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**

|  |  |  |
| --- | --- | --- |
|  | **ADC** | **A**nalog-to-**D**igital **C**onverter |
|  | **AQNM** | **A**dditive **Q**uantization **N**oise **M**odel |
|  | **AP** | **A**ccess **P**oint |
|  | **BUG** | **B**eamforming **U**ncertainty **U**nit |
|  | **MIMO** | **M**ultiple **I**nput **M**ultiple **O**utput |
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**Abstract**

Detection Error Probability Maximization for Disguised Full-Duplex Covert Communications

Refat Khan

Advisor: Jihwan Moon

This thesis delves into the optimization of covert communication systems, with a primary focus on maximizing the minimum detection error probability (DEP) at the warden node. The study examines a complex setup involving a source node, a disguised full-duplex (FD) destination node, a hidden receiver, and a monitoring warden node. By establishing a comprehensive system model that encapsulates various communication dynamics such as channel links, transmit powers, and noise characteristics, we lay the foundation for our analysis. Formulating an optimization problem, we seek to enhance DEP while ensuring successful message decoding and maintaining quality of service. Through proposed solutions, we explore the intricate trade-offs between power allocation and covert rate, deriving an expression for optimal transmit power. Subsequent numerical analysis validates our methodologies, offering insights into the influence of system parameters on worst-case DEP. Comparative evaluations with alternative approaches underscore the efficacy of our proposed solutions. 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]. The 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]. Even though cryptography and physical layer security can keep your messages safe from eavesdroppers, your communication habits might still pose privacy risks. The way we communicate can sometimes lead to privacy worries. For instance, if a commander's position is exposed because of electromagnetic signals on the battlefield, it could have serious consequences [7]. A suitable solution for such scenarios involves covert or low-probability-of-detection communications, which

conceal the presence of crucial communication links [8]. Covert communication is designed to allow two users to communicate while ensuring there's very little chance that a warden will detect this communication. It works by hiding the fact that any transmission is happening, which helps reduce the risk of the transmitter or the communication itself being discovered in wireless networks [9][10][11]. Extensive research has also been conducted on covert communications within full duplex systems. Let's imagine a situation where there's someone sending secret messages (Alice) to another person who can both send and receive messages at the same time (Bob). But there's a third person (Willie) keeping an eye on them, trying to figure out if Alice and Bob are talking to each other or not. In this setup, Alice and Willie each have one antenna. On the other hand, Bob has a receiver antenna and an extra antenna for transmitting a signal, which we'll call AN. This additional signal aims to confuse Willie and create uncertainty for him [12]. The paper investigates covert communication using a full-duplex receiver under limited channel information and demonstrates that random noise improves performance. By optimizing transmit and AN power to minimize outage probability at Bob, Authors observe a non-linear relationship between AN power and performance. Additionally, simulations reveal differences in performance behavior between channel distribution information (CDI) and channel state information (CSI) scenarios [13]. In previous research, [14] explored receiver antenna selection, while [15] proposed a strategy for transmission time selection and power control, utilizing channel state information (CSI). This paper examines a two-way wiretap channel with a multi-antenna Eve, employing artificial noise (AN) and deriving a secrecy rate approximation. Simulations indicate that optimized power allocation minimizes Eve's rates while maximizing the sum rates [16]. In the studied paper, 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 full-duplex (FD) receiver, such as in UAV relay networks. Constraints encompass conditions necessary for achieving covert communication and establishing non-deployed zones (NDZ) [17]. 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 maximum detection error probability (DEP) under the age of information constraint. As for more complex FD systems, covert communications performance in different relay systems: decode-and-forward (DF), compress-and-forward (CF), and amplify-and-forward (AF). By optimizing power distribution between public and covert messages, considering minimum detection error probability (DEP) at the relay, it achieves maximum covert rate. The study 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 decode-and-forward (DF) relay-based covert communications. This protocol allows the relay to both forward and harvest energy simultaneously. Furthermore, [26] investigated full-duplex relay-aided covert communications from a satellite to a ground node in the context of integrated satellite–terrestrial communications. Recently, the research community has given significant attention to the IRS communication paradigm [27][28][29]. References [30] and [31] presuppose that the presence of the covert device is acknowledged by the warden. Reference [32] examines an IRS communication scenario where a covert user possesses full control over the IRS and remains concealed from the warden. In [33] the authors Analyz that covert user is unknown to the warden and the covert user does not have control over the IRS. In [34], optimization of a transmit beamforming vector and reflecting coefficients is conducted for intelligent reflecting surface (IRS)-aided covert communications, where an FD receiver emits random artificial noise (AN) to confuse the warden. Additionally, [35] explores uplink covert communications assisted by an IRS. [36] discusses the utilization of an active IRS, inherently full duplex, for covert communications between user pairs. Finally, [37] focuses on minimizing the age of information in a scenario where a receiver covertly transmits confidential messages to the transmitter, protected under public transmissions from the transmitter to the receiver facilitated. The paper centers 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 [38]. 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 unmanned aerial vehicle (UAV) collecting data from a scheduled user and interfering with unscheduled users using artificial noise (AN) [41]. In [42], the authors explored an FD decode-and-forward (DF) UAV relay to facilitate covert communications, where multiple sensors transmit messages to a remote base station in separate time slots [43]. At present, some literature investigates covert communication in CR networks. Chen et al. [44] have analyzed user scheduling performance in covert CR Networks. In [45], the authors have addressed the problem of power allocation with the aid of generative adversarial network in covert CR networks. The authors of [46] have considered covert communication by exploiting cognitive jammers. In this work, a covert jamming scheme is designed to counter an intelligent eavesdropper, enhancing physical layer security within cooperative cognitive radio networks. Investigated [47] in this letter is a power allocation dilemma within a cooperative cognitive covert communication system. Here, the relay secondary transmitter (ST) discretely transmits confidential data under the guidance of the primary transmitter (PT). Optimization of both secrecy and covert rates was performed in [44] where an untrusted full-duplex (FD) amplify-and-forward (AF) relay transmits the covert message to an FD base station. The base station then emits artificial noise (AN) to deceive the warden. In the IoT domain, [48] investigated a covert transmitter with optimized transmission probability, powered wirelessly by artificial noise (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. 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 full-duplex (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.

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.

**1.1 Background**

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.

**1.2 Contributions**

While [1] delves into enhancing cloud radio access networks by optimizing data transfer and adapting to changing connection quality, and [2] explores securing wireless communication against eavesdropping using energy harvesting jamming, my work extends these concepts by focusing on the optimization of covert communication systems in practical scenarios. The primary contributions of our research can be outlined as follows:

1. 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.

2. The worst-case detection error probability (DEP) is calculated considering the uncertainty of noise at the warden node.

3. Observing that covert communications often experience a limited data rate due to strict requirements on detection error probability.

4. Our focus lies in improving the minimum detection error probability 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.

5. We explore the impact of diverse system parameters on the worst-case detection error probability (DEP) using numerical analysis.

6. 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 avenues for future research.

**Chapter 2**

**System Model**

**Hidden Receiver**, R

A black background with a black square

Description automatically generated with medium confidence

Covert message

A blue lock with a blue keyhole

Description automatically generated with medium confidence

A person and a paper

Description automatically generated

A black and white logo

Description automatically generated A black tower with waves

Description automatically generated

**Self-interference**

Public message

**Source**, S

**Disguised FD destination**, D

A black background with a black square

Description automatically generated with medium confidence

**Warden**, W

Figure 1. **System Model**

**2.1 Received Signals**

Figure 1 depicts the system model we're considering. In this model, there's a source node called S that sends a message to a destination node called D. While this happens, the destination node, which appears to only receive messages, secretly sends another message to a hidden receiver node called R using a hidden extra antenna. This covert transmission happens in a full-duplex manner, meaning the destination node can send and receive messages simultaneously. All of this occurs while a warden node, W, is monitoring for any unexpected communications.

First, let's express the received signal at the disguised full-duplex (FD) destination node.

In this system model, the channel coefficient hXY represents communication links between different nodes, such as the source (S), destination(D), hidden receiver(R), or warden(W). The residual self-interference channel accounts for leftover signals after cancelling self-interference. Public messages and covert messages are transmitted with mean 0 and variance 1. Transmit powers and are set by the source and destination nodes, respectively. Additive noise is present at each node. The destination node can estimate the source channel while the hidden receiver can estimate and if provided with pilot sequences. The warden is assumed to have perfect knowledge of certain channel information for worst-case scenario analysis. The source adopts its data rate based on destination feedback, and the achieved data rate at the destination is denoted according to reference [37].

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.

As a result, the hidden receiver must first decode and remove public messages before accessing covert messages. Consequently, the achievable public data rate, denoted as at the hidden receiver.

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

**2.2 Covert message Detection**

Simultaneously, the warden node intercepts the communications.

It first eliminates public messages from to calculate the effective residual signal , assuming it perfectly knows and [38]. We can consider the following two hypotheses:

In the null hypothesis , we assume that there are no covert messages, while in the alternative hypothesis we presume that the source 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 T for equation (7), After observing many signals simplifies to the average residual power as [52]

The warden node determines the presence of a covert transmission based on whether the test statistic T surpassed or falls below a predefined threshold .

Specifically, if T is greater than or equal to , the warden node concludes that a covert transmission exists; otherwise, if T is less than , no covert transmission is deemed to be present. This threshold is chosen to balance the trade-off between false positive and false negative in the detection process.

The uncertainty in the noise variance at the warden node is considered, following the approach outlined in the references [51] and [53].

Specifically, we model the noise variance in decibels as \where , where represents the mean and denotes the bounded range, both of which are non-negative. Subsequently, we derive detection error probability (DEP) , encompassing both false alarm and miss probabilities.

In this scenario, the warden node assumes that the covert transmission occurs randomly, with equal probabilities for both null hypothesis and the alternative hypothesis each set 0.5 [54]. By leveranging the cumulative distribution function (CDF) of (provided in Appendix A). We can further analyz the system performance

,

The false alarm and miss probability are specifically written by

respectively.

Where and

We encounter two distinct scenarios contingent upon the magnitude of and

If

Where

On the other hand,

With .

The warden node may aim for a specific threshold value that helps minimize the detection error probability (DEP). To achieve this, we observe that equation and decreases monotonically from to as ranges within set , and increases monotonically from to as ranges within set Additionally, the first derivative of the sum is calculated as

The first derivative is consistently positive when belongs to set . Thus, the optimal threshold for the warden node in both equations and is established by the dividing the line between sets and or between and as

It is important to point out that equation presents the wors-case scenario for minimum DEP, assuming that the warden node has precise knowledge of the actual value of

**Chapter 3**

**Problem Formulation**

In this study, we seek to pinpoint the ideal public data rate and transmission power at the full-duplex destination node that will increase the minimum error probability at the warden node as much as possible as

Constraint ensures that the hidden receiver can successfully decode and remove the public message before decoding the covert message. Constraint specifics the maximum achievable public data rate, allowing the destination node to inform the source node for adjustment. In , a minimum quality of services for public transmission is considered. specifies a minimum threshold for the covert data rate, denoted , which represents the lowest acceptable rate for the covert transmission and ensures non-zero DEP. Finally, constraint outlines the power budget, denoted as , for the disguised full-duplex destination node.

**Chapter 4**

**Proposed Solutions**

This chapter gives the solution to fulfill our objective that is to maximize the worst-case detection error probability (DEP) in . This requires careful consideration of the relationship between various parameters.

First, it is important to note that DEP decreases as the transmit power increases. Similarly, the upper limits of the public data rate and also decrease as increases. This implies that the covert 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 covert rate, given by

However, the covert rate in increases with an increase Therefore, in order to maximize the worst-case DEP, we should aim to minimize which, unfortunately, leads to a decrease in the covert rate.

Given these trade-offs, the goal is to find an optimal value of that both maintains a minimum covert data rate and maximizes the worst-case DEP. This requires a delicate balance between the different parameters to achieve the best possible outcome.

Therefore, the optimal transmit power can be obtained by taking the minimum of as lower bound and minimum of to as upper bound and we can write optimal

,,

**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 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: BandwidthSource transmit power destination transmit power budget = 23dBm, Public message quality of service mean noise power at the warden node noise uncertainty bound , noise power at the destination node and hidden receiver residual self-interference minimum DEP threshold , and path loss exponent

A grid with different colored dots and numbers

Description automatically generated with medium confidence

**Figure 2.** Node Placement

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 a number of data

Description automatically generated with medium confidence

**Figure 3**. The average minimum DEP versus the source node power

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 different colored lines

Description automatically generated

**Figure 4.** Covert rate versus the average worst-DEP: optimal shows the highest decreasing rate of DEP compared to the other schemes.

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.

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 .

A graph of the average amount of service for public messages

Description automatically generated

**Figure 5.** The average worst-DEP versus the minimum quality of service for public message.

A graph of a number of points

Description automatically generated

**Figure 6.** The average worst-DEP versus the destination node power budget : Close performance among the presented schemes for low since the optimal is dominantly limited by

**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**

Detection Error Probability Maximization for Disguised Full-Duplex Covert Communications

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Covert communications have arisen as an effective communications security measure that overcomes some of the limitations of cryptography and physical layer security. The main objective is to completely conceal from external devices the very existence of the link for exchanging confidential messages. In this paper, we take a step further and consider a scenario in which a covert communications node disguises itself as another functional entity for even more covertness. To be specific, we study a system where a source node communicates with a seemingly receive-only destination node which, in fact, is full-duplex (FD) and covertly delivers critical messages to another hidden receiver while evading surveillance. Our aim is to identify the achievable covert rate at the hidden receiver by optimizing the public data rate and the transmit power of the FD destination node subject to the worst-case detection error probability (DEP) of the warden. Closed-form solutions are provided, and we investigate the effects of various system parameters on the covert rate through numerical results, one of which reveals that applying more (less) destination transmit power achieves a higher covert rate when the source transmit power is low (high). Since our work provides performance guidelines from the information-theoretic point of view, we conclude this paper with a discussion on possible future research such as analyses with practical modulations and imperfect channel state information.