Delay-Constrained Covert Communications with A Full-Duplex Receiver

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Abstract—In this work, we consider delay-constrained covert communications with the aid of a full-duplex (FD) receiver. Without delay constraints, it has been shown that the transmit power of artificial noise (AN) at the FD receiver should be random in order to enhance covert communications. In this work, we show that transmitting AN with a fixed power indeed improve covert communications with delay constraints, since in a limited time period the warden cannot exactly learn its received power. This explicitly shows one benefit of considering practical delay constraints in the context of covert communications. We analyze the optimal transmit power of AN for either fixed or globally optimized transmit power of covert information, based on which we also determine the specific condition under which transmitting AN by the FD receiver can aid covert communications and a larger transmit power of AN always leads to better covert communication performance.

Index Terms—Covert communication, full-duplex, artificial noise, delay constraint, transmit power.

I. INTRODUCTION

Covert communication aims to enable a communication between two users while guaranteeing a negligible detection probability of this communication at a warden. It shields the very existence of the transmission and thus mitigates the threat of discovering the presence of the transmitter or communication in wireless networks [1]–[3]. As such, it achieves a higher-level security relative to the conventional information-theoretic secrecy technologies, which only protect the content of transmitted messages. In addition, covert communication can address privacy issues in wireless networks. For example, it can aid to hide a transmitter's location information in Internet of Things (e.g., vehicular networks), where the exposure of location information is a critical privacy concern [4]. As such, covert communication is emerging as a cutting-edge research topic in the context of wireless communication security.

Limits of covert communications over additive white gaussian noise (AWGN) channels was established in [5], which is widely known as the square root scaling law. Covert communications in the context of relay networks was examined in [1], showing that a relay can opportunistically transmit its own messages to the destination covertly on top of forwarding

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a source's message. Multi-hop covert communication over an arbitrary network in an AWGN environment and in the presence of multiple collaborating wardens was investigated in [6]. Covert communication over the non-fading and the fading channel with a Poisson field of interferers was studied in [7].

The aforementioned works studied covert communications under the assumption of asymptotically infinite number of channel uses (i.e., $n \to \infty$). However, in many application scenarios (e.g., connected vehicles, smart meters, or automated factories etc.), it requires the transmission of short data packets (e.g., about 100 channel uses), which need to be delivered with stringent requirements in terms of latency [8]. Against this background, the effect of finite blocklength (i.e., with short delay constraints) on covert communications was examined in [9], which showed that using random transmit power of covert information can further enhance the delay-constrained covert communications. Although [9] examined the impact of finite blocklengh on covert communications, they did not consider sending AN by a full-duplex (FD) receiver in the context of covert communications. Meanwhile, [2] discussed the effect of AN transmitted by a FD receiver in covert communications with infinite blocklength. As shown in [2], the transmit power of AN should be random in order to enable the transmitted AN to benefit the covert communications with infinite blocklength. This is due to the fact that as the number of channel uses approaches infinite, the warden Willie will know the AN power and can cancel its impact by adjusting the detection threshold accordingly [2]. In this work, we mainly tackle whether transmitting AN with a fixed power can improve the performance of delay-constrained covert communications (with finite blocklength) and what are the conditions for achieving the benefit of AN in the context of delay-constrained covert communications.

II. SYSTEM MODEL

A. Adopted Assumptions

We consider a scenario, where a transmitter (Alice) tries to send messages to a FD receiver (Bob) covertly under the supervision of a warden (Willie), who is detecting whether Alice is communicating with Bob or not. Alice and Willie are assumed to be equipped with a single antenna each, while besides the single receiving antenna, Bob uses an additional antenna to transmit AN to potentially create uncertainty at Willie.

In this work, we assume that the transmit power at Alice denoted by P_a is fixed for all the available channel uses. As

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per TR 38.802 in 3GPP, the transmission over one channel use only takes roughly 0.01ms [10]. As such, in this work we do not consider different transmit power levels for different channel uses, since varying transmit power within such a short time is not practical.

B. Detection at Willie

Considering AWGN channels, this work focuses on delayconstrained covert communications, where the number of channel uses N for covert communications is finite and we assume that Alice transmits signals over all the available channel uses [9]. The received signal at Willie in the i-th channel use is given by

$$\mathbf{y}_w[i] = \begin{cases} \sqrt{P_b} \mathbf{v}_b[i] + \mathbf{n}_w[i], & \mathcal{H}_0, \\ \sqrt{P_a} \mathbf{x}_a[i] + \sqrt{P_b} \mathbf{v}_b[i] + \mathbf{n}_w[i], & \mathcal{H}_1, \end{cases}$$
(1)

where P_a and P_b are transmit power at Alice and Bob, respectively, \mathbf{x}_a is the signal transmitted by Alice satisfying $\mathbb{E}[\mathbf{x}_a[i]\mathbf{x}_a^{\dagger}[i]] = 1, i = 1, 2, \dots, N, \mathbf{v}_b$ is the AN transmitted by Bob satisfying $\mathbb{E}[\mathbf{v}_b[i]\mathbf{v}_b^{\dagger}[i]] = 1$, and $\mathbf{n}_w[i]$ is the AWGN at Willie subject to $\mathbf{n}_w[i] \sim \mathcal{CN}(0, \sigma_w^2)$. The null hypothesis \mathcal{H}_0 means that Alice does not transmit, while \mathcal{H}_1 means that Alice transmits messages to Bob.

Based on the received signal in (1), Willie makes a binary decision on whether the received signal comes from \mathcal{H}_0 or \mathcal{H}_1 . \mathcal{D}_1 and \mathcal{D}_0 represent the binary decisions that Alice transmits or not, respectively. In general, the false alarm $\mathbb{P}_{FA} \triangleq \mathbb{P}(\mathcal{D}_1|\mathcal{H}_0)$ and missed detection $\mathbb{P}_{MD} \triangleq \mathbb{P}(\mathcal{D}_0|\mathcal{H}_1)$ are adopted as the metrics to measure the detection performance at Willie. Accordingly, the optimal test that minimizes the detection error probability $\xi = \mathbb{P}_{FA} + \mathbb{P}_{MD}$ is the likelihood ratio test with $\lambda = 1$ as the threshold as following

$$\frac{\mathbb{P}_1 \triangleq \prod_{i=1}^N f(\mathbf{y}_w[i]|\mathcal{H}_1)}{\mathbb{P}_0 \triangleq \prod_{i=1}^N f(\mathbf{y}_w[i]|\mathcal{H}_0)} \underset{\mathcal{D}_0}{\gtrless} 1.$$
(2)

We have a lower bound on ξ according to the Pinsker's inequality [5], which provides us with a theoretical basis for the following analysis and is given by

$$\xi \ge 1 - \sqrt{\frac{1}{2}\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)},\tag{3}$$

where $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)$ is the Kullback-Leibler (KL) divergence from \mathbb{P}_0 to \mathbb{P}_1 , \mathbb{P}_0 and \mathbb{P}_1 are the likelihood functions under \mathcal{H}_0 and \mathcal{H}_1 as per (2), respectively. In this work, we adopt this lower bound as the detection performance metric, since the expressions of \mathbb{P}_{FA} and \mathbb{P}_{MD} are too complicated to be used for further analysis, which is mentioned in [9]. Specifically, $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)$ is given by [9]

$$\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) = N \left[\ln(1 + \gamma_w) - \frac{\gamma_w}{1 + \gamma_w} \right], \tag{4}$$

where $\gamma_w = P_a/(\sigma_w^2 + P_b)$ is the signal-to-interference-plusnoise ratio (SINR) at Willie. A small value of $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)$ means that the distance between \mathbb{P}_1 and \mathbb{P}_0 is small, which normally leads to a high detection error probability ξ at Willie. In covert communications, we normally have $\xi \geq 1 - \epsilon$ as the covertness requirement, where ϵ is an arbitrarily small value. Following (3), in this work we adopt $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) \leq 2\epsilon^2$ as the covertness requirement.

III. DELAY-CONSTRAINED COVERT COMMUNICATIONS

In this section, we first determine the optimal transmit power of AN (i.e., P_b) at Bob for a fixed feasible P_a . Then, we jointly optimize P_a and P_b in order to maximize the performance of covert communications.

A. Optimization of P_b for a Fixed and Feasible P_a

For a given transmission rate R, the effective throughput η can be represented as $\eta = NR(1-\delta)$ [9], where δ is the decoding error probability. For a fixed R, this decoding error probability is given by [9],

$$\delta = Q \left(\frac{\sqrt{N}(1+\gamma_b) \left(\ln \left(1 + \gamma_b \right) + \frac{1}{2} \ln N - R \ln 2 \right)}{\sqrt{\gamma_b(\gamma_b + 2)}} \right), \tag{5}$$

where γ_b is the SINR at Bob given by

$$\gamma_b = \frac{P_a}{\sigma_b^2 + hP_b},\tag{6}$$

where σ_h^2 is the variance of AWGN noise at Bob and $0 \le$ $h \leq 1$ is the self-interference cancellation coefficient at Bob corresponding to different cancellation levels [11], [12]. We denote the entire item in the Q function bracket as ζ . Then, the first derivative of ζ with respect to γ_b is given by

$$\zeta'|_{\gamma_b} = \frac{\sqrt{N} \left[\gamma_b^2 + 2\gamma_b + R \ln 2 - \ln \left(1 + \gamma_b \right) - \frac{1}{2} \ln N \right]}{\left[\gamma_b (2 + \gamma_b) \right]^{3/2}}.$$
 (7)

The ultimate goal of our design in covert communications is to maximize the effective throughput η subject to the covertness constraint and the corresponding optimization problem can be written as

(P1)
$$\max_{P_b} \eta$$
 (8a)
s. t. $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) \le 2\epsilon^2$, (8b)

s. t.
$$\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) \le 2\epsilon^2$$
, (8b)

$$P_b \le P_b^{\text{max}},$$
 (8c)

where P_h^{\max} is the maximum transmit power of AN at the fullduplex Bob. The feasible condition of and the corresponding solution to P1 are presented in the following theorem. Note that the following theorem is valid on the condition that γ_w is a small value.

Theorem 1: For given P_b^{\max} and ϵ , the feasible condition of **P1** is $P_a \leq P_a^u$, where

$$P_a^u = \frac{\left(P_b^{\text{max}} + \sigma_w^2\right)\left(\epsilon^2 + \sqrt{\epsilon^4 + 2\epsilon^2 N}\right)}{N}.$$
 (9)

With $P_a \leq P_a^u$, the solution to P1 (i.e., the optimal P_b) can be approximately achieved as

$$P_b^* = \frac{P_a N}{\epsilon^2 + \sqrt{\epsilon^4 + 2\epsilon^2 N}} - \sigma_w^2, \tag{10}$$

and the maximum effective throughput η^* to P1 for a given R can be approximately achieved as

$$\eta^* = NR(1 - \delta^*),\tag{11}$$

where δ^* is obtained by substituting P_b^* into (5).

Proof: We first note that, as per (4), the KL divergence $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)$ in the constraint (8b) monotonically increases with P_a , while it monotonically decreases with P_b . As such, considering the constraint (8c), the feasible condition of the the optimization problem $\mathbf{P1}$ is in terms of the maximum value of P_a and this maximum P_a is achieved by solving $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) = 2\epsilon^2$ with $P_b = P_b^{\max}$.

In order to derive the explicit expressions for the maximum P_a and the optimal P_b , we next detail how to solve $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) = 2\epsilon^2$ as a function of γ_w . Following (4), $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) = 2\epsilon^2$ can be written as

$$N\left[\ln\left(1+\gamma_w\right) - \frac{\gamma_w}{1+\gamma_w}\right] = 2\epsilon^2. \tag{12}$$

We note that, in covert communications, γ_w is normally very small in order to ensure a high detection error probability at Willie. When γ_w is very small, we can adopt the approximation $\ln{(1+x)} \sim x$ in (12). Applying this, we have

$$\gamma_w^2 - \frac{2\epsilon^2}{N} \gamma_w - \frac{2\epsilon^2}{N} = 0. \tag{13}$$

We note that (13) is a quadratic equation and there exists two real solutions to it, since the discriminant is given by $4\epsilon^4(1+2N)/N^2>0$. In addition, the product of these two real solutions is $-\frac{2\epsilon^2}{N}<0$, which means that there is always a positive solution to (13). Specifically, the two real solutions are given by

$$\gamma_w^{\pm} = \frac{\epsilon^2 \pm \sqrt{\epsilon^4 + 2\epsilon^2 N}}{N}.$$
 (14)

We note that $\gamma_w^+>0$ and $\gamma_w^-<0$ due to $\sqrt{\epsilon^4+2\epsilon^2N}>\epsilon^2$ in (14), which confirms that we always have a positive solution to (13), which is $\gamma_w^+=\frac{\epsilon^2+\sqrt{\epsilon^4+2\epsilon^2N}}{N}$. Substituting γ_w^+ into $\gamma_w=P_a/(\sigma_w^2+P_b)$ and setting $P_b=P_b^{\max}$, we obtain the maximum P_a as given in (9)

Substituting γ_w^+ into $\gamma_w = P_a/(\sigma_w^2 + P_b)$ and setting $P_b = P_b^{\max}$, we obtain the maximum P_a as given in (9) and $P_a \leq P_a^u$ is the feasible condition of **P1**. Under this feasible condition, we next derive the optimal P_b for a given feasible P_a . To this end, we first note that η monotonically decreases with P_b , since as proved in [13], η is a monotonically increasing function of γ_b for any valid transmission rate R. We also note that $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)$ in the constraint (8b) monotonically decreases with P_b . As such, the optimal P_b is the one that satisfies $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) = 2\epsilon^2$. Applying the approximation used to obtain (13) and noting $\gamma_w = P_a/(\sigma_w^2 + P_b)$, we obtain the optimal P_b as given in (10). Finally, substituting P_b^* into the definition of η , we achieve the maximum effective throughput as given in (11). This completes the proof of Theorem 1.

B. Joint Optimization of P_a and P_b

In this subsection, we jointly optimize P_a and P_b in order to maximize the throughput at Bob in the considered scenario. Specifically, the focused optimization problem is given by

(P2)
$$\max_{P_a, P_b} \quad \eta$$
s. t.
$$\mathcal{D}(\mathbb{P}_0 || \mathbb{P}_1) \le 2\epsilon^2,$$

$$P_b < P_b^{\max},$$
(15)

where we do not consider a maximum transmit power constraint at Alice, since in covert communications Alice's transmit power is normally low. The solution to this optimization problem **P2** is given in the following theorem.

Theorem 2: For any given covertness constraint ϵ and transmission rate R, the maximum η to $\mathbf{P2}$ is $\eta^* = NR(1 - \delta^*)$. The corresponding optimal transmit power P_a and AN power P_b in δ^* can be approximately achieved as

$$P_a^* = \frac{\epsilon^2 + \sqrt{\epsilon^4 + 2\epsilon^2 N}}{N} (\sigma_w^2 + P_b^*), \tag{16}$$

$$P_b^* = \begin{cases} P_b^{\text{max}}, & \sigma_b^2 \ge h\sigma_w^2, \\ 0, & \sigma_b^2 < h\sigma_w^2. \end{cases}$$
 (17)

Proof: As per (4) and (6), both $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)$ and η monotonically increase with P_a . As such, the equality in the constraint $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) \leq 2\epsilon^2$ is always guaranteed by an optimal P_a for any fixed P_b . We can prove this by contradiction. We first suppose that the optimal P_a , denoted by P_a^{\ddagger} , is achieved with $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) < 2\epsilon^2$. Since both the KL divergence $\mathcal{D}(P_0||P_1)$ in the constraint $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) \leq 2\epsilon^2$ and the objective function η monotonically increase with P_a , we can still increase P_a^{\ddagger} in order to improve η while still ensuring $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) \leq 2\epsilon^2$. This contradicts the supposition that P_a^{\ddagger} is the optimal P_a . Therefore, $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1) = 2\epsilon^2$ is guaranteed by the actually optimal P_a (denoted by P_a^{\dagger}) for any given P_b . This leads to the fact that the optimal P_a can be expressed as a function of P_b , which can be achieved following a similar approach as used in the proof of Theorem 1. This expression is the same as (16), where we have to replace P_a^* and P_b^* with P_a^{\dagger} and P_b , respectively. Since η is a monotonically increasing function of γ_b for given transmission rate R and N [13], we next tackle the monotonicity of $N\gamma_b$ to clarify the monotonicity of η . Then, substituting P_a^{\dagger} into $N\gamma_b$, we have

$$(N\gamma_b)^{\dagger} = \frac{(\epsilon^2 + \sqrt{\epsilon^4 + 2\epsilon^2 N})(\sigma_w^2 + P_b)}{\sigma_h^2 + hP_b}.$$
 (18)

We derive the first derivative of $(N\gamma_b)^{\dagger}$ with respect to P_b as

$$\frac{\partial (N\gamma_b)^{\dagger}}{\partial P_b} = \frac{(\epsilon^2 + \sqrt{\epsilon^4 + 2\epsilon^2 N})(\sigma_b^2 - h\sigma_w^2)}{(\sigma_b^2 + hP_b)^2}.$$
 (19)

As per (19), we can see that the sign of it is solely determined by the term $(\sigma_b^2 - h\sigma_w^2)$. Then we have the following two cases: Case 1: When $\sigma_b^2 < h\sigma_w^2$, $(N\gamma_b)^\dagger$ (and the corresponding

Case 1: When $\sigma_b^2 < h\sigma_w^2$, $(N\gamma_b)^{\dagger}$ (and the corresponding η) decreases with P_b and then we have $P_b^* = 0$ to maximize the effective throughput η .

Case 2: When $\sigma_b^2 \geq h\sigma_w^2$, $(N\gamma_b)^\dagger$ (and the corresponding η) increases with P_b and then we have $P_b^* = P_b^{\max}$ to maximize the effective throughput η .

Considering these two cases above, we achieve the desired results in (16) and (17), which completes the proof.

Note that $\mathcal{D}(\mathbb{P}_1||\mathbb{P}_0)$ is also a widely used metric in covert communications. Similar to the analysis of $\mathcal{D}(\mathbb{P}_0||\mathbb{P}_1)$, we can still draw the conclusions that when $\sigma_b^2 \geq h\sigma_w^2$, $P_b^* = P_b^{\max}$, and when $\sigma_b^2 < h\sigma_w^2$, $P_b^* = 0$.

This result first indicates that transmitting AN with fixed power can still benefit the delay-constrained covert communications, when we have $P_b^* = P_b^{\max}$. Considering the self-interference at the full-duplex receiver, it is also reasonable to

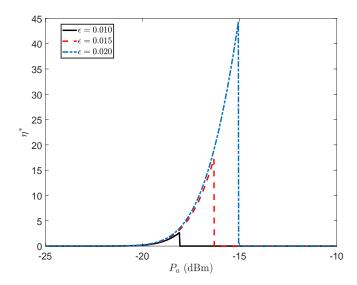


Fig. 1. η^* versus P_a , where $P_b^{\max}=1$ dBm, $\sigma_b^2=\sigma_w^2=0$ dBm, R=3.4, N=100, and h=0.01.

observe $P_b^*=0$ in a specific case, which demonstrates that transmitting AN does not help covert communications under this case.

IV. SIMULATIONS AND DISCUSSIONS

In Fig. 1, we plot the maximum η , i.e., η^* , achieved by the optimal P_b for a fixed P_a with different values of ϵ . We first observe that η^* increases with P_a before all the turning points, which can be explained by substituting P_b^* given in (10) into (6) and noting $\sigma_b^2 > h\sigma_w^2$ in the settings of Fig. 1. We note that the covertness constraint cannot be satisfied when P_a exceeds a certain value due to the maximum transmit power constraint at Bob, which can explain why we have $\eta^* = 0$ when P_a is larger than some specific values. Furthermore, we observe that an increase in ϵ relaxes the covertness constraint and leads to a higher value of η^* . In Fig. 2, we plot the maximum η , i.e., η^{\dagger} , achieved by the optimal P_a and P_b with different values of σ_w^2 and h. The two blue curves are obtained in Case 1, i.e., when $\sigma_b^2 < h\sigma_w^2$, where as confirmed we have $P_b^* = 0$. Meanwhile, the two red curves are achieved for Case 2, i.e., when $\sigma_b^2 \ge$ $h\sigma_w^2$, where we have $P_b^*=P_b^{\max}$. In this figure, we also observe that, for the red curves, the η^{\dagger} decreases with h, which shows that a more efficient self-interference cancellation can improve covert communications. Finally, we observe that, for the red curves, η^{\dagger} tends to an upper bound as P_b increases.

V. CONCLUSIONS

In this work, we studied covert communications with delay constraints over AWGN channels with the aid of a FD receiver. Specifically, we examined the possibility and strategy of using the FD receiver to transmit AN in order to shield the covert transmission from Alice to Bob. Our examination shows that a fixed AN transmit power can improve delay-constrained overt communications. In addition, the conducted analysis indicates that in most practical scenarios the transmit power of AN should be as large as possible when Alice's transmit power can be jointly optimized. We also determine the specific condition

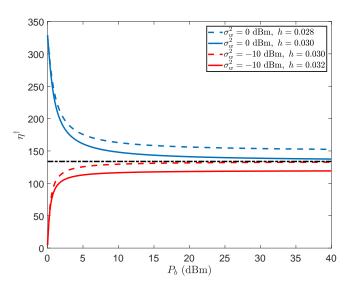


Fig. 2. η^{\dagger} versus P_b , where $\sigma_b^2=-20$ dBm, $\epsilon=0.01,\,R=3.4,\,N=100,$ and $P_b^{\rm max}=40$ dBm.

under which transmitting AN by the FD receiver can aid covert communications and a larger transmit power of AN always leads to better covert communication performance.

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