IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 9, 2016, accepted October 19, 2016, date of publication December 15, 2016, date of current version March 28, 2017.

Digital Object Identifier 10.1109/ACCESS.2016.2636239

Physical Layer Security Jamming: Theoretical Limits and Practical Designs in Wireless Networks

KANAPATHIPPILLAI CUMANAN[1], HONG XING[2], PENG XU[3], GAN ZHENG[4], XUCHU DAI[3], ARUMUGAM NALLANATHAN[2], ZHIGUO DING[5], AND GEORGE K. KARAGIANNIDIS[6]

[1]Department of Electronics, University of York, York, YO10 5DD, U.K.
[2]Department of Informatics, King's College London, London WC2R 2LS, U.K.
[3]Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei 230000, China
[4]Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, U.K.
[5]School of Computing and Communications, Lancaster University, Lancaster, LA1 4WA, U.K.
[6]Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece

Corresponding author: K. Cumanan (kanapathippillai.cumanan@york.ac.uk)

The work of K. Cumanan and Z. Ding was supported by H2020-MSCARISE-2015 under Grant 690750. The work of Z. Ding was supported by the U.K. EPSRC under Grant EP/L025272/1. The work of H. Xing and A. Nallanathan was supported by the U.K. EPSRC under Grant EP/N005651/1. The work of G. Zheng was supported by the U.K. EPSRC under Grant EP/N007840/1. The work of X. Dai was supported in part by the National Natural Science Foundation of China under Grant 61471334.

ABSTRACT Physical layer security has been recently recognized as a promising new design paradigm to provide security in wireless networks. In addition to the existing conventional cryptographic methods, physical layer security exploits the dynamics of fading channels to enhance secured wireless links. In this approach, jamming plays a key role by generating noise signals to confuse the potential eavesdroppers, and significantly improves quality and reliability of secure communications between legitimate terminals. This article presents theoretical limits and practical designs of jamming approaches for physical layer security. In particular, the theoretical limits explore the achievable secrecy rates of user cooperation-based jamming whilst the centralized and game theoretic-based precoding techniques are reviewed for practical implementations. In addition, the emerging wireless energy harvesting techniques are exploited to harvest the required energy to transmit jamming signals. Future directions of these approaches and the associated research challenges are also briefly outlined.

INDEX TERMS Physical layer security, cooperative jamming, full-duplex systems, game theory, wireless energy harvesting.

I. INTRODUCTION

In wireless communications, the exponential growth of mobile traffic and newly emerging wireless applications introduce different security risks due to their broadcasting nature. The secured communication links in traditional wireless networks are established through conventional cryptographic methods. However, these methods impose different challenges in terms of key exchange and distribution, especially in the current trend of dynamic network configurations. Recently, physical layer security has been recognised as one of the potential solutions to enhance security in wireless networks by exploiting characteristics of wireless channels [1]. In addition, this novel paradigm complements the conventional cryptographic methods, and well suits for dynamic networks and distributed processing techniques.

Physical layer security jamming is a well known approach to enhance the quality of secure wireless transmissions [2]–[4]. In this technique, additional jamming signals are transmitted to confuse the potential eavesdroppers or to degrade the decoding capability of the unintended receivers. These jamming signals can be introduced by embedding them with the intended signals, which are referred as artificial noise (AN) approach in the literature. On the other hand, a receiver can be also used to transmit jamming signals with the help of full duplex (FD) radios, which have the capability to simultaneously transmit and receive the signals. Hence, FD receiver can be exploited to receive the required signals while sending jamming signals at the same time to confuse the eavesdroppers [3]. However, this transmit and receive jamming scheme might not be possible under all circumstances due to limited available number of antennas and the strong self-interference (SI). In this scenario, the external nodes can be employed to send jamming signals, where they could be relay nodes or private jammers [5], [6].

In case of private jammers, they could introduce charges for their dedicated jamming services. The problems associated with these private jammers can be formulated into different game theoretic problems by considering the legitimate nodes and the private jammers as the players of the game.

This article focuses on physical layer security jamming techniques based on user cooperations and external nodes. Firstly, theoretical limits of jamming through user cooperation is presented, and then multi-antenna based jamming techniques are reviewed by exploiting their spatial diversity and degrees of freedom (DoF). For example, the advantages of jamming with multi-antenna transmitter can be easily demonstrated by appropriately designing beamformers such that it would cause a significant interference to the eavesdroppers while no or less interference leakage to the intended receivers. However, the study of theoretical limits of jamming and the practical designs are necessary to achieve the optimal performance in secrecy networks. This article presents these theoretical limits and design approaches as follows. First, theoretical limits of user cooperation based jamming are explored. Then, centralized and game theoretic based multiple-input multiple-output (MIMO) transmit and receive precoding techniques are discussed to provide efficient jamming services. In addition, wireless energy harvesting (WEH) based jamming techniques are presented through the recent advancement in simultaneous wireless information and power transfer (SWIPT) concept. Finally, future research challenges of jamming schemes are briefly discussed.

II. INFORMATION-THEORETIC LIMITS OF JAMMING

In this section, we present the theoretical limits of cooperative-users based jamming for physical layer security. The concept of cooperative jamming (CJ) was introduced in [2] for a Gaussian multiple access wiretap channel (GMAC-WT) from an information-theoretic aspect. In the GMAC-WT channel, multiple legitimate users wish to send secret messages to a common receiver in the presence of a passive eavesdropper. In order to maximize all the sum secrecy rate, a user should send pure Gaussian noise as long as the eavesdropping channel from it to the eavesdropper is stronger than the legitimate channel from it to the intended receiver. The CJ scheme can be illustrated via a simple two-user GMAC-WT channel as shown in Fig. 1, where a transmitter (Alice) wishes to send a secret message W_1 to the intended receiver (Bob) under the help of an interferer (Carlo), without leaking any information to the eavesdropper (Eve). The channel gains from Alice to Bob and Eve are normalized to be 1 and $\sqrt{a}$; the channel gains from Carlo to Bob and Eve are normalized to be $\sqrt{b}$ and 1. Note that the channel gains from Alice to Bob and from Carlo to Eve are different with each other although both of them are normalized to 1, which is reflected by the fact that both the channels have different effects on the received signal-noise-ratios (SNRs) at Bob and Eve. This channel model is also called the wiretap channel with a helping interferer (WT-HI) in [7]. When $b < 1$, Carlo can help Alice and Bob

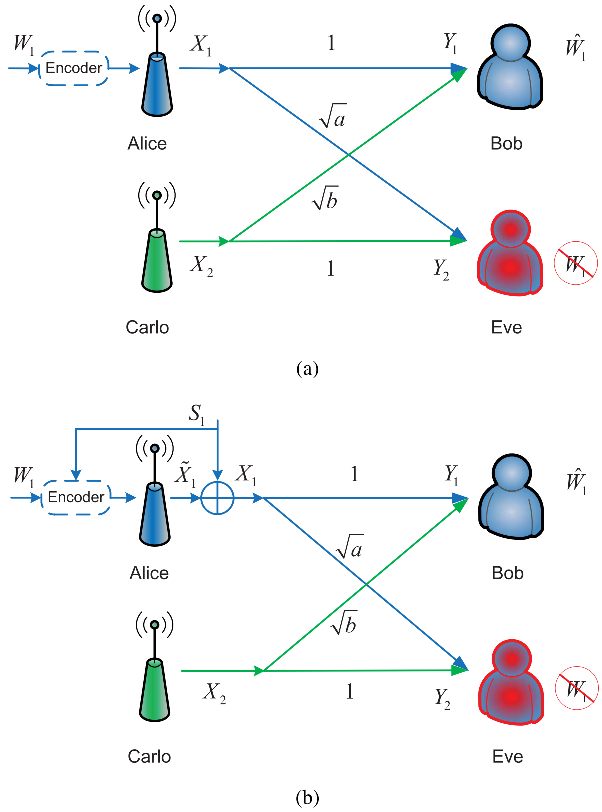


FIGURE 1. (a) The wiretap channel with a helping interferer (WT-HI). (b) The WT-HI channel with artificial state.

to enhance the security level by sending Gaussian noise that is independent of the message-carrying signal. This can be interpreted by the fact that Carlo's jamming signal harms Eve more than Bob when $b < 1$, which may improve the achievable secrecy rate.

CJ is useful only when $b < 1$ in the WT-HI channel in Fig. 1 (a). But, when $b > 1$, i.e., Carlo has a stronger channel to Bob than to Eve, CJ in [2] might not be useful. In this case, Carlo can still help Alice and Bob using the noise forwarding (NF) scheme in [8]. In NF, Carlo can randomly choose a codeword from a known codebook with an appropriate coding rate such that the confusion signal can be decoded by Bob before the decoding of W_1, and hence, without affecting the message-carrying signal, still jams the eavesdropping channel. An interpretation of NF is that the independent confusion codewords can bring additional randomness to the channel to enhance the security level. The main difference between NF and CJ is that, the former designs the confusion signals with structure that does not jam Bob, whereas the latter uses pure noise that jams Bob and Eve simultaneously.

Both CJ and NF can be generalized into a unified framework based on the adaptive adjustment of the coding rate at Carlo, which is called interference assisted (IA) scheme in [7] for the WT-HI channel. The main difference between the IA and NF schemes is that, in the former, Carlo treats its coding rate as a variable, and adaptively adjusts this coding rate to maximize the achievable secrecy rate; while in the latter,

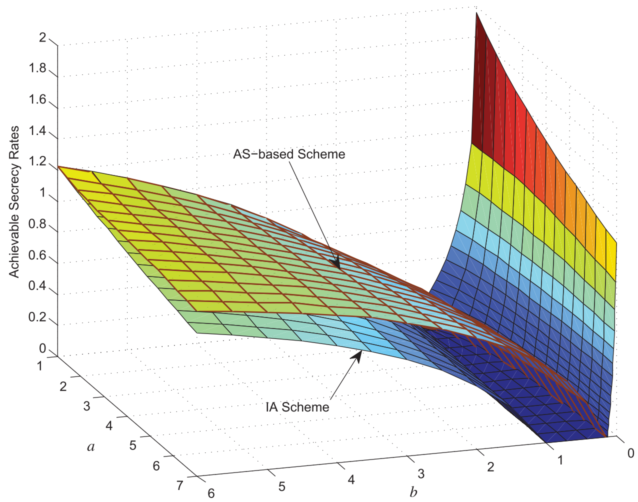


FIGURE 2. Achievable secrecy rates of the IA and AS-based schemes for the WT-HI channel shown in Fig. 1 (a), where the maximum transmit power at Alice and Carlo are 20 and 50, respectively. Since the IA scheme is a generalization of the CJ and NF scheme, its achievable secrecy rate is the same as that of the CJ scheme when $b < 1$ and the same as that of the NF scheme when $b > 1$.

Carlo always chooses a coding rate such that the interference transmitted by him does not affect Bob. Both CJ and NF can be viewed as the special cases of the IA scheme. When the coding rate at Carlo is lower than a certain rate such that Bob can decode the interference before decoding the secret message, the IA scheme reduces to NF; when the coding rate at Carlo is sufficiently large such that both Bob and Eve have no choice but to treat the interference as pure noise, the IA scheme reduces to CJ.

CJ and NF can also be generalized by the channel prefixing scheme in secure communications. As shown in the Gaussian WT-HI channel in Fig. 1 (a), the confusion signal transmitted by Carlo can consist of two parts, i.e., $X_2 = U_2 + Z_2$, where one part (U_2) is the codeword with the structure following the NF scheme, and the other part (Z_2) is pure Gaussian noise following the CJ scheme. In this channel prefixing scheme, the channel input X_2 at Carlo becomes a noisy version of the interference codeword U_2 in terms of the Markov chain $U_2 - X_2 - Y_1, Y_2$. In addition to Carlo's channel prefixing, the work in [9] also adopted a channel prefixing scheme at Alice based on artificial state (AS), and the achievable secrecy rate can be further enhanced. Specifically, Alice spends part of its transmit power to generate an AS S_1, i.e., it sets the channel input as $X_1 = \tilde{X}_1 + S_1$ as shown in Fig. 1 (b). Now, the WT-HI channel in Fig. 1 (a) becomes a WT-HI channel with state information as shown in Fig. 1 (b), where the random state S_1 is known by Alice a priori and $\tilde{X}_1$ can be viewed as the virtual channel input. Then following the concept of dirty paper coding (DPC), we introduce an auxiliary variable $U_1 = \tilde{X}_1 + \beta S_1$ as the message-carrying codeword. According to DPC, S_1 will not affect the decoding of the message-carrying codeword U_1 at Bob by appropriately setting the value of β.

Fig. 2 shows achievable secrecy rates of the IA and AS-based schemes for the WT-HI channel shown in Fig. 1 (a), where the maximum normalized transmit power at Alice and Carlo are 20 and 50. For both schemes, Gaussian codebooks are adopted, where the message-bared signal $X_1 \sim \mathcal{N}(0, P_1)$, and the Gaussian interference $X_2 \sim \mathcal{N}(0, P_2)$, $0 \leq P_1 \leq 20$, $0 \leq P_2 \leq 50$. Furthermore, the AS-based scheme sets $\tilde{X}_1 \sim (0, (1-\lambda)P_1)$, $S_1 \sim (0, \lambda P_1)$. The optimal values of these parameters (P_1, P_2, λ) are established via exhaustive searches. As shown in Fig. 2, when $a > 1$, the AS at Alice is important to get a larger secrecy rate if compared with the NF (or IA) scheme. Particularly, when $b = 1$, Carlo can still assist Alice to achieve a positive secrecy rate, whereas the CJ, NF and IA schemes fail. This can be interpreted by the fact that the AS at Alice can associate with the helping interference at Carlo to further confuse Eve without affecting Bob. Fig. 2 also shows that the gap between the AS-based and the NF schemes can be enlarged by increasing a from 1 to 7. Moreover, the AS-based scheme reduces to the CJ (or IA) scheme when $b < 1/a$, thanks to the channel prefixing at Carlo.

The works in [2] and [7]–[9] used information-theoretical Gaussian codebooks with infinite alphabets, which is hard to implement in practice. Alternatively, the work in [10] has proposed an achievable scheme based on layered nested lattice codes with an finite alphabets. Interestingly, unlike traditional communications without secrecy constraints, the use of more practical lattice codes can outperform the Gaussian codebook for the channel model in Fig. 1 (a) for certain cases. Specifically, the scheme in [10] can achieve non-zero secure degree of freedom (s.d.o.f.) for all values of channel gain pair $(\sqrt{a}, \sqrt{b})$ except when $ab = 1$, whereas the works [2] and [7]–[9] fail to achieve non-zero s.d.o.f.. This is because, based on nested lattice codes, the signals transmitted by both the source and the cooperative jammer can be aligned at the eavesdropper but remain separable at the intended receiver; whereas the Gaussian noise transmitted by the cooperative jammer simultaneously interferes with the eavesdropper, and hurts the intended receive.

III. MIMO JAMMING: CENTRALIZED APPROACH

In this section, we review key results of using MIMO to transmit judiciously jamming signals with an aim to achieve higher secrecy rate. Specifically, centralized transmit and receive jamming techniques are discussed in the following subsections.

A. TRANSMIT JAMMING

Consider a basic three-node system, which consists of a transmitter, an intended receiver and an eavesdropper. The transmitter has multiple antennas, while the receiver and the eavesdropper may have multiple antennas or a single antenna. The secrecy capacity is well known [1] when the channel state information (CSI) is available to all nodes. While it is reasonable to assume to have the receiver's CSI, it is usually unrealistic to obtain the eavesdropper's CSI. In the case where only the receiver's CSI is known but the eavesdropper's CSI is absent, the transmit jamming or AN is an effective means

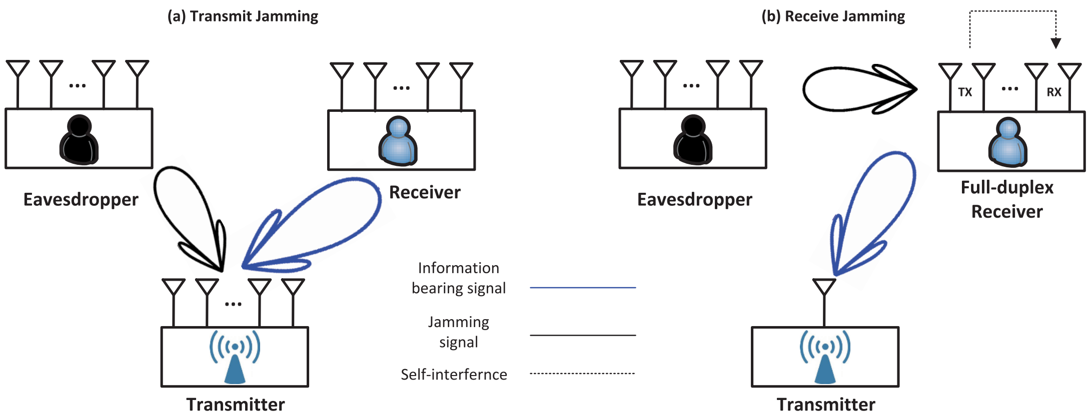


FIGURE 3. MIMO Jamming. (a) Transmit jamming when the transmitter has multiple antennas; (b) Receive jamming when the receiver has multiple antennas and works in the FD mode.

to improve the secrecy rate. As shown in Fig. 3 (a), the total transmit signal is split into two parts. The first one is the information-bearing message towards the direction of the receiver, which can be designed based on the receiver's CSI. The second part is the transmit jamming, which is isotropic Gaussian noise in the orthogonal space of the receiver's channel. By doing so, the transmit jamming does not affect the intended receiver but only degrades the quality of the signal received by the eavesdropper. A remarkable result about this simple transmit jamming scheme shown in [1] is that, it can achieve secrecy rate close to the capacity in the high SNR regime when the receiver has a single antenna.

The use of transmit jamming consumes some transmit power so it reduces the SNR at the receiver. Therefore it is important to allocate power to the information-bearing signals and the jamming signals properly. While it is in general difficult to achieve the optimal power allocation, a general rule of thumb is to allocate more power to jamming when the receiver's CSI is more accurate or the number of the eavesdropper's antennas increases to achieve effective jamming.

B. RECEIVE JAMMING

Transmit jamming is useful but requires the support of multiple antennas. When the transmitter has a single antenna, is it still possible to take advantage of jamming? Fortunately, there is a positive answer to this question. One possible solution is to use jamming at the receiver side to confuse the eavesdropper. There are different implementations. For instance, the transmitter repeats the transmission for a certain times, and the receiver randomly jams the transmissions [11]. Because the eavesdropper does not know which transmission is left unjammed, it cannot decode the message correctly. One drawback of this scheme is that, it requires retransmission, which is less bandwidth efficient and may be critical for delay-sensitive applications. Next we introduce a receive jamming scheme without using retransmissions.

Traditionally a wireless node works in the half-duplex (HD) mode. The FD operation, which allows a wireless node to transmit and receive simultaneously in the same frequency band has emerged as an attractive solution to improve the spectral efficiency. The FD operation has also shown great potential to improve physical layer security. As depicted in Fig. 3(b), the main idea is that the intended receiver sends jamming signals to degrade the eavesdropper's channel and protect its own reception [3]. Obviously the receive jamming will affect both the intended receiver itself and the eavesdropper because of the resulting SI, but if the SI can be well controlled/optimized, it will favor the intended receiver. When the receiver has multiple transmit or receive antennas, it can employ joint transmit and receive beamforming for simultaneous signal detection, SI suppression and jamming emission. An interesting result in [3] is that when the global CSI is available, the secrecy rate increases unbounded as the SNR goes up, which is in contrast to the traditional HD case without receive jamming. Even when only statistical information about the eavesdropper's channel is known, substantial secrecy rate improvement is observed. Obviously, transmit and receive jamming can be combined to further improve the secrecy rate in a MIMO wiretap channel. In addition, both of these jamming techniques can be directly applied to the relay jamming schemes, where a set of trusted half-duplex or full-duplex relays can help the communication between legitimate terminals while introducing jamming signals to the eavesdroppers. The half-duplex relays could introduce artificial noise to the eavesdroppers while transmitting the signal to the legitimate users. On the other hand, the full-duplex relays could transmit jamming signal, while receiving the signals from the source. Specifically, the artificial noise approach with half-duplex relays can be considered as the transmit jamming, whereas the receive jamming represents the full-duplex relay based jamming scheme.

IV. MIMO JAMMING: GAME THEORETIC APPROACH

In this section, we review game theoretic based jamming approaches for physical layer security. The centralized transmitter-receiver based jamming schemes discussed in the previous section might not be able to achieve the required

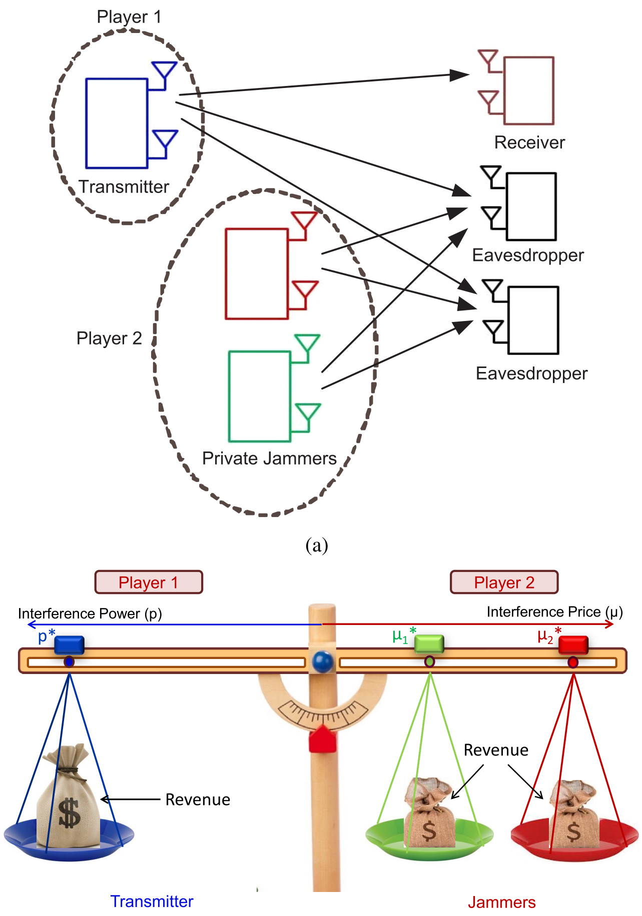


FIGURE 4. (a) A MIMO secrecy network with multiple eavesdroppers and private jammers. (b) The concept of equilibrium for the transmitter-private jammers game.

performance under all circumstances due to channel conditions and the strong SI. In this scenario, external jammers can be employed to improve the quality of the secure communications by introducing jamming signals to the eavesdroppers as shown in Fig. 4 (a) [5], [6]. However, these external (private) jammers charge for their dedicated jamming services from the transmitter based on the amount of interference caused at the eavesdroppers. In order to compensate these prices, the transmitter introduces charges for its enhanced secure transmission from the legitimate users. In this scenario, both the transmitter and the private jammers compete to maximize their revenues by providing higher secrecy rates at the legitimate users and selling the interference to the transmitter, respectively.

In order to analyze the interactions between the transmitter and the private jammers, game theory provides the mathematical structure and concepts to formulate this scenario into different games, where both the transmitter and the private jammers will be the players of the game [12]. In addition, analytical results obtained through these games based on the strategic decisions of the players will help to conclude whether there is an equilibrium in their revenues for the proposed game as shown in Fig. 4(b), at which both players achieve their maximum revenues. On the other hand, achieving these equilibria among the players might introduce more complexity in the network, even though they are beneficial for all players. To circumvent these complexity issues, game theory also facilitates to develop distributed and low complexity based implementation to attain these equilibria. Based on whether it is a collaboration or competition among the players, these games can be classified into cooperative and non-cooperative games, respectively [12].

A secrecy network model is considered with one transmitter and one legitimate user, where private jammers help to improve the secure transmission by causing interference to the eavesdroppers as shown in Fig. 4(a). The transmitter, the legitimate user and the private jammers are all equipped with multiple antennas. As mentioned earlier, the interaction of buying interference from private jammers and announcing interference prices to the transmitter can be formulated into a *Stackelberg* game, where the private jammers and the transmitter are the *leaders* (Player 1) and the *follower* (Player 2) of the game, respectively [12]. In order to study this game, the best responses of both the players should be derived, where the best interference requirements for a given interference price and the best interference price for a given interference requirements will be obtained at both the players. Based on these best responses, the *Stackelberg* equilibrium can be achieved by deriving the optimal interference requirement and the interference prices. At this equilibrium as shown in Fig. 4(b), both of the players will achieve their maximum revenues and the deviation of any player from this equilibrium will cause a loss in their revenues. This equilibrium can be implemented by exchanging the associated channel responses between the transmitter and the private jammers. However, this might introduce more complexity in the network. Therefore, a distributed implementation of this equilibrium would be more appropriate to reduce the complexity, where the interference prices offered by the jammers and the interference requirements at the transmitter can be iteratively updated [5].

The secrecy network might consist of multiple legitimate multi-antenna transmitter-receiver pairs as well as a friendly jammer in the presence of multiple eavesdroppers. In this scenario, each pair tries to maximize its secrecy rate with the help of the friendly jammer by introducing interference to the eavesdroppers. However, the jamming signals will cause interference not only to the eavesdroppers but also to the destinations, which will degrade the secrecy rate performance. Therefore, the jammer should distribute its power among the users such that the secrecy rate performance is improved. These interactions between the pairs and the jammer can be formulated into an *auction* game, where the transmitters and the jammer will be the bidders and auctioneer [12], respectively. The transmitters will submit their bids to the jammer depending on the payment of the corresponding jammer-power and the secrecy rate improvement whereas the jammer will determine the optimal power allocations between the users based on these bids. For this game, a distributed solution can be developed by exploiting the distributed auction theoretic approach, where the bids from the transmitters and power allocations between the users will be updated iteratively.

V. ENHANCING PHYSICAL LAYER SECURITY IN WIRELESS ENERGY HARVESTING NETWORKS

Since there has been an upsurge of research interest as well as emerging applications for radio-frequency (RF) signal-enabled wireless energy transfer, which avails the broadcasting and far-field radiative properties of electromagnetic (EM) wave to power wireless devices in particular, while transferring information, new challenges as well as opportunities for physical layer security begin arising in these WEH-enabled networks. In this section, we discuss the-state-of-art technologies enhancing physical layer security for one important class of WEH application, i.e., *wireless powered communication network* (WPCN).

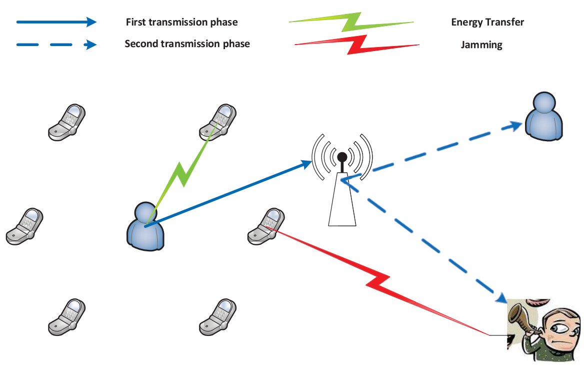


FIGURE 5. **A WPCN model employing harvest-and-jam (HJ) protocol.**

Physical layer security issues in the rapidly developed cooperative networks such as device-to-device systems, relay networks etc., have already drawn significant attention and inter alia, CJ has been widely studied as a promising technology [2], [4]. However, the benefits of CJ would be quite compromised if those energy-limited potential helpers are unwilling to cooperate. In the following, we introduce how this bottleneck could be broken with self-sustainable terminals in a WPCN. Benefiting from dense radio-frequency (RF) signals of increasing amount of data transmission in the cooperative networks, a newly designed two-phase protocol, i.e., *harvest-and-jam* (HJ) was proposed in [13] to achieve secrecy transmission by CJ and yet not to add extra power cost. Specifically, as illustrated in Fig. 5, in the first transmission phase, a single-antenna transmitter sends confidential information to a multi-antenna amplify-and-forward (AF) relay with conventional power supply and simultaneously transfers power to a group of idle multi-antenna users serving as helpers; in the second transmission phase, the AF relay amplifies, and forwards the message to the legitimate receiver under the protection of jamming, which is generated from each of the helpers by its harvested power in the previous transmission phase. The secrecy rate is maximized by optimizing the transmit beamforming matrix for the AF relay and the jamming covariance matrices for each of the helpers subject to transmit power constraints, under circumstances of perfect and imperfect CSI available at the coordinating node, respectively.

The results in [13] showed that the HJ scheme plays a prominent role in improving secret communications in practical scenarios of imperfect CSI. Especially, when CSIs related to the eavesdropper are hard to obtain and more imperfect than those related to the legitimate users, the optimal power allocation scheme inclines to jam the eavesdropper using all available power, and hence considerably degrades its information reception while minimizing the interference caused to the legitimate receiver. Typically, in a WPCN setup where helpers are fixed and evenly distributed around a disk centered on the transmitter with radius 2m, assuming a simple channel fading model comprising Rayleigh fading and pathloss given by $(\frac{d}{d_0})^{-\alpha}$, given the reference distance $d_0 = 1$m and the attenuation factor $\alpha = 3$, if the transmit power is set to be 0dBm and the energy conversion efficiency is 50%, the average per-antenna harvested power at each helper is around 62.5μW.

Besides increasing the secrecy rate (short-term metric) via adaptive power allocation over antennas for AF beamforming and jamming signal design, [14] considered a similar idea of increasing the confidential information transmission throughput (long-term metric) via a wireless-powered friendly jammer by proposing a delicately designed protocol with not necessarily equal time duration for the "harvest" and "jam" phases. Specifically, defining a "power transfer (PT)" block for the jammer to harvest energy from the source and an "information transmission (IT)" block for confidential information to be transmitted under the protection of a jamming signal, a threshold amount of energy, i.e., $\mathcal{P}_J T$, which supports jamming using power $\mathcal{P}_J$ for a transmission block of T time unit, is examined at the jammer's battery storage at the beginning of each transmission block. Only when this threshold is achieved, and meanwhile the source-destination (main channel) does not suffer from communications outage, the IT block with jamming starts. Otherwise, the transmission enters into either *dedicated PT block* (when the threshold condition is not satisfied) or *opportunistic PT block* (when communication outage over the main channel occurs). Based on this protocol design, four types of PT-IT cycles consisting of varied combination of these blocks are characterized, and as a result, the long-term behavior of this stochastic process has been analyzed with a closed-form achievable throughput. Finally, the design parameters, $\mathcal{P}_J$ and the fixed transmission rates are optimized to further maximize the secrecy throughput under the constraint of the secrecy outage probability.

VI. RESEARCH CHALLENGES

In this section, we provide future research challenges associated with the physical layer security jamming schemes discussed in the previous sections.

A. THEORETICAL LIMITS

Though existing works have proposed a variety of jamming schemes to enhance security level, the secrecy capacity has not been found even for the simple WT-HI channel in Fig. 1. Future work of interest is to design more intelligent coding schemes to achieve the secrecy capacity. For example, though the AS-based scheme in [9] showed that the channel prefixing technique is crucial to improve the achievable secrecy rate, the effects of channel prefixing has not been fully revealed. Moreover, this paper only considers the jamming schemes based on Gaussian random coding, which cannot achieve a positive secure DoF at high SNR, while recent works have shown that the non-Gaussian codes (e.g., structured codes) can achieve a positive secure DoF at high SNR. Hence the design of non-Gaussian codes is also an interesting future research area.

B. SMART MIMO JAMMING

The majority of literature assumes ideal Gaussian signalling and therefore the optimal jamming also uses Gaussian signalling. However, Gaussian signalling is not practical and wireless systems often employ constant envelop signalling schemes like phase-shift-keying (PSK). In this case, it is shown that Gaussian jamming is no longer effective, and can be removed by the multi-antenna eavesdropper using blind source separation techniques such as constant modulus algorithms [15]. Therefore, there is a need to design the smart jamming signals adaptive to the specific constellation used.

Massive MIMO is a great enabler to achieve spectrum-efficient and energy-efficient wireless communications. However, its security implication is not well understood. Our previous work shows that massive MIMO systems, if carefully designed, are actually quite robust against both passive and active attacks [16]. Further investigation is needed to understand its potential to effectively jam the eavesdroppers.

C. ROBUST JAMMING GAMES

Effective jamming requires perfect CSI, which is difficult to obtain in practice. Imperfect CSI may not only degrade the performance of the legitimate communications but also results in information leakage to the eavesdroppers. In order to deal with this issue, it is necessary to consider robust transmit jamming to achieve guaranteed outage performance of the secrecy rate. Most of the game theoretic approaches proposed for physical layer security have been assumed that the players have the perfect CSI of the eavesdroppers. In order to overcome the imperfect CSI issues associated with eavesdroppers in the existing games, robust techniques should be considered for secure communications. Therefore, the development of robust jamming games by incorporating channel uncertainties or the cases of no eavesdroppers' CSI along with the corresponding analysis of equilibria would be very challenging. These robust jamming games could be formulated into *Bayesian* games, which are well known for the scenarios with incomplete information. The jamming games with imperfect eavesdroppers CSI would be one of the possible interesting future directions in game theoretic based jamming for physical layer security.

D. WIRELESS ENERGY HARVESTING

More sophisticated transmission protocols incorporating adaptive power/rate designs are expected to be studied for further improving the long-term secrecy throughput in [14]. Besides, to further motivate the potential WEH-enabled helpers to assist secure communications, more practical energy and communications mechanism needs to be properly designed. For example, neighbour-users of the transmitter could be self-interested and prefer to storing the harvested energy for their own use rather than help jam. In this situation, the transmitter needs to offer some spare communications resource as incentives, such as spectrum, to increase the cooperation utility and reduce the overall system cost.

VII. CONCLUSIONS

In this article, the jamming techniques for physical layer security have been discussed with different approaches. In particular, the theoretical limits of user cooperation based jamming and the practical designs of MIMO jamming as well as the game theoretic based jamming techniques have been reviewed. In addition, the WEH based jamming has also been presented for improving energy efficiency in secure communications by exploiting the wireless harvested energy to generate jamming signals to the eavesdroppers. Finally, future research challenges of these jamming schemes for physical layer security have been briefly outlined.

REFERENCES

[1] A. Khisti and G. W. Wornell, "Secure transmission with multiple antennas I: The MISOME wiretap channel," *IEEE Trans. Inf. Theory*, vol. 56, no. 7, pp. 3088–3104, Jul. 2010.

[2] E. Tekin and A. Yener, "The general Gaussian multiple-access and two-way wiretap channels: Achievable rates and cooperative jamming," *IEEE Trans. Inf. Theory*, vol. 54, no. 6, pp. 2735–2751, Jun. 2008.

[3] G. Zheng, I. Krikidis, J. Li, A. P. Petropulu, and B. Ottersten, "Improving physical layer secrecy using full-duplex jamming receivers," *IEEE Trans. Signal Process.*, vol. 61, no. 20, pp. 4962–4974, Oct. 2013.

[4] A. Mukherjee, S. A. A. Fakoorian, J. Huang, and A. L. Swindlehurst, "Principles of physical layer security in multiuser wireless networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1550–1573, 3rd Quart., 2014.

[5] R. Zhang, L. Song, Z. Han, and B. Jiao, "Physical layer security for two-way untrusted relaying with friendly jammers," *IEEE Trans. Veh. Technol.*, vol. 61, no. 8, pp. 3693–3704, Oct. 2012.

[6] Z. Chu, K. Cumanan, Z. Ding, M. Johnston, and S. Y. Le Goff, "Secrecy rate optimizations for a MIMO secrecy channel with a cooperative jammer," *IEEE Trans. Veh. Technol.*, vol. 64, no. 5, pp. 1833–1847, May 2015.

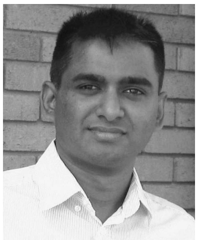
[7] X. Tang, R. Liu, P. Spasojević, and H. V. Poor, "Interference assisted secret communication," *IEEE Trans. Inf. Theory*, vol. 57, no. 5, pp. 3153–3167, May 2011.

[8] L. Lai and H. El Gamal, "The relay–eavesdropper channel: Cooperation for secrecy," *IEEE Trans. Inf. Theory*, vol. 54, no. 9, pp. 4005–4019, Sep. 2008.

[9] P. Xu, Z. Ding, X. Dai, and K. K. Leung, "A general framework of wiretap channel with helping interference and state information," *IEEE Trans. Inf. Forensics Security*, vol. 9, no. 2, pp. 182–195, Feb. 2014.

[10] X. He and A. Yener, "Providing secrecy with structured codes: Two-user Gaussian channels," *IEEE Trans. Inf. Theory*, vol. 60, no. 4, pp. 2121–2138, Apr. 2014.

[11] S. Gollakota and D. Katabi, "Physical layer wireless security made fast and channel independent," in *Proc. IEEE Int. Conf. Comput. Commun.*, Shanghai, China, Apr. 2011, pp. 1125–1133.
[12] Z. Han, D. Niyato, W. Saad, T. Başar, and A. Hjørungnes, *Game Theory in Wireless and Communication Networks: Theory, Models, and Applications*. Cambridge, U.K.: Cambridge Univ. Press, 2010.
[13] H. Xing, K.-K. Wong, Z. Chu, and A. Nallanathan, "To harvest and jam: A paradigm of self-sustaining friendly jammers for secure AF relaying," *IEEE Trans. Signal Process.*, vol. 63, no. 24, pp. 6616–6631, Dec. 2015.
[14] W. Liu, X. Zhou, S. Durrani, and P. Popovski, "Secure communication with a wireless-powered friendly jammer," *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 401–415, Jan. 2016.
[15] O. Bakr and R. Mudumbai, "A new jamming technique for secrecy in multi-antenna wireless networks," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, Austin, TX, USA, Jun. 2010, pp. 2513–2517.
[16] D. Kapetanovic, G. Zheng, and F. Rusek, "Physical layer security for massive MIMO: An overview on passive eavesdropping and active attacks," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 21–27, Jun. 2015.



KANAPATHIPPILLAI CUMANAN (M'10) received the B.Sc. (Hons.) degree in electrical and electronic engineering from the University of Peradeniya, Sri Lanka, in 2006, and the Ph.D. degree in signal processing for wireless communications from Loughborough University, Loughborough, U.K., in 2009.

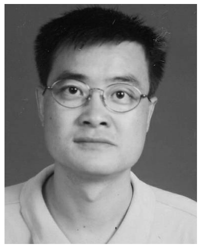
He is currently a Lecturer with the Department of Electronics, University of York, U.K. He was with the School of Electronic, Electrical and System Engineering, Loughborough University, U.K. He was a Teaching Assistant with the Department of Electrical and Electronic Engineering, University of Peradeniya, Sri Lanka, in 2006. In 2011, he was an Academic Visitor with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore. He was a Research Associate with the School of Electrical and Electronic Engineering, Newcastle University, U.K., from 2012 to 2014. His research interests include physical layer security, cognitive radio networks, relay networks, convex optimization techniques, and resource allocation techniques.

He was a Research Student with Cardiff University, Wales, U.K., from 2006 to 2007. He was a recipient of an Overseas Research Student Award Scheme from Cardiff University.

HONG XING (S'12–M'16) received the B.Eng. degree in electronic sciences and technologies, and the B.A. degree in English literature from Zhejiang University, Hangzhou, China, in 2011, and the Ph.D. degree in wireless communications from King's College London, London, U.K., in 2015. Since 2016, she has been a Research Associate with the Department of Informatics, King's College London. Her research interests include physical layer security, wireless information and power transfer, cooperative communications, cognitive radio, and applications of convex optimization in wireless communications.

PENG XU received the B.Eng. and the Ph.D. degrees in electronic and information engineering from the University of Science and Technology of China, Anhui, China, in 2009 and 2014, respectively. From 2014 to 2016, he has been a Post-Doctoral Researcher with the Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei, China. Since 2016, he has been with the Chongqing University of Posts and Telecommunications. His current research interests include cooperative communications, information theory, information-theoretic secrecy, and 5G networks. He received the IEEE Wireless Communications Letters Exemplary Reviewer 2015.

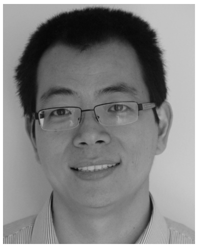
GAN ZHENG (S'05–M'09–SM'12) received the B.Eng. and the M.Eng. degree in electronic and information engineering from Tianjin University, Tianjin, China, in 2002 and 2004, respectively, and the Ph.D. degree in electrical and electronic engineering from The University of Hong Kong in 2008. He is currently a Senior Lecturer with the Signal Processing and Networks Research Group, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, U.K. He held various research and visiting positions with the University College London, the KTH Royal Institute of Technology, and the University of Luxembourg, and was with University of Essex as a Lecturer in Communications. His research interests include MIMO precoding, cooperative communications, cognitive radio, physical-layer security, full-duplex radio, and energy harvesting. He was the First Recipient of the 2013 IEEE Signal Processing Letters Best Paper Award, and received the 2015 GLOBECOM Best Paper Award. He currently serves as an Associate Editor of the IEEE Communications Letters.



XUCHU DAI received the B.Eng. degree in electrical engineering from Air force Engineering University, Xian, China, in 1984, and the M.Eng. and Ph.D. degrees in communication and information systems from the University of Science and Technology of China, Hefei, China, in 1991 and 1998, respectively. He was with the Hong Kong University of Science and Technology as a Post-Doctoral Researcher from 2000 to 2002. He is currently a Professor with the Department of Electronic Engineering and Information Science, University of Science and Technology of China. His current research interests include wireless communication systems, blind adaptive signal processing, and signal detection.

ARUMUGAM NALLANATHAN (S'97–M'00–SM'05–F'17) is currently a Professor of Wireless Communications with the Department of Informatics, King's College London (University of London). He served as the Head of Graduate Studies with the School of Natural and Mathematical Sciences, King's College London, from 2011 to 2012. He was an Assistant Professor with the Department of Electrical and Computer Engineering, National University of Singapore from 2000 to 2007. His research interests include 5G wireless networks, molecular communications, energy harvesting and cognitive radio networks. He published nearly 300 technical papers in scientific journals and international conferences. He was a co-recipient of the Best Paper Award presented at the IEEE International Conference on Communications 2016 and IEEE International Conference on Ultra-Wideband 2007. He is currently an IEEE Distinguished Lecturer. He has been selected as a Thomson Reuters Highly Cited Researcher in 2016.

He is an Editor of the IEEE Transactions on Communications and the IEEE Transactions on Vehicular Technology. He was an Editor of the IEEE Transactions on Wireless Communications (2006–2011), the IEEE Wireless Communications Letters, and the IEEE Signal Processing Letters. He served as the Chair of the Signal Processing and Communication Electronics Technical Committee of the IEEE Communications Society, the Technical Program Co-Chair (MAC track) of the IEEE WCNC 2014, the Co-Chair of the IEEE GLOBECOM 2013 (Communications Theory Symposium), the Co-Chair of the IEEE ICC 2012 (Signal Processing for Communications Symposium), the Co-Chair of the IEEE GLOBECOM 2011 (Signal Processing for Communications Symposium), the Technical Program Co-Chair of the IEEE International Conference on UWB 2011, the Co-Chair of the IEEE ICC 2009 (Wireless Communications Symposium), the Co-chair of the IEEE GLOBECOM 2008 (Signal Processing for Communications Symposium), and the General Track Chair of IEEE VTC 2008. He was a recipient the IEEE Communications Society SPCE Outstanding Service Award 2012 and the IEEE Communications Society RCC Outstanding Service Award 2014.



ZHIGUO DING (S'03–M'05) received the B.Eng. degree in electrical engineering from the Beijing University of Posts and Telecommunications in 2000, and the Ph.D. degree in electrical engineering from Imperial College London in 2005. From 2005 to 2014, he was with Queen's University Belfast, the Imperial College, and Newcastle University. From 2012 to 2016, he was an Academic Visitor with Princeton University. Since 2014, he has been with Lancaster University as a Chair Professor.

His research interests are 5G networks, game theory, cooperative and energy harvesting networks, and statistical signal processing. He is currently an Editor of the IEEE Transactions on Communications, the IEEE Transactions on Vehicular Technology, the IEEE Wireless Communication Letters, the IEEE Communication Letters, and the *Journal of Wireless Communications and Mobile Computing*. He received the Best Paper Award in IET Communications Conference on Wireless, Mobile and Computing, 2009, the IEEE Communication Letter Exemplary Reviewer 2012, and the EU Marie Curie Fellowship 2012–2014.

GEORGE K. KARAGIANNIDIS (M'96–SM'03–F14) was born in Pithagorion, Greece. He received the University Diploma (5 years) and Ph.D. degrees in electrical and computer engineering from the University of Patras, in 1987 and 1999, respectively. From 2000 to 2004, he was a Senior Researcher with the Institute for Space Applications and Remote Sensing, National Observatory of Athens, Greece. In 2004, he joined the Faculty of Aristotle University of Thessaloniki, Greece where he is currently a Professor with the Electrical and Computer Engineering Department and the Director of the Digital Telecommunications Systems and Networks Laboratory. He is also an Honorary Professor with South West Jiaotong University, Chengdu, China.

His research interests are in the broad area of digital communications systems and signal processing, with emphasis on wireless communications, optical wireless communications, wireless power transfer and applications, molecular communications, communications and robotics, and wireless security.

He has authored or co-authored over 400 technical papers in scientific journals and presented at international conferences. He is also an author of the Greek edition of a book on *Telecommunications Systems* and a co-author of the book *Advanced Optical Wireless Communications Systems*, (Cambridge Publications, 2012).

Dr. Karagiannidis has been involved as the General Chair, the Technical Program Chair, and a member of the Technical Program Committees in several IEEE and non-IEEE conferences. He was an Editor of the IEEE Transactions on Communications, a Senior Editor of the IEEE Communications Letters, an Editor of the *EURASIP Journal of Wireless Communications and Networks* and several times Guest Editor of the IEEE Selected Areas in Communications. From 2012 to 2015, he was the Editor-in Chief of the IEEE Communications Letters.

Dr. Karagiannidis is one of the highly-cited authors across all areas of electrical engineering, recognized as 2015 and 2016 Thomson Reuters highly-cited researcher.