Multi-Antenna Relay Aided Wireless Physical Layer Security

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Abstract

With growing popularity of mobile Internet, providing secure wireless services has become a critical issue. Physical layer security (PHY-security) has been recognized as an effective means to enhance wireless security by exploiting wireless medium characteristics, e.g., fading, noise, and interference. A particularly interesting PHY-security technology is cooperative relay due to the fact that it helps to provide distributed diversity and shorten access distance. This article offers a tutorial on various multi-antenna relaying technologies to improve security at physical layer. The state of the art research results on multi-antenna relay aided PHY-security as well as some secrecy performance optimization schemes are presented. In particular, we focus on large-scale MIMO (LS-MIMO) relaying technology, which is effective to tackle various challenging issues for implementing wireless PHY-security, such as short-distance interception without eavesdropper channel state information (CSI) and with imperfect legitimate CSI. Moreover, the future directions are identified for further enhancement of secrecy performance.

Index Terms

Physical layer security, multi-antenna relay, LS-MIMO, secrecy performance optimization.

I. Introduction

We have witnessed significant growth in wireless communications due to the rapid technological advancements in cellular, sensor, cyber-physical, and machine-to-machine (M2M) communication networks. Applications based on these diverse wireless systems are used to transmit and

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receive confidential/private data (e.g., credit card information, energy pricing, e-helath data, command and control messages, etc.). Therefore, it is important to guarantee secure communications in the presence of possible undesired third parties, e.g., attackers, eavesdroppers, adversaries with malicious data injection capability, etc. Traditionally, secure communication systems were implemented using upper layer protocols and tools, such as cryptography. However, cryptography requires an extra secure channel for exchange of private keys. Note that for mobile or unstructured networks, it is difficult to provide a reliably secure channel. Recently, a new paradigm known as PHY-security that exploits the randomness of wireless propagation medium has emerged [1]. The benefits of PHY-security are two-fold. First, heavy dependence on complex higher-layer encryption may not be necessary, leaving more computation resources for communications. Second, PHY-security avoids the use of private keys, and thus it can be made more applicable. And in practical systems, PHY-security can serve as an additional layer of protection on top of the existing security features.

From an information-theoretic viewpoint, the essence of PHY-security is to maximize the performance difference between legitimate and eavesdropper channels [2]. Generally speaking, it aims to enhance the legitimate signal and impair the eavesdropper signal simultaneously, thus realizing secure, reliable, and QoS-guaranteed communications. In this context, a variety of physical layer techniques can be utilized to enhance wireless security. Wherein, multi-antenna technique is one of the most powerful ways for secure communications. Making use of spatial degrees of freedom, it is possible for us to increase the legitimate channel rate and concurrently decrease the eavesdropper channel rate. As a simple example, if signal is transmitted in the null space of the eavesdropper channel, the eavesdropper cannot receive any information, and thus information leakage is avoided. It is worth pointing out that the quality of both legitimate and interception signals are related largely to the propagation distance. If the interception distance is short, it is difficult to provide a high QoS-guaranteed secure communication even exploiting the benefit of multi-antenna technique. This is because the gain from multi-antenna technique is small compared to path loss of signal propagation. To address this challenge, the relaying technology was introduced into PHY-security, so as to shorten the propagation distance of the legitimate signal [3]. Especially, the multi-antenna relaying technology has attracted considerable

attention as it has the advantages of both multi-antenna and relaying technologies.

To fully exploit the benefits of multi-antenna relaying technology for PHY-security, it is necessary to adaptively adjust the transmit parameters, such as transmit beams, transmit powers, transmit durations, and relaying protocols [4]. Intuitively, in order to implement these secrecy performance optimization schemes, the transmitters require full or at least partial CSI. Unlike traditional relaying systems, the secrecy relaying system involves different types of CSI. In addition to the legitimate CSI about source-relay and relay-destination channels, there is the eavesdropper CSI about source-eavesdropper and relay-eavesdropper channels. As revealed in the literatures, the CSI has a great impact on the performance of adaptive transmission techniques. If full CSI is available at the source and the relay, it is possible to attain a steady secrecy rate, or even achieve the secrecy capacity. However, eavesdropper CSI is usually unavailable, since an eavesdropper can be passive and keeps silent. In this case, it is impossible to provide a steady secrecy rate over all realizations of fading channels. To this end, some new performance metrics, i.e., ergodic secrecy rate, secrecy outage probability, and interception probability, are proposed accordingly to evaluate wireless security in a statistical sense [5]. Moreover, legitimate CSI may also be imperfect as normally it is obtained through limited feedback or by making use of channel reciprocity. Under this condition, it is nontrivial to design adaptive performance optimization schemes.

In this article, we intend to provide an overview on various state-of-the-art multi-antenna relaying technologies from the perspective of PHY-security. Especially, we investigate viable secrecy performance optimization schemes in the framework of multi-antenna secure relaying system. Then, we discuss and analyze an up-to-date multi-antenna relaying technology, namely large-scale MIMO (LS-MIMO) relaying, to show the benefits of cooperative schemes for wireless security. At the end, we conclude the whole article with a discussion on future research directions on secure relaying systems.

II. State-of-the-Art Multi-Antenna Secure Relaying Technologies

Some pioneering works on multi-antenna relaying technologies for PHY-security revealed the fundamental functions on wireless security. Specifically, the multi-antenna relay plays two roles:

- 1) To help the source by enhancing channel quality to the legitimate destination;
- 2) To repress the interception by deteriorating the channel condition to the eavesdropper.

The performance of multi-antenna relay for PHY-security depends mainly on relaying protocols and schemes. For example, amplify-and-forward (AF) and decode-and-forward (DF) are two commonly used relaying protocols [6] [7]. AF protocol forwards the signal polluted by noise, while DF protocol forwards the original signal by decoding the received signal at the relay. From the perspective of PHY-security, it is not easy to judge which protocol is better. In general, the relaying protocol is selected according to relaying scheme and channel condition. In what follows, we provide an overview of various multi-antenna secure relaying schemes.

A. One-Way Relaying

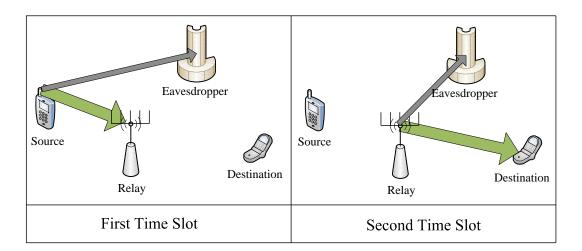


Fig. 1. A model of one-way secure relaying system.

One-way multi-antenna secure relaying technology is the most popular relaying scheme. In this case, to accomplish a transmission two time slots are required. As shown in Fig. 1, during the first time slot, the source sends message to the relay, and then the relay forwards the post-processed signal to the legitimate destination within the second time slot. Meanwhile, the eavesdropper also receives the signals and tries to decode them. In order to improve the secrecy performance, a feasible way is the use of multi-antenna techniques at the relay. For both AF and DF protocols, zero-forcing (ZF), minimum mean square error (MMSE) or match filter (MF) receiver can be

utilized in the first time slot. Similarly, ZF, MMSE or MF transmitter is applicable within the second time slot [8]. Then, with different transceivers and relaying protocols at the relay, there are eighteen combinations in total. According to channel conditions, it is possible to select an optimal combination. For example, the MMSE receiver can mitigate the noise, and then AF is used due to its low complexity. Moreover, a ZF transmitter can effectively decrease the information leakage if eavesdropper CSI is available. Even without eavesdropper CSI, the transceiver designed based only on legitimate CSI is beneficial for secrecy performance enhancement.

Moreover, with multiple antennas at the relay, cooperative jamming can also be used to further improve the secrecy performance. Specifically speaking, a relay generates interference independent of the source message (such as artificial noise) towards an eavesdropper. In order to avoid interference to the destination, the jamming signal is transmitted in the null space of the relay-destination channel, making use of spatial degrees of freedom of the multi-antenna relay. Similarly, the source can also send the jamming signal to interfere with the eavesdropper in the second time slot. It is worth pointing out that there are two potential problems for cooperative jamming. First, if CSI is imperfect, cooperative jamming may result in residual interference to the destination. However, even with residual interference, it may be still beneficial for wireless security to adopt cooperative jamming as long as legitimate CSI is sufficiently accurate. Second, the jamming signal consumes extra power. Thus, in power-limited secure systems, it makes sense to design an energy-efficient cooperative jamming scheme.

B. Two-Way Relaying

In a two-way relaying case, the source and the destination exchange message with the aid of a multi-antenna relay in two time slots. Specifically, two nodes send their signals simultaneously to the relay during the first time slot. Then, the relay broadcasts the post-processed mixed signal based on AF or DF relaying protocol. Each node subtracts its transmitted signal from the received signal, and then recovers the information from the other node. Compared to one-way relaying, two-way relaying has two advantages from the perspective of wireless security. First, two-way relaying doubles the spectral efficiency of the legitimate signal transmission. Second, the current transmission of two signals may degrade the quality of the interception signal, since there is no

interference cancelation at the eavesdropper.

The key of two-way relaying for PHY-security lies on the design of transceiver at the multiantenna relay. On one hand, the interference between two legitimate signals should be avoided,
while still guaranteeing a high spectral efficiency. To this end, some advanced network coding
techniques can be used at the relay [9]. For example, physical layer network coding performs
XOR operation to the two signals on bit level after decoding the two signals from the mixed
signal, and then the desired signal can be recovered at each source using XOR operation to
the received signal based on its own transmit signal. Moreover, ZF beamforming can also be
adopted to separate the two signals in space. On the other hand, wireless security should be
fulfilled by decreasing information leakage to the eavesdropper. If full or partial eavesdropper CSI
is available, ZF or MMSE beamforming is an effective way to reduce the information leakage.
Otherwise, if there is no eavesdropper CSI, cooperative jamming can be used to enhanced wireless
security.

Note that in order to decrease the complexity of separating the mixed signal at a relay, it is likely to transform the traditional two-slot two-way relaying to a three-slot scheme. Specifically, one source first sends message, and then the other source transmits its signal. Finally, the relay broadcasts the post-processed signal. This transformed scheme may weaken the wireless security, since there is no self-interference during the first two time slots. Moreover, it requires a longer transmission time. However, it may achieve a balance between security and complexity. In addition, if the compute-and-forward protocol is used, the relay does not need to decode each signal from the mixed signal. Instead, it can decode a function of the signals and forward it, which can further reduce the complexity.

C. Full-Duplex Relaying

Both one-way and two-way relaying adopt half duplex scheme, which separates the processes of transmitting and receiving in time. However, if the relay can simultaneously transmit and receive signals, namely full-duplex relaying [10], as seen in Fig. 2, the spectral efficiency can be doubled with respect to one-way relaying. In addition, the signals from the source and the relay may produce extra interferences to the eavesdropper, and thus improve the secrecy performance.

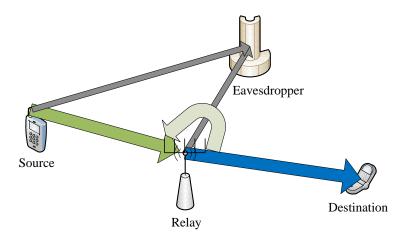


Fig. 2. A model of full-duplex secure relaying system.

Although full-duplex brings great benefits for wireless security, still it faces many challenging issues. The biggest problem is the self-interference from the transmitted signal from the relay to the received signal at the relay [10]. Due to relatively short propagation distance, the self-interference may severely degrade the performance. Intuitively, it is possible to cancel the interference from the received signal, since the relay knows the transmit signal perfectly. However, self interference is also affected by the loop channel from the transmitter to the receiver. If the CSI for the loop channel is imperfect, the interference cannot be cancelled completely. More importantly, since interference has its pros and cons in PHY-security, it may not be optimal to cancel interference completely for full-duplex relaying. A feasible way is a joint design of transmit and receive beams at the relay in order to achieve a fine balance between the effects of self-interference on the legitimate and interception signals.

D. Cooperative Relaying

If there is a strict spatial limitation at the relay, it may be impossible to deploy multiple antennas. In this case, multiple single-antenna relays can cooperatively assist secure communications [11]. The advantages of cooperative relaying for PHY-security are two-fold. First, these relays are geographically distributed, then the access distance of the destination may be shortened, and thus the secrecy performance is improved. Second, these relays can play different roles according to channel conditions. For example, the relays close to the eavesdropper may act

as cooperative jammers, so as to generate strong interferences to the eavesdropper. The other relays still forward the legitimate signal cooperatively. Compared to cooperative jamming in a co-located multi-antenna relay, the one with cooperative relaying has a lower complexity.

However, cooperative relaying also faces some implementation difficulties. Specifically, cooperative relaying is in general carried out in a distributed way. Thus, the synchronization for multiple relays is a nontrivial task, especially for the relays with different roles. Moreover, CSI exchange between the relays is also challenging. It may increase overheads, and an intelligent eavesdropper can obtain the CSI. If it succeeds, these kind of disruptive attacks can be a serious thread and will significantly impair the secrecy performance as a whole.

E. Untrusted Relaying

A key feature in relaying systems as described above is that they all assumed that the relay can be trusted. In other words, the relay will assist secure transmissions in the best way they can. However, from recent research works, several papers have considered the use of untrusted relays [12]. In a untrusted relay model, although the relay is a cooperative node, information intended for the destination must be kept secret from it. Another line of works assumed that the relay is "malicious", i.e., the relay may try to modify the retransmitted signal towards the destination. The use of untrusted relay may occur in several cases. For example, in public networks, the relays that are used for connectivity may belong to a third party. Such relays can operate with standard protocols although they can be unauthenticated. Malicious relay scenarios can occur in military applications as well, where an enemy can "pretend" to be a cooperative node forwarding the malicious data to the destination.

The untrusted relaying has a great impact on the secrecy performance. The achievable secrecy rate of the DF protocol is zero, while the AF protocol can achieve a nonzero secrecy rate. A feasible solution to the untrusted relaying is the use of cooperative jamming. A friend sends a jamming signal to interfere the relay, but the destination can completely cancel the interference with aprior knowledge. Thus, the secrecy performance in the case of the untrusted relaying can be improved.

III. ADAPTIVE RESOURCE ALLOCATION FOR MULTI-ANTENNA SECURE RELAYING

In multi-antenna relay networks, there are different types of resources, such as power, time, space and antenna resources. These resources will affect the quality of both legitimate and interception signals, and thus it makes sense to allocate them according to channel conditions and system parameters [13]. However, resource allocation in secure communications is a nontrivial task. In what follows, we discuss several key issues on resource allocation in multi-antenna secure relaying systems.

A. Adaptive Beamforming

Beamforming has a great impact on the secrecy performance. As aforementioned, if the legitimate signal is transmitted in the null space of the eavesdropper channel, the eavesdropper cannot receive any information. However, implementation of beamforming in secure relaying systems is not easy, especially in the case without eavesdropper CSI. In general, the source and the relay design the beams independently. Then, the source constructs a beam aiming at the relay if it knows legitimate CSI only. However, the beamforming design at the relay involves multiple factors. It is quite complex and can only be made suboptimal. On one hand, the beamforming scheme is related to the relaying protocols. For example, the AF protocol will forward the noise, and then it is better to adopt a beam that may achieve a tradeoff between enhancing the signal and mitigating the noise, i.e., ZF and MMSE. The DF forwards the original signal, and thus MF beamforming can maximize the signal-to-noise ratio (SNR) at the destination. On the other hand, the receive beam in the first time slot and the transmit beam in the second time slot should be designed jointly. Generally speaking, the receive beam will determine the quality of the legitimate signal, while the transmit beam can impair the interception signal. In addition, if full-duplex relaying is adopted, the receive and transmit beams should be designed carefully to deal with the effect of self-interference.

B. Power Allocation

In traditional communications without security requirements, the communication quality, e.g., transmission rate, is usually an increasing function of transmit power. However, the power has a

side effect in secure communications. This is because increasing the power would simultaneously improve the performance of the legitimate and the eavesdropper channels. Thus, the power should be allocated adaptively to the conditions of the legitimate and the eavesdropper channels.

In secure relaying systems, power allocation becomes more complicated, since the powers at the source and the relay are inter-related. For example, based on the DF relaying protocol, the legitimate channel rate is determined by the smaller of the rates of the source-relay and the relay-destination channels. Therefore, it does not make sense to increase the power on one side, but fix the other. For the AF relaying protocol, increasing the relay power may amplify the noise, resulting in performance saturation. In addition, if a more advanced relaying scheme is adopted, power allocation should be adjusted accordingly. As a simple example, in full-duplex relaying systems, the relay power directly determines self-interference, and thus the power allocation should consider the interference cancelation scheme and the effect of the interference on the interception signal. Moreover, for secure relaying systems with cooperative jamming, if the total relay power is constrained, it is necessary to distribute the power between the forwarding signal and the jamming signal.

C. Time Allocation

In general, the durations for the first and the second time slots in relaying systems are equally allocated. Such an allocation scheme is simple and asymptotically optimal, if the relay is at the middle of the source and the destination. However, in secure relaying systems, since the channels from the source to the eavesdropper and that from the relay to the eavesdropper may be quite different, equal duration allocation may result in obvious secrecy performance loss. Specifically, if the eavesdropper is closer to the relay, it makes sense to distribute a longer duration to the first time slot. Intuitively, time allocation is also related to the other system parameters, i.e., relaying protocol and transmit power. Hence, time allocation can effectively enhance the secrecy performance.

D. Antenna Selection

In multi-antenna secure relaying systems, the antennas at the relay have different effects on the secrecy performance if the channels experience independent fadings. As mentioned in cooperative

relaying, some relays may be closer to the eavesdropper, and thus the forwarding of these relays may lead to information leakage. Even in a co-located multi-antenna relaying system, certain channels from a relay antenna to the destination may experience deep fading, but the channel to the eavesdropper may have a high gain. In this case, the use of these antennas not only wastes the power, but also degrades the secrecy performance.

Antenna selection in secure relaying systems is not a trivial issue, since it is a combinatorial optimization problem from a pure mathematical viewpoint. If the number of antennas is not so large, it is possible to select the optimal antennas by exhaustive searching. Otherwise, some suboptimal scheme may be used to select the antennas. For example, if eavesdropper CSI is unavailable, the antennas can be selected only according to the quality of the legitimate channels.

E. Relaying Protocol Switch

There exist various relaying protocols, where AF and DF are two most commonly used ones. In secure relaying systems, there is no dominant protocol. As channel conditions change, the optimal relaying protocol may also vary. Thus, it makes sense to switch the relaying protocols according to channel conditions in order to optimize the secrecy performance.

It is worth pointing out that the above resource allocation schemes are interactive. For example, power allocation scheme may affect the time allocation. Thus, it is better to optimize these resources jointly in order to maximize the secrecy performance.

IV. LARGE-SCALE MIMO RELAYING FOR PLS

In secure communications, there may be some adverse conditions, e.g., no eavesdropper CSI and imperfect legitimate CSI. In this context, if the interception distance is relatively short, then even with a multi-antenna relay, the secrecy performance may be very poor. As a result, it is difficult to provide secure, reliable and QoS guaranteed communications.

To solve the problem with short-distance interception in secure communications, we recently proposed to use large-scale MIMO (LS-MIMO) relaying technology to enhance wireless security significantly [14]. LS-MIMO can generate a very high-resolution spatial beam, making use of a large number of antennas. Thus, on one hand, the performance of the legitimate channel

can be improved enormously due to the high array gain. On the other hand, the information leakage to unintended users can be made very small. Especially, as the number of antennas tends to be infinity, the information leakage is negligible. Then, even under adverse conditions, it is still likely to achieve a good secrecy performance. Additionally, compared to traditional multi-antenna secure relaying technologies, LS-MIMO secure relaying technology offers several appealing advantages. First, LS-MIMO simplifies the signal processing, and even with a low-complexity transceiver at the relay, i.e., maximum ratio combination (MRC) and maximum ratio transmission (MRT), it is still able to achieve a good performance. Second, it is easy to improve the secrecy performance by adding antennas only at the relay. Third, due to channel hardening in LS-MIMO systems, the performance analysis and optimization becomes simpler. In what follows, we show the performance gain of several adaptive resource allocation schemes in LS-MIMO secure relaying systems through numerical simulations.

Let us consider a one-way secure relaying system, where the source communicates with the destination with the aid of an LS-MIMO relay. The number of antennas N_R at the relay is very large, e.g., $N_R=100$ or even bigger. The relay has full CSI about the source-relay channel through channel estimation, imperfect CSI of the relay-destination channel due to channel reciprocity, but no CSI of the relay-eavesdropper channel. The eavesdropper is closer to the relay, but not the source, since it assumes that the signal is from the relay directly. We use $\alpha_{S,R}$, $\alpha_{R,D}$, and $\alpha_{R,E}$ to denote the normalized path loss of the source-relay channel, the relay-destination channel, and the relay-eavesdropper channel, respectively. Note that we take secrecy outage capacity as the performance metric, since eavesdropper CSI is unavailable. Secrecy outage capacity is defined as the maximum transmission rate, while secrecy outage probability needs to satisfy a given constraint. In this manuscript, the bound on secrecy outage probability is set to 0.05.

First, we show the performance gain of joint resource allocation over fixed resource allocation scheme in a DF LS-MIMO secure relaying system. For analysis convenience, we normalize $\alpha_{S,R} = \alpha_{R,D} = 1$, and use $\alpha_{R,E} >> 1$ to represent short-distance interception. We consider the optimization of source power, relay power and duration ratio between the first and the second hops. As seen in Fig. 3, joint power and time allocation scheme obviously performs

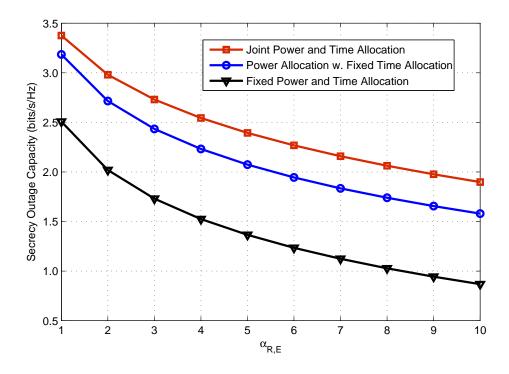


Fig. 3. Secrecy performance comparison with joint and fixed power allocation.

better than power allocation with fixed time allocation scheme. This is because duration ratio between the two hops also has a great impact on the secrecy performance. For example, if the eavesdropper is close to the relay, it is better to use a small duration in the second hop. Meanwhile, transmit powers at the source and the relay also affect the duration ratio. Thus, it makes sense to optimize power and time jointly. Moreover, if both power and time are fixed regardless of channel conditions and system parameters, there will be more performance loss. Thus, joint resource allocation can effectively improve the secrecy performance.

Then, we examine the impact of the number of antennas at the relay on the secrecy performance in an AF LS-MIMO secure relaying system with $\alpha_{S,R} = \alpha_{R,D} = \alpha_{R,E} = 1$. Intuitively, adding more antennas can always improve secrecy outage capacity, but also increases resource consumption, such as power. In this case, we take secrecy energy efficiency as the performance metric, which is defined as the ratio of secrecy outage capacity and total consumed power, including transmit power, circuitry power per antenna, and basic power independent of the number of antennas. In Fig. 4, we use P_C to denote the circuitry power per antenna. It is

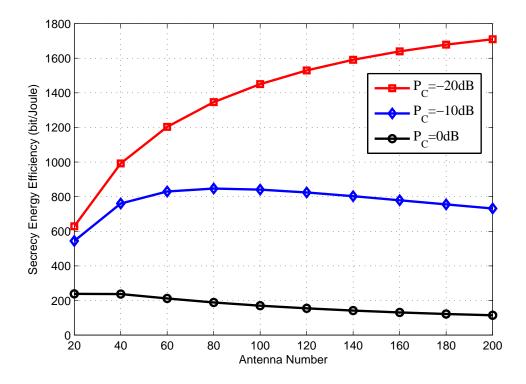


Fig. 4. Secrecy energy efficiency of a secure relaying system with different numbers of antennas.

found that if P_C is very small, i.e., $P_C = -20$ dB, adding more antennas is always helpful to increase the secrecy energy efficiency. However, with $P_C = -10$ dB, the energy efficiency first increases and then decreases as the number of antennas increases. This is because when the number of antennas is small, adding more antennas can increase the secrecy outage capacity significantly. However, when the number of antennas is relatively large, although adding more antennas can further increase the secrecy outage capacity, the consumed power increases sharply. Thus, it makes sense to select the optimal number of antennas in order to maximize the energy efficiency.

In summary, adaptive resource allocation can effectively improve the secrecy performance. LS-MIMO secure relaying technology simplifies the signal processing and thus it is possible to optimize the utilization of different resources jointly, such as power and time. Therefore, wireless security can be enhanced significantly.

V. FUTURE RESEARCH DIRECTIONS

Wireless security is always a critical issue. Although the introduction of multi-antenna relay can improve the secrecy performance effectively, there are many challenges remained to be tackled. As our future works, we intend to solve these problems in the following directions to enhance wireless security further.

A. Mobile Relay

The position of the relay has a great impact on the performance, especially in secure mobile communications. As channel conditions change, the optimal position of the relay may also need to vary accordingly. Hence, a fixed relay may result in an obvious performance loss. If it is a vehicular relay, it should be able to flexibly move the position and select the secrecy scheme. For example, the relay moves closer to the eavesdropper to strengthen the interference to the eavesdropper through cooperative jamming. However, it is not a trivial task to design the scheme of mobile relay. First, it requires full CSI, which increases the overhead. Second, there is a balance between secrecy performance and implementing complexity, which is again an open issue.

B. Multiuser Access

In modern communications, multiuser concurrent transmission is commonly used to improve the spectral efficiency. For example, the LTE system supports multiple users' access through a relay. In multiuser secure relaying systems, multiuser transmission faces several challenges. On one hand, the inter-user interference degrades the secrecy performance. On the other hand, the inter-user interference can be used to impair the interception signal. Thus, it is necessary to design effective user scheduling and precoding schemes to optimize the secrecy performance.

C. Combination of Encryption and PHY-Security

PHY-security emphasizes mainly on pure signal processing techniques, while high-layer cryptographic techniques works well independent of channel conditions. In secure relaying systems, the CSI may be imperfect or even unavailable, and then we can integrate cryptographic techniques

into the transceiver design. Combining cryptographic techniques and PHY-security offers another way to improve the secrecy performance significantly.

VI. CONCLUSION

This article provides an overview of multi-antenna relaying technologies in PHY-security, and discusses the opportunities and challenges in the design of secure relaying systems. Through analyzing the characteristics of secure relaying communications, we give a comprehensive tutorial on adaptive resource allocation schemes to further improve the secrecy performance. To solve the problem with short-distance interception under adverse conditions, we proposed to use LS-MIMO relaying technology and showed its effectiveness through simulations. Finally, we identified several research directions as our future works.

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