} z - \lambda_{cw} z\right), & \lambda_{cw} \neq \lambda_0, \\ \lambda_{cw}^2 z \exp\left(-\lambda_{cw} z\right), & \lambda_0 = \lambda_{cw}. \end{cases}$$

(29)

By substituting the (29) into (28), we derive the result of (9).

**APPENDIX B**

**PROOF OF THEOREM 1**

In order to determine the optimal detection threshold corresponding to the minimum sum of error probabilities, we need to tackle the optimization problem as follows

$$\min_{\tau} \xi,$$

(30)

where $\xi$ is the sum of error probabilities, which is given by

$$\xi = \begin{cases} 1, & \tau \leq \sigma_w^2, \\ 1 - \lambda_{cw} \exp(-\lambda_{cw} z) - \lambda_{cw} \exp(-\lambda_{cw} z), & \tau > \sigma_w^2 \text{ and } \lambda_0 \neq \lambda_{cw}, \\ 1 - \lambda_{cw} \varphi \exp(-\lambda_{cw} z), & \tau > \sigma_w^2 \text{ and } \lambda_0 = \lambda_{cw}. \end{cases}$$

(31)

Then, we analyze three possible cases in (31), separately.

**Case I:** $\tau \leq \sigma_w^2$

Here, $\xi = 1$ cannot be minimized by $\tau$.

**Case II:** $\tau > \sigma_w^2$ and $\lambda_0 \neq \lambda_{cw}$

Based on the first derivative of $\xi$ w.r.t. $\tau$, we conclude that the optimal value of $\tau$ is $\tau^\star = \frac{\ln\lambda_{cw} - \ln\lambda_0}{\lambda_{cw} - \lambda_0} P + \sigma_w^2$.

**Case III:** $\tau > \sigma_w^2$ and $\lambda_0 = \lambda_{cw}$
Similarly, based on the first derivative of $\xi$ w.r.t. $\tau$, the optimal value of $\tau$ is $\tau^* = \frac{1}{\tau_{\text{opt}}} P + \sigma_w^2$.

The corresponding $\xi^*$ for the choice of optimal threshold, i.e., $\tau^*$, can be found by using the appropriate expressions of $\xi$ in (31), hence concluding the proof.

REFERENCES


