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論　文　要　旨

Wireless communication systems for 5G and beyond require transformative technologies that promise unprecedented data rates, ultra-reliable low-latency communications, and massive device connectivity for various scenarios. To achieve these applications, researchers have focused on Terahertz (THz) communication, which can address burgeoning bandwidth demands and high-speed data rates. Spanning frequencies from 0.1 to 10 THz, this radio band offers immense potential for high-throughput, short-range communication, enabling applications like Tbps Internet-of-Things (Tera-IoT), holographic teleportation, extended reality (XR), and nano-networks.

The openness of radio propagation makes it susceptible to eavesdropping on signals. Traditional encryption measures, which can resist many forms of eavesdropping, are still vulnerable to emerging computing threats such as quantum computing. Additionally, encryption measures can protect communication data, but they cannot hide communication behavior. Covert communication, which aims to hide the existence of transmissions, has become a significant technology in wireless communication security. On the other hand, THz wireless transmissions are inherently less susceptible to eavesdropping than conventional radio frequency (RF) transmissions due to the narrow beam of directional antennas and the extra molecular absorption effect of the THz band. However, the high gain in the narrow main lobe indicates that eavesdroppers within the main lobe area still have a non-negligible eavesdropping performance. Therefore, this dissertation explores the application of THz transmission in covert communications against multiple wardens and conducts related protocol design and performance analysis for the covert THz communications.

We first explore a one-hop covert THz communication system consisting of a transmitter (Alice), a receiver (Bob), and multiple randomly distributed wardens. Specifically, considering the high directivity of antennas and the molecular absorption effect of THz radios, the propagation space around Alice is divided into three regions, and the communication covertness varies significantly in each region. Based on these regions, we propose a one-hop covert communication protocol in the considered scenario. We then discuss the performance of covert communication against multiple non-colluding wardens. We further formulate a covert throughput maximization problem and propose an optimization algorithm to

determine Alice's optimum transmission power while satisfying the covertness requirement. Finally, numerical results illustrate that our proposed protocol can increase the overall detection error probability (DEP) of non-colluding wardens compared to the case where no protocol is used. To better highlight the protocol’ s advantage, we also provide simulation results under colluding wardens as a comparison, and find that the protocol increases the overall DEP.

We then consider covert communications against non-colluding unmanned aerial vehicle (UAV) wardens in a UAV-assisted THz relay system (UTRS), where a transmitter (Alice) transmits confidential signals to its desired receiver (Bob) via a UAV relay (Ray), and two wardens (Willie and Sam) attempt to detect the presence of wireless transmissions of each hop, respectively. We first propose a two-hop covert communication protocol based on the joint optimization of transmission probability and transmission power, where the relay can operate in decode-and-forward mode. We then derive the DEP associated with Alice's and Ray's transmission probabilities and transmission power. We further model the system covert throughput and formulate the maximum system covert throughput as an optimization problem, considering constraints such as the covertness requirement, transmission probability, and power. Additionally, we employ the heuristic algorithm, genetic algorithm (GA), to solve the optimization problem by jointly optimizing transmission probabilities and power in two hops. Finally, we present numerical results to validate our theoretical analysis and illustrate the impacts of system parameters on the maximum system covert throughput. Assuming that wardens know or correctly guess the prior probabilities of covert transmissions over two hops in their hypothesis testing, we find that prior probabilities are not always equal to 0.5 when achieving maximum system covert throughput in the UTRS, which indicates that covert communications with general prior probabilities and such wardens need more consideration and discussion.

We further investigate covert communications against colluding UAV wardens in a UTRS, where a transmitter (Alice) transmits confidential signals to its desired receiver (Bob) via a UAV relay (Ray), and two colluding wardens (Willie and Sam) attempt to detect the existence of two-hop transmissions. The decision fusion (DF) and centralized testing (CT) schemes are examined to characterize the colluding detection capabilities. We first propose a two-hop covert communication protocol based on the joint optimization of transmission power and interference power, where the relay can operate in amplify-and-forward mode. We then derive each warden's DEP and characterize the overall DEP of wardens under two colluding schemes. We further formulate a system covert throughput maximization problem by jointly optimizing the transmission power and interference power, subject to the covertness and signal-to-interference-plus-noise ratio (SINR) constraints. An optimization algorithm using gradient descent (GD) and block coordinate descent (BCD) methods is designed to solve the problem. Finally, numerical results validate the theoretical analyses and illustrate the influence of key parameters on covert communication performance. In particular, the maximum system covert throughput against wardens of the DF scheme is lower than that of the CT scheme, given a specific covertness requirement.

This dissertation provides extensive numerical results to illustrate the performance of covert communication in the considered THz systems. The works in this dissertation are expected to shed light on the implementation of covert communications in THz wireless systems against multiple wardens in next-generation communication applications.

審査結果の要旨

・要旨

This thesis investigates the protocol design and performance analysis for covert Terahertz (THz) communications in wireless communication systems. Firstly, for a one-hop THz system, we propose a

covert communication protocol, develop theoretical frameworks for the covert performance modeling, and optimize the transmission power for system covert throughput maximization. Then, we extend our study to a two-hop UAV-relay THz system with non-colluding wardens, conduct the protocol design and performance analysis, and also explore the joint optimization of transmission power and transmission probability in the two hops of the system for covert throughput maximization. Finally, we focus on a two-hop UAV-relay THz system with colluding wardens and consider two different colluding schemes. We devise the covert communication protocol for this system, and build the theoretical frameworks for covert performance analysis under both colluding schemes, respectively. We also explore the joint optimization of transmission power and interference power in two hops of the system to maximize system covert throughput.

・学位論文の構成

Chapter 1 Introduction
Chapter 2 Related Works
Chapter 3 Covert THz Communication in One-Hop Systems against Non-Colluding Wardens
Chapter 4 Covert THz Communication in Two-Hop Relay Systems against Non-Colluding Wardens
Chapter 5 Covert THz Communication in Two-Hop Relay Systems against Colluding Wardens
Chapter 6 Discussion
Chapter 7 Conclusion

・研究目的の妥当性，従来の手法との比較においての有意性，および理論・実験手法の新規性

This thesis explores the protocol design and performance optimization of covert THz communications in wireless systems.

This thesis first focuses on the covert THz communication in a one-hop wireless system. Notice that existing works only focus on the single warden scenario, we consider a more general scenario with multiple non-colluding wardens. We explore the characteristics of THz bands and different transmission regions around the transmitter to propose a covert THz communication protocol for the system. The theoretical expression for the detection error probability (DEP) of a warden is derived, and the system covert throughput maximization problem is formulated and discussed. The numerical results are also provided to demonstrate the performance of our proposed protocol against multiple non-colluding wardens in the one-hop wireless system.

This thesis then investigates the covert THz communication in a two-hop UAV-assisted THz relay system (UTRS). Notice that the existing work considers multiple non-colluding wardens and covertness guarantee only in one hop, we extend this work to explore the covert THz communication in a UTRS with multiple non-colluding wardens and covertness guarantee in both hops. We explore the cooperative interference technology to propose a covert THz communication protocol for the system. We derive the DEP of wardens based on a general setting for prior probabilities at transmitters. We also explore the joint optimization of the transmission power and transmission probabilities at the transmitter and relay for system covert throughput maximization, and develop a genetic algorithm to solve this optimization problem. Numerical results are provided to illustrate the performance of the proposed protocol.

This thesis further investigates the covert THz communication in a UTRS with multiple colluding wardens and covertness guarantee in both hops, where two colluding schemes are considered, i.e., the decision fusion (DF) scheme and the centralized testing (CT) scheme. We explore the cooperative interference technology to propose a covert THz communication protocol for the system. We derive the DEPs of wardens under the DF scheme and the CT scheme, respectively. We further formulate an optimization problem for system covert throughput maximization by optimizing the transmission power and interference power. Numerical results are provided to illustrate the performance of the proposed protocol under two colluding schemes.

・得られた知見のシステム情報科学の分野における意義

The results of this thesis provide the following valuable insights.

1. This work helps to reveal the potential applications of THz communication technologies in covert communications.

2. The proposed covert THz communication protocols can facilitate the covert communications in

various systems, and the related theoretical models and optimization frameworks developed in this thesis lay the foundation for the performance modeling and optimization of various covert THz communication systems.

It is expected that the work in this thesis can shed light on applications of THz communication in future covert wireless communication systems.