

Low-Probability-of-Detection Downlink Transmission in Time Division Multiple Access

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Abstract—This paper studies low-probability-of-detection downlink transmission in a time division multiple access (TDMA) system. A source sends public messages to scheduled users over orthogonal time slots while embedding covert messages for a hidden destination. Since the scheduled users may detect the covert signal, the transmit power, public/covert power split, and time-slot power proportions should be designed under detection error probability (DEP) constraints. Based on the downlink TDMA covert communications framework in our previous work, we summarize the received-signal model, DEP characterization, and sum covert rate maximization problem. We further provide new numerical results that evaluate how the average sum covert rate changes with the position of the covert destination node and the scheduled user nodes. The results show that the optimized TDMA design is especially beneficial when the covert destination is close to the source or when the public users are far enough to weaken their detection capability.

Index Terms—Covert communications, low probability of detection (LPD), physical layer security (PLS), time division multiple access (TDMA), detection error probability (DEP)

I. INTRODUCTION

The broadcast nature of wireless channels makes wireless transmissions vulnerable to interception and monitoring. Conventional cryptographic techniques protect the contents of a message, but they usually require key management and may impose computational overhead on resource-limited devices [1]. Physical-layer security (PLS) complements cryptography by exploiting channel randomness, noise, fading, and interference to improve wireless confidentiality [2]. Covert communications, also referred to as low-probability-of-detection communications, pursue a stronger goal: the communications itself should remain undetectable to a warden [3], [4]. This property is attractive for privacy-sensitive Internet-of-Things, surveillance, and mission-critical wireless applications.

A large body of covert communications research has considered point-to-point, relay, intelligent reflecting surface (IRS), non-orthogonal multiple access (NOMA), and rate-splitting multiple access (RSMA) settings [5]–[10]. By contrast, downlink TDMA systems have received less attention even though TDMA is a simple and widely used multiple-access technique.

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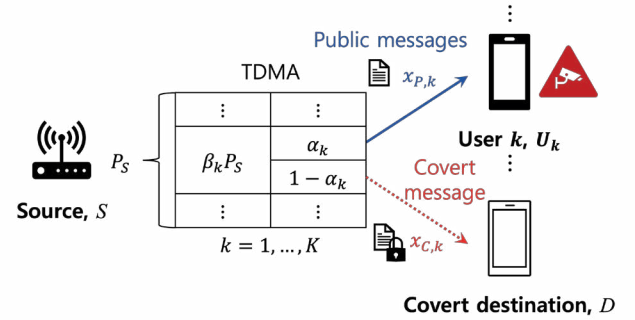


Fig. 1: System model

In a TDMA downlink, each scheduled user receives a public message during its time slot and may regard any additional signal component as suspicious. Therefore, when a source embeds a covert message for a hidden destination, the public users themselves become potential detectors.

Our previous work [11] investigated this downlink TDMA covert communications problem, derived the detection error probability (DEP) under bounded noise uncertainty, and formulated a sum covert rate maximization problem with public-rate and covertness constraints. This paper follows the same system model and focuses on additional performance observations. In particular, we add numerical evaluations for the average sum covert rate as a function of (i) the source-to-covert-destination distance and (ii) the source-to-user distance. These results provide geometric insight into when TDMA-based covert downlink transmission becomes more or less favorable.

II. SYSTEM MODEL

As shown in Fig. 1, a source node S serves K users U_k , $k = 1, \dots, K$, over a unit-duration TDMA block. The k -th time slot is used for the public message $x_{P,k}$ intended for U_k , while the source also embeds a covert message $x_{C,k}$ for the covert destination D . Let P_S denote the total transmit power, β_k the power proportion assigned to the k -th slot, and α_k the fraction of $\beta_k P_S$ used for the public message. Thus, the public and covert components in the k -th slot use $\alpha_k \beta_k P_S$ and $(1 - \alpha_k) \beta_k P_S$, respectively, with $\sum_{k=1}^K \beta_k = 1$.

A. Received Signals

Let $g_k = |h_{SU_k}|^2$ and $g_D = |h_{SD}|^2$ be the channel power gains from S to U_k and D , respectively. Assuming $x_{P,k}, x_{C,k} \sim \mathcal{CN}(0, 1)$, the signal received at user U_k is

$$y_{U_k} = h_{SU_k} \sqrt{\beta_k P_S} (\sqrt{\alpha_k} x_{P,k} + \sqrt{1 - \alpha_k} x_{C,k}) + z_{U_k}, \quad (1)$$

where $z_{U_k} \sim \mathcal{CN}(0, \sigma_{U_k}^2)$. Treating the covert component as interference at U_k , the achievable public rate is

$$\bar{r}_{P,k} = \frac{1}{K} \log_2 \left(1 + \frac{g_k \beta_k P_S \alpha_k}{g_k \beta_k P_S (1 - \alpha_k) + \sigma_{U_k}^2} \right). \quad (2)$$

The received signal at D is

$$y_{D,k} = h_{SD} \sqrt{\beta_k P_S} (\sqrt{\alpha_k} x_{P,k} + \sqrt{1 - \alpha_k} x_{C,k}) + z_{D,k}, \quad (3)$$

where $z_{D,k} \sim \mathcal{CN}(0, \sigma_{D,k}^2)$. The public message rate at D is obtained by replacing g_k and $\sigma_{U_k}^2$ in (2) with g_D and $\sigma_{D,k}^2$. After decoding and canceling $x_{P,k}$, D decodes $x_{C,k}$ at

$$\bar{r}_{C,D,k} = \frac{1}{K} \log_2 \left(1 + \frac{g_D \beta_k P_S (1 - \alpha_k)}{\delta g_D \beta_k P_S \alpha_k + \sigma_{D,k}^2} \right), \quad (4)$$

where $\delta \in [0, 1]$ models residual public-message interference after imperfect cancellation [11].

B. DEP

Each user performs radiometer-based detection on the residual signal after subtracting its decoded public-message component. Under the null hypothesis $\mathcal{H}_0$ that no covert message is transmitted and the alternative hypothesis $\mathcal{H}_1$ that a covert message is present, the test statistic with sufficiently many samples becomes

$$\begin{aligned} H_0 : T_k &= \sigma_{U_k}^2, \\ H_1 : T_k &= |h_{SU_k}|^2 \beta_k P_S (1 - \alpha_k) + \sigma_{U_k}^2. \end{aligned} \quad (5)$$

The user compares T_k with a threshold τ_k , which gives false-alarm and missed-detection events. As in [11], bounded noise uncertainty is modeled by $\sigma_{U_k, \text{dB}}^2 \sim \mathcal{U}(\bar{\sigma}_{U_k, \text{dB}}^2 - \zeta_k, \bar{\sigma}_{U_k, \text{dB}}^2 + \zeta_k)$. Let $q_k = g_k \beta_k P_S (1 - \alpha_k)$, $\tau_{k,1, \text{UB}} = \zeta_k \bar{\sigma}_{U_k}^2$, and $\tau_{k,2, \text{LB}} = q_k + (1/\zeta_k) \bar{\sigma}_{U_k}^2$. With equally likely hypotheses, the minimum DEP is

$$\min_{\tau_k} \Pr(e|k) = \begin{cases} 0, & \text{if } \tau_{k,1, \text{UB}} < \tau_{k,2, \text{LB}}, \\ \frac{1}{2} \left(1 - \frac{\ln \left(1 + \frac{q_k \zeta_k}{\bar{\sigma}_{U_k}^2} \right)}{2 \ln \zeta_k} \right), & \text{if } \tau_{k,1, \text{UB}} \geq \tau_{k,2, \text{LB}}. \end{cases} \quad (6)$$

Equation (6) shows that reducing the received covert-signal power at the user improves covertness.

III. PROBLEM FORMULATION

The objective is to maximize the achievable sum covert rate while guaranteeing public-message delivery and covertness at all scheduled users. The optimization problem is

$$(P1): \max_{P_S, \{\alpha_k\}, \{\beta_k\}} \sum_{k=1}^K \bar{r}_{C,D,k}, \quad (7a)$$

$$\text{subject to } r_{P,k} \leq \bar{r}_{P,D,k}, \forall k, \quad (7b)$$

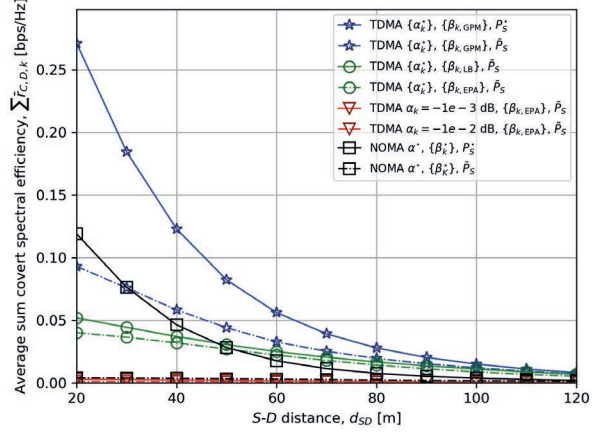


Fig. 2: The average sum covert rate versus the distance between the source and covert destination node

$$r_{P,k} \leq \bar{r}_{P,k} |_{\sigma_{U_k} = \zeta_k \bar{\sigma}_{U_k}^2}, \forall k, \quad (7c)$$

$$r_{P,k} \geq r_{P,k, \text{min}}, \forall k, \quad (7d)$$

$$\min_{\tau_k} \Pr(e|k) \geq \varepsilon_k, \forall k, \quad (7e)$$

$$\tau_{k,1, \text{UB}} \geq \tau_{k,2, \text{LB}}, \forall k, \quad (7f)$$

$$\sum_{k=1}^K \beta_k = 1, \quad (7g)$$

$$P_S \in [0, \bar{P}_S], \alpha_k, \beta_k \in [0, 1], r_{P,k} \geq 0, \forall k, \quad (7h)$$

The first two constraints ensure public-message decoding at D and U_k , while the remaining constraints impose the public-rate threshold, the DEP requirement, the nonzero-DEP regime, and the feasible power region. Because P_S , α_k , and β_k are coupled in both the covert rate and DEP constraints, (P1) is non-convex. The prior work [11] reformulated this problem and proposed a two-layer solution: a one-dimensional search for the total transmit power and a gradient projection method (GPM)-based update for the time-slot power allocation. Readers are referred to [11] for the detailed derivation and algorithm.

IV. NUMERICAL RESULTS

We evaluate the average sum covert rate $\sum_{k=1}^K \bar{r}_{C,D,k}$ under the same simulation setup as [11]. The channel is modeled as $h_{XY} = \sqrt{L_{XY}} \hat{h}_{XY}$, where $L_{XY} = L_0 (d_{XY}/d_0)^{-\beta}$, $d_0 = 1$ m, and $\hat{h}_{XY} \sim \mathcal{CN}(0, 1)$ [12]. Unless otherwise stated, $K = 3$, $W = 20$ MHz, $d_{SU_k} = d_{SD} = 40$ m, $\bar{P}_S = 23$ dBm, $\sigma_{D,k}^2 = \bar{\sigma}_{U_k}^2 = -160$ dBm/Hz, $r_{P,k, \text{min}} = 0.25$ bps/Hz, $\zeta_k = 5$ dB, $\varepsilon_k = 0.45$, $\delta = -10$ dB, and $\beta = 3.5$. We compare the optimized TDMA design, TDMA baselines using fixed $P_S = \bar{P}_S$, equal power allocation (EPA), lower-bound-based slot allocation, and fixed α_k values. Equivalent NOMA benchmarks are also included for reference as in [11], [13].

Fig. 2 plots the average sum covert rate versus d_{SD} . As D moves farther from the source, all schemes suffer from

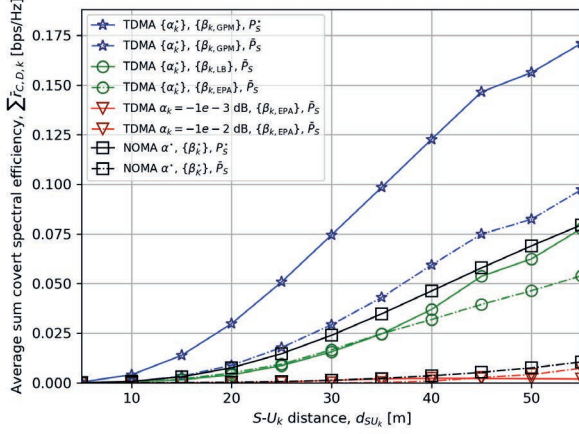


Fig. 3: The average sum covert rate versus the distance between the source and user nodes

stronger path loss on the covert link, and the sum covert rate decreases. The optimized TDMA scheme with $\{\alpha_k^*\}$, $\{\beta_{k, \text{GPM}}\}$, and P_S^* achieves the highest rate over the whole range. Its gain is especially large at small d_{SD} because the covert destination has a strong channel and the optimizer can allocate a larger useful covert component while still satisfying the DEP constraints at the users. When P_S is fixed to $\bar{P}_S$, the performance is lower because using the entire power budget can make the received covert component of the users more detectable. The design must then increase α_k and reduce the covert power fraction. The EPA and lower-bound baselines follow the same decreasing trend but cannot adapt the slot powers as effectively. The fixed- α_k curves remain near zero, indicating that a static public/covert split is not robust to distance-dependent covertness constraints.

Fig. 3 presents the average sum covert rate as the common source-to-user distance d_{SU_k} increases. When the users are close to the source, their received signal strength is high, which makes the covert component easier to detect and severely restricts $(1 - \alpha_k)\beta_k P_S$. Consequently, most schemes provide little covert throughput. As the users move farther away, the received covert leakage at the potential detectors becomes weaker, and the DEP constraint in (7e) becomes less restrictive. The sum covert rate therefore increases with d_{SU_k} in the considered range. The optimized TDMA schemes benefit most from this relaxation because they can jointly tune P_S , α_k , and β_k . The NOMA benchmarks also improve with distance, but the best TDMA curve remains superior because TDMA avoids simultaneous inter-user interference and can exploit slot-wise power allocation.

V. CONCLUSION

This paper summarized a downlink TDMA covert communications framework in which a source simultaneously serves scheduled public users and a covert destination. The received-signal model, DEP expression under bounded noise

uncertainty, and sum covert rate maximization problem were presented based on the prior work. New numerical results showed that the covert rate is highly sensitive to node positions. Increasing the source-to-destination distance degrades the covert link and reduces the achievable sum covert rate, whereas increasing the source-to-user distance weakens the detection capability of the users and can improve covert throughput. Across both distance studies, joint optimization of the total transmit power, public/covert power split, and slot power allocation consistently outperformed fixed-power, EPA, lower-bound, and fixed-splitting baselines. These observations emphasize the importance of geometry-aware power allocation for practical low-probability-of-detection TDMA downlink transmission.

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