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研究課題名（和文）隠蔽無線通信の秘密容量に関する研究

研究課題名（英文）Secrecy capacity study of covert wireless communication

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研究成果の概要（和文）：本研究プロジェクトでは，隠蔽無線通信(CWC)の秘密容量（SC）に関しては，シングル-ホップ，2-ホップ，そして，ネットワークの CWC SCを調査した．隠蔽機能停止確率，伝送機能停止確率と秘密機能停止確率のモデリング，そして，SCと機能停止性能間の固有のトレードオフについての研究を行った．SCの増大/最適化に関しては，シングル-ホップ SCの最大化を目的に伝送電力と人工的ノイズの最適制御，2-ホップCWC SCの最大化を目的に伝送電力と協調ジャミングの最適制御，そして，CWC ネットワークのSCの最大化を目的に最適なジャミングとスペクトラム分割とモード選択に関する調査を行った．

研究成果の学術的意義や社会的意義
隠蔽無線通信（CWC）は，プライバシー保護通信や沿岸監視などの多くの重要なアプリケーションにとって非常に魅力的である．隠蔽性かつ信頼性のある通信を保証しつつ，各ノードペア間の最大通信容量を特徴づける指標として秘密容量（SC）があり.それゆえ，本プロジェクトでは，物理層の秘密技術の上に構築されるCWCのSCに関する詳細な研究を行った．特に，本研究では，SCの研究において基本的な問題として知られる，SC分析，SCと通信停止トレードオフ，SCの拡張と最適化の3つの問題について調査した．本研究は，現代の通信理論の開発と未来のセキュアな通信の持続的な成功に確実に貢献するものと思われる．

研究成果の概要（英文）：This project investigated the secrecy capacity (SC) of covert wireless communication (CWC), in terms of SC analysis, SC/Covert Outage/Transmission Outage tradeoffs and SC enhancement/optimization. About the SC study, we explored the SC of single hop CWC, CWC in two-hop relay systems, and CWC in wireless networks. About SC/Covert Outage/Transmission Outage tradeoffs, we studied the modeling of covert outage probability, transmission outage probability and secrecy outage probability, and the inherent trade-offs between the SC and outage performances. About SC enhancement/optimization, we explored the joint designs of power control and artificial noise for SC maximization in single hop CWC, the joint designs of cooperative jamming and power control for SC maximization in two-hop relay CWC, and the joint designs of jamming, spectrum partition and mode selection for SC maximization in CWC networks.

研究分野：総合領域

キーワード：隠蔽無線通信　秘密容量　物理層のセキュリティ

１．研究開始当初の背景

Covert wireless communication (CWC) is highly appealing for many important applications, like privacy preserving communications, coastal surveillance, undersea warfare, etc. The well-known Wyner's SC theory, which is built on the classic Shannon security notion and has been vital for characterizing the link SC of conventional secure communication paradigm where only the protection of information content is concerned, is not well suited to characterize the SC of the new CWC paradigm. Thus, despite some research efforts on CWC, the SC theory of CWC - a theory defining the maximum secrecy rates achievable between node pair(s) while ensuring a covert and reliable communication, has remained an open problem. The PHY security technologies (like cooperative jamming, artificial noise, etc.), which exploit the inherent randomness of channels and noise for secret communication, have recently attracted considerable attention for CWC since they characterize the fundamental ability of PHY to hide a CWC from warden(s). This is why there is an increasing interest in developing a powerful PHY security-based SC theory for CWC, as evident from several ongoing national projects in the USA and Europe. It is expected that such a theory not only helps us to understand the basic SC limit of CWC but also serves as an instruction guideline for the design and optimization of CWC systems.

２．研究の目的

The goal of this project is to research on the three fundamental issues of CWC SC study in the context of PHY security, namely the SC analysis, SC/COP/TOP tradeoff and SC enhancement/optimization. We first study the SC for single-hop CWC, two-hop CWC, and CWC in different network scenarios. The main PHY security technologies to be considered include the cooperative jamming, artificial noise and link/relay selection. Second, for the SC/COP/TOP tradeoff, we will investigate the SC/COP/TOP tradeoff under various PHY security technologies, channel models and warden's models. Some new reply/jammer selection schemes will also be developed for a flexible SC/COP/TOP tradeoff. Finally, we will explore a joint design of the cooperative jamming, artificial noise, power control, spectrum partition and mode selection SC enhancement/optimization.

３．研究の方法

(1) Secrecy Capacity (SC) Study:

We first explored the fundamental single-hop CWC. For covert communications with a finite blocklength over AWGN channels, we employed the incomplete Gamma functions to develop an efficient numerical method for the evaluation of SC. We also explored a new secure wireless communication paradigm with both covertness and secrecy guarantees, and applied the Constrained Nonlinear Optimization theory and Lambert's W function to establish a complete theoretical framework for its SC capacity study. We then explored the CWC in two-hop relay systems. For a two-hop and half-duplex (HD) two-way relay system, we proposed covertness strategy to resist the warden's detection for various scenarios, and provided theoretical SC analysis for each scenario. For a two-hop and HD multi-relay system, we proposed reply/jammer selection schemes based random selection or relay channel state information, and applied the Hypothesis test theory and Shannon Theory to develop theoretical frameworks for SC study. For a two-hop full-duplex (FD) relay system, we applied probability theory to conduct theoretical modeling for the SC when the system works under the FD mode, HD mode, or the joint FD/HD mode. Based these studies, we further explored the CWC in wireless networks. We first considered a random wireless network, and applied stochastic geometry to develop theoretical framework for the SC analysis under warden colluding for both non-fading and fading channels scenarios. We then explored the CWC in a D2D-enabled cellular network, and applied Probability Theory to develop theoretical frameworks for SC analysis when D2D pair operates under the underlay mode, overlay mode, or the probabilistic mode selection.

(2) SC/Covert Outage/Transmission Outage Tradeoffs:

For the new secure wireless communication paradigm with both covertness and secrecy guarantees, we applied the Hypothesis Test Theory, Shannon Information Theory and Probability Theory to develop theoretical frameworks for the modeling of covert outage probability (COP), secrecy outage probability (SOP) and transmission outage probability (TOP). Based on these results, we explored the tradeoffs among SC, COP, SOP, and TOP under various scenarios determined by the detector-eavesdropper relationships and secure transmission schemes. For two-hop multi-relay wireless communication systems, we applied the Hypothesis test theory and Shannon Information Theory to develop a theoretical framework for the analysis of TOP and COP, and also proposed two classes of reply/jammer selection schemes to explore the inherent tradeoffs among SC, COP and TOP. We further extended such tradeoff study to the scenarios with cooperative jamming and active warden. Based on the Probability Theory and the techniques of convolution and Laplace transform, we developed theoretical frameworks for the modeling of COP and TOP in a D2D-enabled cellular network and in a random wireless network, and then apply these models to explore the inherent tradeoff among SC, COP and TOP in these networks.

(3) SC Enhancement/Optimization:

For the new secure wireless communication paradigm with both covertness and secrecy guarantees, we explored the techniques of power control and artificial noise for SC maximization under various scenarios determined by the detector-eavesdropper relationships and the secure transmission schemes. For a two-hop multi-relay wireless communication system, we applied the efficient numerical searches and power control techniques for SC maximization under scenarios with active/passive warden and cooperative jamming. For a wireless FD relay system, we first proposed a joint FD/HD mode for SC enhancement, and then applied the probability theory and Karush-Kuhn-Tucker conditions for optimal transmit power control and SC maximization. For a random wireless network, we applied the particle swarm optimization method and the joint design of transmit power and transmission rate for SC maximization. For a D2D-enabled cellular network, we applied the Constrained Nonlinear Optimization theory to explore the joint designs of jamming signal power, spectrum partition and mode selection for SC maximization.

4．研究成果

(1) Secrecy Capacity (SC) Study:

① We explored the SC of fundamental single hop CWC. We first developed the theoretical framework and numerical methods to explore the SC of covert communications with a finite blocklength over AWGN channels. We then studied the SC under the new secure wireless communication paradigm where the covertness and secrecy properties are jointly guaranteed, and conducted detailed theoretical analysis to study the SC of this paradigm under quasi-static Rayleigh fading channel and various scenarios determined by the detector-eavesdropper relationships and the secure transmission schemes adopted by transmitters. We further explored the SC of this new paradigm with active attacker where attackers can perform detection/eavesdropping and jamming simultaneously.

② We studied the SC of CWC in two-hop relay systems. We first studied the SC in two-hop and HD two-way relay system. We considered various scenarios regarding the warden's prior knowledge about the relay, the sources/relay's prior knowledge about the warden, as well as different relaying patterns, and then proposed corresponding covertness strategy to resist the warden's detection for each scenario. We provided theoretical analysis of SC for each scenario with a given covertness strategy. We then explored the SC study of two-hop and HD multi-relay system. We considered the scenarios of passive warden, cooperative jamming and active warden, and proposed two classes of reply/jammer selection scheme based on random selection or relay channel state information. We developed corresponding theoretical frameworks of SC study for each scenario and each reply/jammer selection scheme. We further examined the SC in a two-hop FD relay system. We conducted theoretical modeling for the SC when the system works solely under the FD mode or HD mode. For an improvement of SC, we proposed a joint FD/HD mode that flexibly switches between the FD and HD modes depending on channel state of the relay self-interference channel, and also provided the theoretical modeling for SC under the joint FD/HD mode.

③ We studied the SC of CWC in wireless networks. We first considered a random wireless network consisting of a multi-antenna source node, a single-antenna destination node and multiple single-antenna interferers and wardens. For both non-fading and fading channels scenarios, we developed theoretical framework for the SC analysis under warden colluding, where multiple wardens can combine their observations for transmission detection. We further studied the SC of covert communication in a D2D-enabled cellular network. We developed theoretical frameworks to model the SC of cellular user when D2D pair operates solely under the underlay mode or overlay mode, and further explored the SC under the mode selection scheme allowing D2D pair to select either mode with certain probability.

(2) SC/Covert Outage/Transmission Outage Tradeoffs:

① For CWC in two-hop multi-relay wireless communication systems, we proposed two classes of reply/jammer selection scheme based on random selection or relay channel state information, and developed a theoretical framework to analyze the TOP and COP for a given relay/jammer selection protocol. We then explored the inherent tradeoffs among SC, COP and TOP, and further extended such tradeoff study to the scenarios with cooperative jamming and active warden.

② For a D2D-enabled cellular network, we first developed theoretical frameworks to model the COP and TOP, and then explored the inherent tradeoff among SC, COP and TOP. We further explored such tradeoff to network scenario with mode selection scheme allowing D2D pair to select underlay mode or overlay mode with certain probability. For a random wireless network consisting of a multi-antenna source node, a single-antenna destination node and multiple single-antenna interferers and wardens, we applied the techniques of convolution and Laplace transform to derive the COP and TOP, and then explored the tradeoff among SC, COP and TOP in such network.

③ We explored a new secure wireless communication paradigm where the physical layer security technology is applied to counteract both the detection and eavesdropping attacks, such that the critical covertness and secrecy properties of the communication are jointly guaranteed. We first provided theoretical modeling for COP, secrecy outage probability (SOP) and TOP to depict the covertness, secrecy and transmission performances of the paradigm. We further explored the tradeoffs among SC, COP, SOP, and TOP under various scenarios determined by the detector-eavesdropper relationships and the secure transmission schemes adopted by transmitters.

(3) SC Enhancement/Optimization:

① For CWC in two-hop multi-relay wireless communication systems, we applied the efficient numerical searches and power control techniques to explore the SC maximization issue in the system, and further explored the SC maximization under scenarios with cooperative jamming and active warden. For a wireless FD relay system, we first explored the optimal transmit power control of relay for the SC maximization when the system works solely under the FD mode or HD mode. We then proposed a joint FD/HD mode, which explores the channel state of the relay self-interference channel to flexibly switch between the FD and HD modes such that an enhancement of SC is achieved. Under the joint FD/HD mode, we also examined the related problem of optimal transmit power control of relay for SC maximization.

② For a random wireless network, we developed an algorithm based on the particle swarm optimization method to identify the optimal designs for the transmit power and transmission rate and thus to achieve SC maximization. We demonstrated that the maximal SC for both the non-fading and fading channels is invariant to the density of interferers and the interfering power, regardless of the number of transmit antennas. For D2D-enabled cellular networks, we first explored the optimizations of jamming signal power and spectrum partition for SC maximization, and further explored the joint optimizations of jamming signal power, spectrum partition and mode selection for SC maximization.

③ For the new secure wireless communication paradigm where the covertness and secrecy properties are jointly guaranteed, we explored the SC optimization in the paradigm under various scenarios determined by the detector-eavesdropper relationships and the secure transmission schemes adopted by transmitters. In particular, we explored the power control technique and artificial noise technique in transmitters for the SC maximization. We further extended such SC maximization study to the active attacker scenario where attackers can simultaneously perform detection/eavesdropping and jamming.

５．主な発表論文等

〔雑誌論文〕　計21件（うち査読付論文　21件／うち国際共著　20件／うちオープンアクセス　0件）

１．著者名 Ranran Sun, Bin Yang, Siqi Ma, Yulong Shen, Xiaohong Jiang	４．巻 69
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２．論文標題 Performance, Fairness and Tradeoff in UAV Swarm Underlaid mmWave Cellular Networks with Directional Antennas	５．発行年 2021年
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関