碩士學位論文

위장 전이중 은닉 통신에서의 탐지 오류 확률 최대화

Detection Error Probability Maximization for Disguised Full-Duplex Covert Communications

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**List of Abbreviations**

|  |  |  |
| --- | --- | --- |
|  | **FD** | **F**ull **D**uplex |
|  | **DEP** | **D**etection **E**rror **P**robability |
|  | **CSI** | **C**hannel **S**tate **I**nformation |
|  | **DF**  **CF**  **AF**  **IRS** | **D**ecode-and-**F**orward  **C**ompress-and-**F**orward  **A**mplify-and-**F**orward  **I**ntelligent **R**eflecting **S**urface |
|  | **AN** | **A**rtificial **N**oise |
|  | **UAV** | **U**nmanned **A**erial **V**ehicle |
|  | **CR** | **C**ognitive **R**adio |
|  | **IoT** | **I**nternet of **T**hings |
|  | **D2D** | **D**evice to **D**evice |
|  | **UE** | **U**ser **E**quipment |
|  |  |  |
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**Abstract**

Detection Error Probability Maximization for Disguised Full-Duplex Covert Communications

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This thesis delves into reliable covert communications with a disguised full-duplex (FD) node. Seemingly half-duplex receive-only, this node in our considered system simultaneously listens to a transmitter and secretly transmits covert messages to another hidden receiver. In the meantime, a warden attempts to detect this covert link. We first study the detection error probability (DEP) and identify the minimum DEP from the perspective of the warden. After that, we derive an optimal transmit power of the disguised FD node that concurrently maximizes the minimum DEP and guarantees a given reliability of covert rate. Numerical results validate the effectiveness of our proposed solution, and present how different system parameters affect the DEP performance. Numerical results validate the effectiveness of our proposed solution, and present how different system parameters affect the DEP performance. In conclusion, we provide valuable guidance for the design of secure communication systems and suggest avenues for future research in this critical domain.

**Chapter 1**

**Introduction**

Wireless technology has transformed numerous facets of human existence, including connectivity, healthcare, education, and economic systems, reshaping the very fabric of daily life [3][4]. Besides, a number of foundational studies in traditional cryptography and physical layer security hold profound importance in fortifying information security against unauthorized interception, paving the way for advancements in safeguarding sensitive data [5][6]. Nonetheless, even though these technologies keep your messages safe from eavesdroppers, communication links might still be at privacy risk. For instance, the electromagnetic signals from a commander on the battlefield may expose his position to nearby enemies, communicating in the presence of an authoritarian government who may want to curtail any organization by certain entities [7]. A suitable solution for such scenarios involves covert or low-probability-of-detection communications, which conceal the presence of crucial communication links [8].

Extensive research has also been conducted on covert communications within full duplex (FD) systems. The authors in [12] investigated covert communication using a FD receiver under limited channel information and demonstrated that random noise improves performance. By optimizing transmit and AN power to minimize outage probability at Bob, authors observed a non-linear relationship between AN power and performance. Additionally, the numerical results in [13] presented some performance differences between circumstances with and without channel state information (CSI). The work in [14] explored a receiver antenna selection, and [15] proposed a strategy for transmission time selection and power control in a two-way wiretap channel with a multi-antenna Eve, employing artificial noise (AN) and deriving a secrecy rate approximation. In [16], a constrained multi objective optimization problem (MOP) is formulated to maximize two conflicting objectives: the transmission rate between legitimate transceivers and the average covert probability (ACP) for eavesdroppers. This optimization involves adjusting transmit power and the position of the FD receiver, such as in UAV relay networks. Research on delay-constrained covert communications with fixed artificial noise (AN) power was explored in [18], while joint optimization problems for AN power and receiver position were discussed in [19][20]. Consideration of uncertain warden node locations was addressed in [21]. Additionally, [22] studied random covert channel selection by the transmitter to further confuse the warden, and [23] identified the DEP under the age of information constraint.

In complex FD systems, the performance of covert communications varies across different relay systems: decode-and-forward (DF), compress-and-forward (CF), and amplify-and-forward (AF). The study in [REF] compares DF, CF, and AF systems, accounting for system parameters like processing delay, quality of service, and DEP threshold, revealing performance variations under different conditions [24]. In [25], authors devised a protocol for energy harvesting full-duplex DF relay-based covert communications. Furthermore, [26] investigated FD relay-aided covert communications from a satellite to a ground node in the context of integrated satellite–terrestrial communications. Optimization of both secrecy and covert rates was performed in [44] where an untrusted FD AF relay transmits the covert message to an FD base station. The base station then emits AN to deceive the warden. In the IoT domain, [48] investigated a covert transmitter with optimized transmission probability, powered wirelessly by AN from an FD receiver. Moreover, [49] optimized covert uplink transmissions of devices to FD IoT gateways using a mean-field Stackelberg game approach. Additionally, [50] utilized an ambient backscatter system, where a radio frequency tag modulates an ambient signal into a covert signal for an FD receiver concurrently broadcasting AN.

Recently, the research community has given significant attention to possibilities of covert communications in IRS [27][28][29]. The authors of [30] and [31] collectively contribute to advancing the field of covert communication within intelligent reflecting surface (IRS) aided communication systems. They focus on optimizing transmission power, phase shifts, and beamforming vectors to maximize secrecy while leveraging IRS technology. Additionally, they propose novel algorithms to address the optimization challenges posed by imperfect channel state information (CSI), offering practical solutions to enhance covert communication performance. By exploring the potential of IRS in multi-antenna systems and tackling non-convex optimization problems using penalty dual decomposition (PDD) and successive convex approximation (SCA) methods, these papers provide valuable insights and techniques for improving covert communication in the presence of surveillance. The authors of [32] examined an IRS communication scenario where a covert user possesses full control over the IRS and remains concealed from the warden. In [34], optimization of a transmit beamforming vector and reflecting coefficients is conducted for IRS-aided covert communications, where an FD receiver emits random AN to confuse the warden. Additionally, [35] explored uplink covert communications assisted by an IRS and [36] discusses the utilization of an active IRS, inherently full duplex, for covert communications between user pairs. In [37] the authors focus on minimizing the age of information in a scenario where a FD covertly transmits confidential messages to the transmitter, protected under public transmissions from the transmitter to the receiver facilitated. In [38], the authors concentrated on a covert communication setup utilizing UAVs equipped with full-duplex receivers. It delves into optimizing the system's location design leveraging physical layer security technology and a novel scheme is proposed via a UAV carrying an IRS to establish air-ground links to assist covert transmission, where the phase shifts of IRS are randomized to preserve the covertness. Additionally, the legitimate receiver can act as a jammer in the full-duplex mode to defuse the detection of a warden [39].[40] employed to help the transmission and confuse the warden. The maximum lowest average covert rate was achieved in the case of an FD UAV collecting data from a scheduled user and interfering with unscheduled users using AN [41]. In [42], the authors explored an FD DF UAV relay to facilitate covert communications, where multiple sensors transmit messages to a remote base station in separate time slots [43].

Some literature investigates covert communication in CR networks. Chen et al. [44] analyzed user scheduling performance in covert CR Networks. In [45], the authors addressed the problem of power allocation with the aid of generative adversarial network in covert CR networks. The authors of [46] considered covert communication by exploiting cognitive jammers to counter an intelligent eavesdropper. enhancing physical layer security within cooperative cognitive radio networks. In [47] the authors talked about dilemmas, the primary dilemmas involve balancing covertness and secrecy. On one hand, the goal is to prevent detection by Willie of the D2D communication, while on the other hand, the untrusted relay poses a threat of eavesdropping on the user equipment (UE) message. Another dilemma arises in determining the optimal power control strategy at the UE, relay, and base station (BS) to maximize the average covert rate while ensuring covertness and security requirements are met.

Many previous studies have presumed that surveillance nodes possess complete knowledge about the hardware specifications of covert nodes. However, covert nodes have the potential to enhance their concealment by masquerading as different functional entities. For example, an initial FD node transmitting sensitive messages covertly might masquerade as a receiver-only half-duplex (HD) node. To the author's knowledge, there is a scarcity of research on covert communications that

incorporates such deceptive strategies beside our initial result of [56].

**1.1 Background**

This study explores a covert communication setup involving a source node and a disguised full-duplex (FD) destination node. Despite appearing as receive-only, this destination node clandestinely transmits vital messages to a concealed receiver using an imperceptible additional antenna, all while minimizing detection by a warden node. We identify the optimal public data rate and the transmit power of the FD destination node that maximizes the worst-DEP at the warden node. We offer analytical solutions and explore how different system parameters affect the minimum DEP using numerical evaluation.

**1.2 Contributions**

In our covert communication system, the setup involves a source node transmitting a public message to a destination node. What makes our system unique is that the transmission from the seemingly receive-only destination node is conducted covertly. This covert signal is then transmitted to a hidden receiver using an unseen antenna setup. Our transmission environment utilizes full-duplex (FD) communication, allowing for simultaneous transmission and reception. However, we operate under the watchful eye of a warden node, which monitors for any suspicious communications. Our primary focus is on ensuring secure and undetectable transmission from the destination to the hidden node, all while under the surveillance of the warden node.

The primary contributions of our research can be outlined as follows:

* Unlike previous studies assuming the surveillance party's knowledge of covert node hardware specifications, we advance by exploring a practical scenario where a covert communication node assumes the guise of a different functional entity to enhance its stealth further.
* The worst-case DEP is calculated considering the uncertainty of noise at the warden node.
* Covert communications frequently encounter a restricted data rate due to stringent requirements on detection error probability.
* Our focus lies in improving the minimum DEP at the warden node by optimizing both the public data rate and transmit power of the FD destination node. Additionally, we prioritize maintaining a minimum covert rate within the system.
* We explore the impact of diverse system parameters on the worst-case detection error probability (DEP) using numerical analysis.
* Given that our study offers insights from an information-theoretic standpoint, we propose exploring practical modulation techniques and the implications of imperfect channel state information (CSI) as promising for future research.

**Chapter 2**

**System Model**

**2.1 Received Signals**

**A diagram of a communication system

Description automatically generated**

**Figure 1.1:** Schematic diagram

Figure 1 depicts the system model we are considering. There is a source node that sends a public message to a destination node which appears to be half-duplex receive-only, but in fact, secretly sends a covert message to a hidden receiver node using a concealed extra antenna. Meanwhile, a warden node monitors for any unexpected communications i.e., covert messages.

Let us express the received signal at the destination node as

. (1)

In this system model, the channel coefficient represents communication links between different nodes X, Y {S, D, R, W}. The residual self-interference channel accounts for leftover signals after cancelling self-interference. Public messages and covert messages are transmitted. Transmit power and by the source and destination nodes, respectively. Additive noise is present at each node, and we assume that the destination node can estimate the while the hidden receiver can estimate and if provided with pilot sequences [55]. The warden is assumed to have perfect knowledge of all channel state information (CSI) for the worst-case scenario analysis. We also consider that the source adopts its data rate based on destination feedback, and the achievable data rate at the destination is denoted by as [58]

. (2)

Next, the hidden receiver receives two types of messages: a public message directly from the source node and a covert message from the destination node. Accordingly, the received signal of the hidden receiver can be written by

. (3)

The hidden receiver first decodes and removes the public message before accessing the covert message. Consequently, the achievable public data rate, denoted by , at the hidden receiver is given as

. (4)

The resulting achievable covert rate after removing from can also be calculated as

. (5)

**2.2 Covert Message Detection**

The received signal at the warden is expressed by

. (6)

It first eliminates public messages from to calculate the effective residual signal , assuming it perfectly knows and [55]. Then, the warden can consider the following two hypotheses:

(7)

The null hypothesis indicates a case that there are no covert messages, the alternative hypothesis presumes that the destination node did not transmit a covert message.

In this study, a radiometer [51] is utilized as a detection method at the warden. The test statistic for equation (7), after observing number of symbols leads to the average residual power as [52]

(8)

The warden node determines the presence of a covert transmission if surpasses a predefined threshold .

In this thesis, we consider uncertainty on the noise variance at the warden, similar to [51] and [53].

Specifically, we model the noise variance in decibels as where represents the mean and denotes the bounded range. The resulting detection error probability (DEP) , that encompasses both false alarm and miss detection probabilities is then expressed by

. (9)

With equal probabilities for both null hypothesis and the alternative hypothesis [54]. By leveraging the cumulative distribution function (CDF) of [55] as

, . (10)

the false alarm and miss probability are calculated by

, (11)

, (12)

respectively, where and . We encounter two distinct scenarios upon the magnitude of and

If ,

(13)

where . On the other hand, if ,

(14)

with , , and .

It is apparent that the warden prefers to set the threshold that helps minimize the DEP. To achieve this, we observe that equation and decreases monotonically from to for , and increases monotonically from to as . Additionally, the first derivative of the sum is calculated as

. (15)

which is consistently positive . Thus, the optimal threshold for the warden node in both equations and is obtained by

. (16)

It is worth pointing out that we take a conservative assumption that the warden has perfect knowledge of the actual value of , which corresponds to the worst-case scenario from the perspective of covert communications.

**Chapter 3**

**Problem Formulation**

In this study, we aim to optimize the public data rate and transmission power at the disguised FD destination node that maximizes the minimum error probability at the warden node as

, (17a)

subject to , (17b)

, (17c)

, (17d)

, (17e)

, (17f)

. (17g)

Constraint (17b) ensures that the hidden receiver can successfully decode and remove the public message before decoding the covert message. Constraint (17c) specifies the maximum achievable public data rate, allowing the destination node to inform the source node for adjustment. In (17d), a minimum quality of services for public transmission is considered. (17e) specifies a minimum threshold for the covert data rate for reliable covert transmission and ensures a non-zero DEP. Finally, constraint indicates the power budget for the disguised FD destination node.

**Chapter 4**

**Proposed Solutions**

This chapter discusses the solution for (P1) that maximizes the worst-case DEP in (17a).

First, it is important to note that DEP is a decreasing function of (i.e., the derivative of DEP equation (15) is negative with respect to .Similarly, the upper limits of the public data rate and also decrease as increases ( is denominator at equation (2) and (4)). This implies that the public rate cannot surpass a certain threshold, which is defined by the minimum of two upper limits, namely , i.e. Consequently, it's advantageous for to remain at its lowest feasible level to consistently uphold a minimum public rate, given by

However, the covert rate in increases with an increase Therefore, in order to maximize the worst-case DEP, we can easily see that the covert rate should be set to the minimum possible value, which is the required threshold .

Given these trade-offs, (P1) reduces to the following:

, (19a)

Subject to , (19b)

, (19c)

, (19d)

, (19e)

, (19f)

Therefore, this leads to the optimal as

. (20)

**Remark 1**: In certain scenarios, it is plausible for the upper bound to be lower than the lower bound. In such cases, the optimal transmit power is determined to be zero.

**Chapter 5**

**Numerical Results**

We assess the proposed methodologies for maximizing the worst-case detection error probability (DEP) with the disguised full-duplex (FD) node through numerical analysis. The forthcoming figures will investigate the impacts of different system parameters, including source transmit power, disguised FD destination transmit power budget, noise uncertainty bound, and minimum quality of service , along with the derived optimal destination transmit power as indicated in equation (20).

We adopt a distance-dependent channel model for ,where Here, represent the path loss between nodes and . In this equation denotes the path loss at a reference distance meter. signifies the path loss exponent, and indicates the distance between nodes and . Additionally, the small-scale channel variable follows a complex normal distribution . The four nodes are positioned at certain distance from the origin in a cartesian coordinate system, with coordinates for and denoted as and respectively (refer to figure 2). The overall system parameters are predefined as follows, unless stated otherwise: Bandwidth MHz, m. Source transmit power dBm, destination transmit power budget = 23dBm, Public message quality of service bps/Hz, mean noise power at the warden node dBm/Hz, noise uncertainty bound dB, noise power at the destination node and hidden receiver dBm/Hz, residual self-interference dB, minimum DEP threshold , and path loss exponent

A grid with different colored dots and numbers

Description automatically generated with medium confidence

Figure 5.1: Node placement

A graph of a number of data

Description automatically generated with medium confidence

Figure 5.2: DEP versus source power

Figure illustrates how the minimum detection error probability (DEP) changes with variations in the source transmit power Recognizing the necessity for the destination transmit power to be significantly lower than to ensure successful covert transmission. We evaluate the performance of the optimal scheme against an alternative approach denoted as “”. In this alternative scheme, is fixed as the minimum value between a certain percentage of and the average destination transmit power. Our observation indicates that the proposed strategy, incorporating the public data rate optimization from equation and the destination transmit power optimization from equation , Consistently yields the highest worst-DEP rate across various values. This underscores the critical importance of optimization both and .

A graph of different colored lines

Description automatically generated

Figure 5.3: DEP versus covert rate

Figure 4 presents a comparison of the average worst-case Detection Error Probability (DEP) with changes in the covert rate . It's evident that the worst-case DEP exhibits a monotonically decreasing trend as the covert rate increases. This observation stems from the fact that while the destination transmit power increases, the covert rate consistently increases, resulting in a decrease in DEP.

A graph of the average amount of service for public messages

Description automatically generated

Figure 5.4: DEP versus minimum quality of service for public message

Figure illustrate the average worst-DEP and minimum quality of services for public message respectively, when the changes. The average worst-DEP rates decline in monotonic manner as increases.

A graph of a number of points

Description automatically generated

Figure 5.5: DEP versus destination transmit power

Figure 6 illustrates a comparison of the average worst-DEP​ with variations in the destination transmit power budget ​. Notably, when ​ is low, both the "" and random ​ schemes demonstrate performance close to the optimal scheme . This closeness in performance arises because the influence of ​ is dominant in this range, and the fixed or randomly chosen ​ in the compared schemes converges to ​ if ​. However, for other regions of , our proposed solutions consistently achieve the highest Worst-DEP rate. This once again underscores the importance of optimizing both and .

**Chapter 6**

**Conclusion**

In this study, we explored a covert communication setup where a source node communicates with a disguised full-duplex (FD) destination node. Despite appearing as a receiver-only node, the destination secretly transmits crucial messages to a hidden receiver while evading detection by a monitoring warden node. Our focus was on determining the optimal public data rate and transmit power for the FD destination node, aiming to maximize the minimum detection error probability (DEP) at the warden node.

The analytical solution we derived revealed several key insights: When the link between the destination and receiver is exceptionally strong, the optimal transmit power for the destination node tends towards zero. This occurs because the hidden receiver cannot effectively filter out source messages before receiving covert messages. Similarly, insufficient suppression of self-interference also leads to an optimal transmit power close to zero, as the public data rate cannot maintain the required quality of service. Additionally, in scenarios where the channel gain between the destination and warden node is significantly high, the optimal transmit power for the destination node approaches zero, as the warden node can more easily detect the covert link due to the large power difference.

Given that our work offers valuable insights from an information-theoretic perspective, we recommend further exploration of practical modulation techniques and the impact of imperfect channel state information (CSI) as promising avenues for future research.

**6.1 Future Work**

Future work for this research paper could encompass several avenues of exploration. First and foremost, practical implementation of the proposed covert communication system in real-world scenarios would be essential to validate its efficacy and assess its performance under realistic conditions. This could involve field tests or simulations to evaluate its robustness and reliability. Additionally, further analysis could delve into the security aspects of the system, investigating its resilience against potential attacks or vulnerabilities. Integration with emerging technologies, such as artificial intelligence or blockchain, could also be explored to enhance the system's capabilities and adaptability to evolving communication landscapes. Moreover, considerations regarding legal and ethical frameworks surrounding covert communication systems would be pertinent, ensuring compliance with regulations and ethical standards. Incorporating user feedback and iterative improvements based on user experiences could further refine the system's design and usability, ensuring it meets the needs and expectations of its intended users.

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**Abstract**

This thesis delves into reliable covert communications with a disguised full-duplex (FD) node. Seemingly half-duplex receive-only, this node in our considered system simultaneously listens to a transmitter and secretly transmits covert messages to another hidden receiver. In the meantime, a warden attempts to detect this covert link. We first study the detection error probability (DEP) and identify the minimum DEP from the perspective of the warden. After that, we derive an optimal transmit power of the disguised FD node that concurrently maximizes the minimum DEP and guarantees a given reliability of covert rate. Numerical results validate the effectiveness of our proposed solution, and present how different system parameters affect the DEP performance. Numerical results validate the effectiveness of our proposed solution, and present how different system parameters affect the DEP performance. In conclusion, we provide valuable guidance for the design of secure communication systems and suggest avenues for future research in this critical domain.