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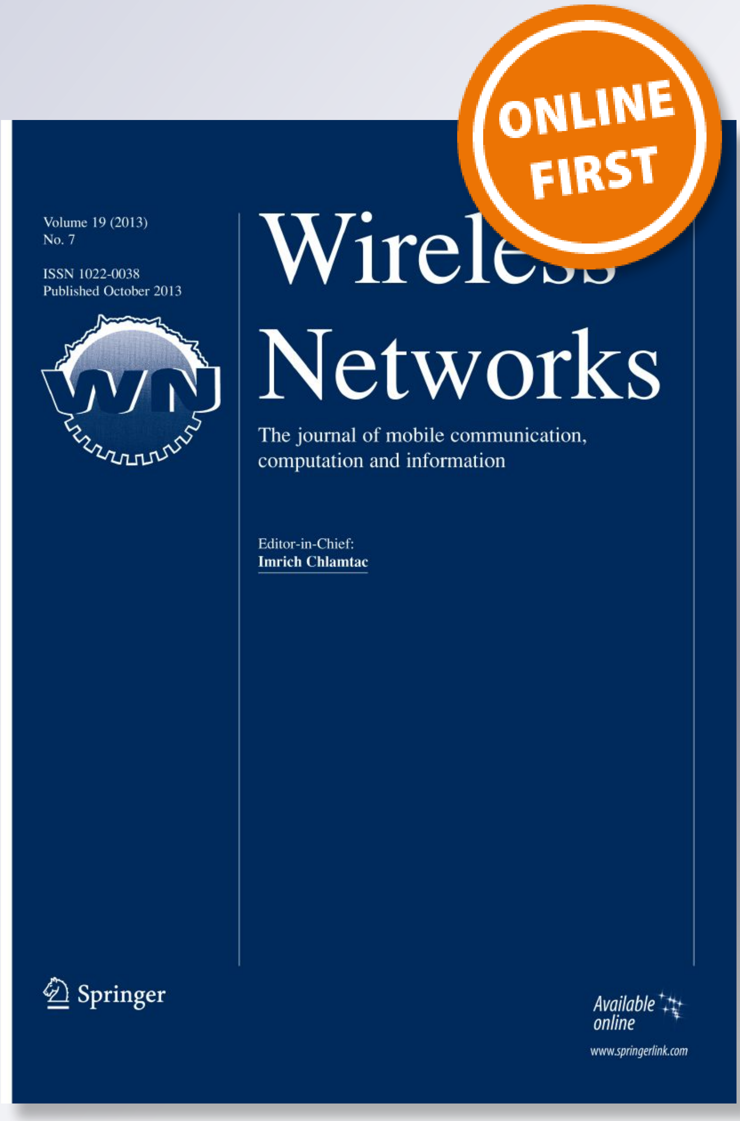

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Improving physical layer security and efficiency in D2D underlay communication

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Abstract
Device-to-device (D2D) communication is a core technology for expanding the next generation wireless cellular network. To deal with the security challenges and optimize the system communication quality, this paper investigates the security and efficiency problem of D2D underlay communication in a base station cell area with the presence of malicious eavesdroppers. Fairness and strategy space of both D2D User Equipment and Cellular User Equipment are taken into consideration under the control of Efficiency Functions. The optimization problems are formulated as a game model series of utility functions built on the unit price of jamming power and the amount of jamming service. We extracting the system into a price bargain game with a buyer and a seller both desiring maximum profits, a bargaining game approach is adopted to solve this problem by reaching an agreement of unit price. The step number of bargain process is also a restriction under consideration. For the non-steps model, an Evaluation Function and a Comprehensive Utility Function are demonstrated to analyze the bargain process. For steps-contained model, the step number of iteration is involved and an attenuation function is introduced to modify the bargaining game. The algorithms of two models are proposed to derive the equilibrium point for reaching an agreement. Finally, extensive simulations are illustrated for verifying proposed theory.

Keywords Physical layer security · Bargaining game · Price bargain · Jamming power allocation · Device-to-device communication

1 Introduction

As an important part of the fifth generation mobile communication system, D2D (Device-to-Device) communication receives more and more attention as it can improve spectrum efficiency, share network load for the base station and apply in emergency situations. D2D communication does not require direct communication through the base station, and spectrum sharing can be enhanced by sharing channels with cellular users. At the same time, due to the geographical proximity of the D2D device, the terminal transmit power is reduced, thereby solving the problem of lack of spectrum resources in the wireless communication system to a certain extent and improving the energy efficiency of the system. This technology can further expand the coverage of the cellular network, benefit the user with poor signal at the edge of the cell, and reduce the management pressure of the core base station.

The overall performance of the wireless network can be significantly improved [1]. These advantages have attracted

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a great deal of attention to the research on D2D communication technology in the industry.

Most previous works separate source and jammer, and take one side as a leader. In the practical situation, both source and jammer should be taken into consideration, particularly in device-to-device underlay communication because one D2D pair needs at least one jammer to help. In addition, the previous evaluation criterion is relatively single.

In this paper, we focus on promoting the whole quality and efficiency in a cellular base station area, mainly evaluating in aspects of guaranteeing physical channel security to DUEs and improving communication rates to CUEs. To meet these two requirements, cooperative jammers performed by CUEs are adopted to assist DUEs in resistance to eavesdropping. Considering the selfishness of CUEs, an incentive mechanism based on bargaining game theory is derived to balance the concerns of both sides. We model the system under several evaluation standards and give priority to the overall revenue of the wireless network. Moreover, we analyze problems under a bargaining game theory that is suitable for a price competition with a buyer and a seller. Different from most bargaining games, the affection on the iteration steps is added into the algorithm we proposed. The major contributions of this paper are listed as follows:

1. We optimize the efficiency of whole wireless network by maximizing the physical layer security of DUEs and transmission rate of CUEs simultaneously. We divide the cell area into multiple DUE-to-CUE pairs and simplify the system as the integration of these pairs.
2. We introduce multiple evaluation criteria to refine the system model and make it closer to the practical situation. These criteria include total promotion of a base station, security utilities of DUE sources, service profits of CUE jammers, cooperation efficiency of each DUE-to-CUE pair, and threshold of price competition. With these criteria, a bargaining game is employed to analyze the system model.
3. In our bargaining game, there is no leader and follower so DUEs and CUEs are equal to each other, we assume that both sides can maximize its own profits self-consciously without considering the strategies of opponents. We obtain the strategy space of source and jammer in each DUE-to-CUE pair. On the basis of the strategy space, two algorithms are proposed to demonstrate the price bargaining game under non-steps model and steps-contained model respectively.
4. In non-steps model, we proposed a comprehensive utility function to express the total utility of buyer and seller when they reach an agreement. In steps-contained model, we take time factor into consideration, which means the steps of iteration process will cause an affection on the utility of buyer and seller when they complete a bargain. An attenuation function is proposed to describe the property that final utility is decreasing with the accumulation of time. Function samples are given and people can design different forms to meet practical demands in further research.

The remainder of paper is organized as follows. In Sect. 2, the related works is briefly described. In Sect. 3, system model is established and introduced. In Sect. 4, system security and efficiency problems are formalized as a Bargaining Game. In Sects. 5 and 6, analysis is based on Non-Steps model and Steps-Contained model respectively. Simulation results are illuminated in Sects. 7 and 8 draws conclusion of this paper.

2 Related work

2.1 Ratio resource allocation in D2D communication

There are already many works discussing about the resource allocation problem in D2D communication, most of them made efforts on maximizing spectrum efficiency or power efficiency in systems which D2D users shared the spectrum with cellular users. In [2], an optimal resource allocation and mode selection algorithm for both cellular and D2D users is focused on, and formulate a problem of maximizing the weighed sum rate of all the users. In [3], four energy-efficient resource allocation algorithms for spectrum sharing systems following the underlay and overlay paradigms are proposed, which are effective in real world scenarios both in terms of achieved energy efficiency and in terms of computational complexity. In [4], energy efficient power control for D2D communications underlying cellular networks is investigated, where both the total energy efficiency and individual energy efficiency have been considered. In [5], a BS (Base Station)-centric system scheme for D2D resource allocation is proposed and the Unknown Channel Quality (UCQ) problem which exists uniquely in D2D communication is focused.

Recently, the potential for security risks is a relatively new area in security research with the development in communication technologies, such as 5G wireless networks [6, 7]. In [8, 9], two fundamental and interrelated aspects of D2D communication, security and privacy, which are essential for the adoption and deployment of D2D are investigated.

Wireless communication networks are particularly vulnerable to eavesdropping and impersonation attacks due to the broadcasting nature of wireless channels, which makes traditional security approaches employed symmetric and asymmetrical cryptographic algorithms to achieve communication confidentiality and authentication respectively is not suitable any more. Fortunately, Shannon's information theory [10] secrecy analysis, which defined that security level depends on the amount of information known by eavesdroppers. A perfect secrecy can be achieved when the eavesdroppers ignore the transmitted information completely, except for just randomly guessing the original information bit by bit [11, 12]. Based on Shannon's work, Wyner defined secrecy capacity [13] in 1975, which means the confidential communications can achieve a maximum message transmission rate using wiretap channel coding and becomes a measurement criterion for describing a perfect secure communication in a wiretap channel. In Wyner's theory, secure information can be transmitted at a nonzero rate when the propagation condition of main channel is superior to that of eavesdropping channel. And in [14], the secrecy capacity of Gaussian wiretap channel was study. The private information can be perfectly protected when the transmitting channel is better than the eavesdropping channel. However, in the real world, it is hard to meet the restrictions of secrecy capacity [15, 16]. Artificial noise is an interested application that is created such to degrades the eavesdropper's channel but does not affect the channel of the intended receiver, thus allowing perfectly secure communication [17].

In [18], a scheme that some jamming nodes transmit factitious noise to interfere the malicious eavesdropping nodes is proposed. This cooperative-jammer model has become a hotspot in physical layer security research. However, since jammers have to consume additional energy to provide the jamming service, source nodes that benefit from it need to compensate jammers [19, 20]. Cost balance and incentive mechanism in this cooperation is also a research direction. To optimize a profit of both sources and jammers and allocate resource efficiently, game theory is employed [21].

In [22], the problem of robust uplink power control for SINR maximization in OFDMA-based D2D cellular networks under bounded channel state information (CSI) uncertainty and outage probability constraints is solved under a Stackelberg Game model. With Auction Game theory, [23] achieves a unique Nash equilibrium point for a new spectrum trading scheme based on supply and demand curves for service providers (SPs) and the D2D user.

2.2 Physical challenges in D2D communication

In [24], the pioneering concept of device-to-device communication is proposed, which is a promising technology [25] to permit wireless equipment to exchange information directly without the control of central servers or base stations. Since direct communication between device-to-device users is employed [26, 27], the physical properties of resource sharing and energy control are critical evaluation criterion for cellular wireless network. Spectrum multiplexing, power allocation and mode selection are adopted in [28–31] for improving the system efficiency.

Physical layer attacks and security risks are classified by the Third Generation Partnership Project (3GPP) Security Workgroup in [32]. In [33], five secure requirements are introduced in wireless communication for resisting different attacks including malicious eavesdropping [34, 35]. Due to the natural properties, D2D communication is more vulnerable to suffer attacks in wireless networks [36].

2.3 Security solutions for D2D communication

For the requirements of transmission security, different approaches [37–41] are proposed for D2D communication including developing a Stackelberg game to maximize the secrecy capacity and power efficiency of both cellular and D2D users in an underlay communication. Game theory has become a new and effective approach for this problem [42, 43]. Literature [44] develops a Stackelberg game in which cellular users are considered as leaders and D2D users are considered as followers. This approach maximizes the rate of cellular users and secrecy capacity of D2D links by optimizing the transmission power and channel access of D2D links. Wang et al. in [45] introduced Stackelberg game to deal with the resource sharing problem in cognitive radio networks. In [46], Pei and Liang proposed a resource allocation protocol overlaying two-way cellular networks with the concept of Pareto Boundary. Auction is another popular approach to solve the resource allocation problem. In [47], Xu et al. proposed a reversed iterative-combinatorial auctions (I-CAs) algorithm for spectrum allocation and reduced the interference between D2D and cellular users.

In [48], Zhang et al. modeled the system in which both D2D pairs and cellular users reach for a set of resource blocks. They made the users cooperate with one another in a coalition-game-approach. Resource allocation with game theoretic approaches has been a research direction. The above references are mainly based on power allocation and concentrates on physical layer security in device-to-device communication.

3 System model

3.1 Model assumptions

In this paper, system communication model is considered as a multi-user wireless cellular network in the control of a central base station, where several DUEs simultaneously exist as legitimate users and share resources with common CUEs.

On the one hand, this communication system is comprised of several CUEs and DUEs. On the other hand, one or more malicious eavesdroppers may conceal real identity and hide in these multiple network nodes to wiretap other users' information silently. As CUEs own more security strategies on application layer with cryptology encryption, DUEs are more vulnerable due to device-to-device transmission characteristics. The eavesdropping risk on DUEs ought to be taken into consideration urgently.

In the above situation, DUEs are supposed as potential victims. Thus, CUEs can act as jammers to assist DUEs get rid of security risk. Jammers broadcast interference signals as noise to deteriorate the wiretap channels. When the propagation condition from DUEs source to malicious users is inferior than that from DUEs source to DUEs destination. The information can be transmitted in a perfectly secure condition with a nonzero value. This value called as secrecy capacity represents the maximum transmission rate of secure information in a communication process. The secrecy capacity is considered as one of factors evaluation standards in this paper.

For this model, the priority of CUEs and DUEs is equal in status. We take both CUEs and DUEs into consideration is reasonable and emphasize the income of entire base station. As a sufficient but unnecessary condition, maximizing the benefits of base station requires to optimize both cellular communication and device-to-device pairs. More refined, each CUE and DUE in the cooperation process acquires optimal utility.

As a common scenario, each CUE and DUE has a single antenna which means a DUE is assisted by a specific CUE. As shown in Fig. 1, there are multiple DUE-to-CUE pairs, where a DUE source is assisted by a specific CUE jammer to resist malicious eavesdroppers in each pair.

4 Proposed bargaining game scheme

4.1 Evaluation standards

4.1.1 Base station

The benefit of the entire base station is comprised of utility of CUEs and DUEs. There are multiple DUE-to-CUE pairs in the network. We denote the set of these pair indices $\{1, 2, 3, \ldots, \Gamma\}$ by Γ. To each pair i, the utility of DUE and CUE is defined as *UDUi* and *UCJi*, respectively. Benefits function of base station is

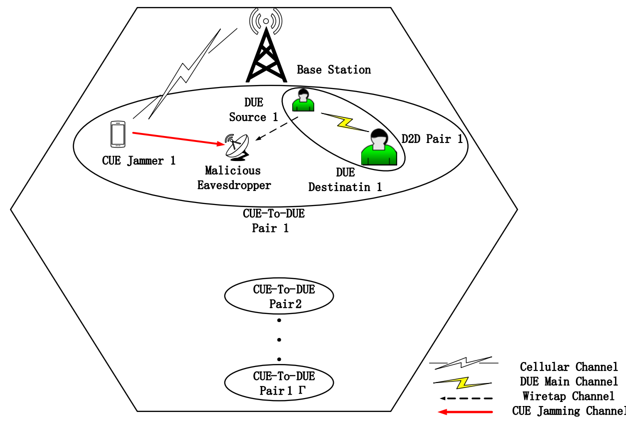

Fig. 1 System model in a cell with a central base station

$$\begin{aligned} U_{BS} &= U_{DU} + U_{CJ} \\ &= \sum_{i \in \Gamma} U_{DU_i} + \sum_{i \in \Gamma} U_{CJ_i} \\ &= \sum_{i \in \Gamma} U_i^{DUE-to-CUE\ pair} \end{aligned} \tag{1}$$

$$= \sum_{i \in \Gamma} (U_{DU_i} + U_{CJ_i}) \tag{2}$$

In order to maximize U_{BS}, this paper concentrates on promoting U_{DU_i} and U_{CJ_i} of each pairs.

4.1.2 DUE sources

DUEs concentrate on the security performance. Assuming the transmitted power of DUE source and CUE jammer is P_{D_i} and P_{CJ_i}. The channel gain from DUE source to DUE destination and malicious eavesdropper is h_{D_i} and h_{DE_i}, respectively. The channel gain from CUE jammer to DUE destination and malicious eavesdropper is h_{CD_i} and h_{CE_i}. The channel bandwidth is W. The Gaussian white noise is N. Each DUE main channel achievable information rate is given as

$$C_{DU_i} = W \log_2 \left(1 + \frac{P_{D_i} h_{D_i}}{N + P_{CJ_i} h_{CD_i}} \right) \tag{3}$$

The corresponding DUE wiretap channel is given as

$$C_{DE_i} = W \log_2 \left(1 + \frac{P_{D_i} h_{DE_i}}{N + P_{CJ_i} h_{CE_i}} \right) \tag{4}$$

To guarantee the security of DUE source and ensure malicious eavesdropper obtain almost nothing from the wiretap channel, the secrecy capacity which means difference value between two channel is defined as

$$R_{DU_i}^{S^+} = (C_{DU_i} - C_{DE_i})^+ \tag{5}$$

where χ^+ means maximum between 0 and χ. According to [21] and [49], we assume the interference from CUE jammer to DUE destination is far less than background thermal noise. Formula (5) can be revised as

$$R_{DU_i}^{S+} = \left(W \log_2 \left(1 + \frac{P_{D_i} h_{D_i}}{N} \right) - W \log_2 \left(1 + \frac{P_{D_i} h_{DE_i}}{N + P_{CJ_i} h_{CE_i}} \right) \right)^{+} \quad (6)$$

As CUEs provides the DUEs with jamming service, DUEs have to pay back compensation because of the selfish of CUEs. Assuming the unit price of jammer power bought from CUE jammers is defined as λ_i and different CUE jammers enact its own specific unit price independently. The payment function of a DUE source is given as

$$\mathrm{U}_{payment} = \lambda_i P_{CJ_i} \quad (7)$$

Therefore, the total utility function of a DUE source is

$$\mathrm{U}_{DU_i} = R_{DU_i}^{S+} - U_{payment} \quad (8)$$

4.1.3 CUE jammers

A CUE mainly considers their remuneration from the DUE, which buys jamming service. The profit function of a CUE jammer is given as

$$\mathrm{U}_{income} = \lambda_i P_{CJ_i} \quad (9)$$

In addition, all of the power allocation is under the control of central base station. Base station allocates extra resource for CUE jamming service and this power can be incorporated into their own transmission. The transmission rate of CUEs is promoted and the gain can be defined as

$$\Delta R_{CJ_i} = R_{CJ_i}^{new} - R_{CJ_i}^{old} \quad (10)$$

$$\Delta R_{CJ_i} = W \log_2 \left(1 + \frac{(P_{C_i} + P_{CJ_i}) h_{C_i}}{N} \right) - W \log_2 \left(1 + \frac{P_{C_i} h_{C_i}}{N} \right) \quad (11)$$

where $R_{CJ_i}^{old}$ is the transmission rate of CUE Jammer without provide jamming service, but $R_{CJ_i}^{new}$ is the transmission rate of CUE Jammer that provide jamming service. Channel gain from a CUE to base station is h_{C_i} and the original transmitted power before adding jamming service is P_{C_i}.

Taking both compensation profit and transmission rate profit into consideration, the total utility function of a CUE jammer can be summarized as

$$\mathrm{U}_{CJ_i} = \Delta R_{CJ_i} + U_{income} \quad (12)$$

4.1.4 Properties of utility functions

As described above, comprehensive utility function of both CUE jammers and DUE sources is involved. Formula (8) and (12) are functions of parameter λ_i and P_{CJ_i}. Notice that when CUE jammer raises the unit price, DUE will reduce the jamming power provided from CUE jammer. When λ_i is fixed, there is an optimal jamming power we denote as $P_{CJ_i}^*$ because if jammer power is too low DUE can't acquire good jamming service but if jamming power is too high DUE can't afford it. And every λ_i corresponding to an optimal jamming power $P_{CJ_i}^*$. So $P_{CJ_i}^*$ is a function of λ_i that the value of λ_i produces an effect on $P_{CJ_i}^*$. This property of feedback function $P_{CJ_i}^*(\lambda_i)$ will be demonstrated in further detail below. Therefore, both formula (8) and (12) are functions of λ_i after revising.

Theorem 1 *To utility function* U_{DU_i}, $\mathrm{P}_{CJ_i}^*$ *is a decreasing feedback function of* λ_i.

Proof The primary goal of a DUE source is to maximize its own revenue, which is reflected by utility function U_{DU_i}. Hence, this strategy can be formulated as

$$\max U_{DU_i}(P_{CJ_i}) \quad (13)$$

□

Definition 1 To $\mathrm{i} \in \Gamma$, let $\gamma_{D_i} = h_{D_i}/N$, $\gamma_{DE_i} = h_{DE_i}/N$, and $\gamma_{CE_i} = h_{CE_i}/N$.

The utility function is revised as

$$U_{DU_i} = W\left(log_2 \left(1 + \frac{P_{D_i} h_{D_i}}{N} \right) - log_2 \left(1 + \frac{P_{D_i} h_{DE_i}}{N + P_{CJ_i} h_{CE_i}} \right) \right) - U_{payment} \quad (14)$$

$$= W\left(log_2 (1 + P_{D_i} \gamma_{D_i}) - log_2 \left(1 + \frac{P_{D_i} \gamma_{DE_i}}{1 + P_{CJ_i} \gamma_{CE_i}} \right) \right) - \lambda_i P_{CJ_i} \quad (15)$$

Differentiate Eq. (15) to argument P_{CJ_i} as follows:

$$\frac{\partial U_{DU_i}}{\partial P_{CJ_i}} = \frac{W P_{D_i} \gamma_{DE_i} \gamma_{CE_i} / ln2}{(1 + P_{CJ_i} \gamma_{CE_i} + P_{D_i} \gamma_{DE_i})(1 + P_{CJ_i} \gamma_{CE_i})} - \lambda_i \quad (16)$$

To acquire extreme values, let

$$\frac{\partial U_{DU_i}}{\partial P_{CJ_i}} = 0 \quad (17)$$

After rearranging, Eq. (17) is formed into a quadratic equation

$$\gamma_{CE_i}^2 \cdot P_{CJ_i}^2 + (2\gamma_{CE_i} + P_{D_i} \gamma_{DE_i} \gamma_{CE_i}) \cdot P_{CJ_i} + \left(1 + P_{D_i} \gamma_{DE_i} - \frac{\ln 2 \cdot W P_{D_i} \gamma_{DE_i} \gamma_{CE_i}}{\lambda_i} \right) = 0 \quad (18)$$

Definition 2 Let $A = \gamma_{CE_i}^2$, $B = 2\gamma_{CE_i} + P_{D_i} \gamma_{DE_i} \gamma_{CE_i}$, $C = 1 + P_{D_i} \gamma_{DE_i}$, and $D = W P_{D_i} \gamma_{DE_i} \gamma_{CE_i} \cdot \ln 2$.

Equation (18) can be simplified as

$$AP_{CJ_i}^2 + BP_{CJ_i} + (C - \frac{D}{\lambda_i}) = 0, A \neq 0 \tag{19}$$

Analysis Closed-form solutions of a quadratic equation is directly related to Δ and can be described as

$$P_{CJ_i}^* = \frac{-B \pm \sqrt{\Delta}}{2A} \tag{20}$$

where

$$\Delta = B^2 - 4A\left(C - \frac{D}{\lambda_i}\right) \tag{21}$$

Notice that $P_{CJ_i}^*$ should be greater than zero, thus Eq. (20) is revised as

$$P_{CJ_i}^* = \frac{-B + \sqrt{\Delta}}{2A} \tag{22}$$

1. If $\Delta = 0$, Eq. (19) gets the only solution $P_{CJ_i}^* = \frac{-B}{2A}$.
2. If $\Delta > 0$, Eq. (19) gets two solutions and derivative function of Eq. (17) holds two extreme values called $P_{CJ_i}^1$ and $P_{CJ_i}^2$. According to the waveform of the curve, Eq. (17) is an increasing function where $P_{CJ_i} < P_{CJ_i}^1$ and $P_{CJ_i} > P_{CJ_i}^2$. Between $P_{CJ_i}^1$ and $P_{CJ_i}^2$, Eq. (17) is a decreasing function. Thus, maximum value $P_{CJ_i}^*$ will get at peak point $P_{CJ_i}^1$ or the rightmost point of the definition domain. Notice that $P_{CJ_i}^1$ is decreasing with λ_i.
3. If $\Delta < 0$, Eq. (17) is always greater than zero which means $P_{CJ_i}^*$ will get at rightmost point of system power threshold.

All of these three cases, $P_{CJ_i}^*$ is related to λ_i. In practical scenario, it is inevitable that there are several extreme values of wave in the curve of derivative function and $P_{CJ_i}^*$ will get at the peak point. Therefore, we can draw a conclusion that $P_{CJ_i}^*$ is a decreasing feedback function of λ_i.

4.1.5 Price mechanism

As a complex system usually has a variety of evaluation criteria, two efficiency functions respectively based on DUE sources and CUE jammers are proposed. The efficiency function of a DUE source is a ratio of secrecy capacity to payment of jamming power:

$$\eta_{DU_i} = \frac{R_{DU_i}^{S+}}{\lambda_i P_{CJ_i}} \tag{23}$$

With a constant factor α to balance the cost of each CUE jamming service, the efficiency function is given as

$$\eta_{CJ_i} = \frac{U_{CJ_i}}{\alpha P_{CJ_i}} \tag{24}$$

Simply based on Eqs. (8) and (12), strategies about how DUE sources and CUE jammers will make decisions on unit price λ_i is unobvious because the bought jamming power is affected by unit price. Even substituting the jamming power in form of $P_{CJ_i}(\lambda_i)$ and rearranging the two formulae into a function just about λ_i, it is highly probable that respective sets of optimal solution λ_i^* are not intersecting each other. Thus, it is hard to achieve the aim of system model by optimization theory just with objective functions Eqs. (8) and (12).

However, by joining the constraint equation based on Eqs. (23) and (24), it is possible to restrain strategies about DUEs and CUEs in a distinct direction.

Theorem 2 *Given a DUE-to-CUE pair, according to constraint Eqs. (23) and (24), on condition that both DUE source and CUE jammer consciously maximize their utility functions, that is to say, to maximize both utility function in constraints of Eqs. (23) and (24), a sufficient and necessary condition is acquired:*

Each DUE source lowers λ_i as much as possible.Each CUE jammer raises λ_i as much as possible.

Proof Both Eqs. (23) and (24) are efficiency functions for evaluating DUE sources and CUE jammers. It is obvious that each DUE-to-CUE's strategy is to maximize these functions:*To a DUE source:*

$$\max \eta_{DU_i} \tag{25}$$

To a DUE source:

$$\max \eta_{CJ_i} \tag{26}$$

□

Firstly, to Eq. (25), it is the reasonable to simplify fraction expression with logarithmic function because we can convert it from division to subtraction for decreasing the complexity of calculation. The conversion is given as

$$\ln \eta_{DU_i} = \ln(R_{DU_i}^{S+}) - \ln(\lambda_i P_{CJ_i}) \tag{27}$$

Definition 3

$$\mathrm{E}_{\mathrm{DU_i}}(P_{CJ_i}) = \ln\left(\eta_{DU_i}\right), E_{DU_i}^{left} = \ln\left(R_{DU_i}^{S+}\right)$$

Then rearrange the Eq. (27) as:

$$\mathrm{E}_{\mathrm{DU_i}}(P_{CJ_i}) = E_{DU_i}^{left} - \ln(\lambda_i P_{CJ_i}) \tag{28}$$

Differentiate Eq. (28) to argument P_{CJ_i} as follows:

$$\frac{\partial E_{DU_i}}{\partial P_{CJ_i}} = \frac{\partial E_{DU_i}^{left}}{\partial P_{CJ_i}} - \frac{1}{\lambda_i P_{CJ_i}} \cdot \lambda_i = \frac{\partial E_{DU_i}^{left}}{\partial P_{CJ_i}} - \frac{1}{P_{CJ_i}} \tag{29}$$

Notice that in this constraint, derivative function of Eq. (28) is independent of λ_i which means the extreme value is just related to P_{CJ_i}. Each DUE source is able to hold the optimal $P^*_{CJ_i}$ for maximizing Eq. (23) explicitly. As a fraction expression, the maximum value of Eq. (23) is still a decreasing function about λ_i. Each DUE source will lower the value of λ_i self-consciously.

Secondly, Eq. (26) can be revised as

$$\eta_{CJ_i} = \frac{W\log_2\left(1 + \frac{(P_{C_i}+P_{CJ_i})h_{C_i}}{N}\right) - W\log_2\left(1 + \frac{P_{C_i}h_{C_i}}{N}\right) + \beta\lambda_i P_{CJ_i}}{\alpha P_{CJ_i}} = \frac{\Delta R_{CJ_i}}{\alpha P_{CJ_i}} \tag{30}$$

Definition 4 Let $E_{CJ_i}(P_{CJ_i}) = \eta_{CJ_i}$, $E^{left}_{CJ_i} = \frac{\Delta R_{CJ_i}}{\alpha P_{CJ_i}}$

Rearrange the Eq. (30)

$$E_{CJ_i}(P_{CJ_i}) = E^{left}_{CJ_i} + \frac{1}{\alpha} \cdot \lambda_i \tag{31}$$

Differentiate Eq. (31) to argument P_{CJ_i} as follows:

$$\frac{\partial E_{CJ_i}}{\partial P_{CJ_i}} = \frac{\partial E^{left}_{CJ_i}}{\partial P_{CJ_i}} \tag{32}$$

Notice that Eq. (32) is also independent of λ_i. As Eq. (31) is a sum form, a rationally CUE jammer will raise the value of as much as possible to maximize its efficiency function.

4.2 Interest competition and bargaining game

The above problem of DUE-to-CUE pairs' utility is a price competition based on unit price λ_i. Each DUE source is a buyer and each CUE jammer is a seller. As being described in Theorem 2, each of sides has its own strategies to maximize utility function respectively and it is difficult to solve this problem simply using optimization theory. Fortunately, as system model can be divided into DUE source sides and CUE jammer sides, this problem can be modeled as a bargain game about λ_i.

In this section, we summarize the optimization problem into a price competition that each participant has a different view of the optimal outcome and they need a collective choice for a compromise. In a DUE-to-CUE pair, there are two opponents and at least one result is beneficial to both sides. The total revenue of the agreement reached by both sides should be greater than the sum of the proceeds obtained separately when participants do not reach an agreement. That is to say, it is not a zero-sum game. Bargaining game is a suitable model to describe the problem mentioned above. In the Bargaining game, the two sides of buyer and seller carry out a game on price and finally negotiate an agreement.

Therefore, it is reasonable to apply Bargaining game approach to system model analysis and acquire the optimal price called Nash Bargaining Solution (NBS) for each DUE-to-CUE pair.

5 Bargaining game under non-steps model

In this section, we concentrate on a bargaining game under a non-steps model. Non-steps means the grand total of iteration process is not in evaluation criteria. First, we analyze both sides of buyers and sellers. Then, we propose a synthetical profit function, which represents the utility function of a bargaining game. Finally, we illustrate the iterative algorithm in pseudocode.

5.1 DUE sources (buyers) side and CUE jammers (sellers) side analysis

5.1.1 DUE sources side

A DUE source prefers to start the bargain from a lower unit price and holds a maximum threshold that the unit price must be less than it, otherwise the DUE source will not buy the jamming service and quit this bargaining game.

Theorem 3 *To each DUE source, there is an acceptable range of unit price λ_i, which is limited by a maximum value λ_i^{max}.*

Proof Considering the restriction that the secrecy capacity with a jammer should be greater than that without jamming service, a difference value representing the practicability is proposed as

$$\Delta R^{S+}_{DU_i} = \left[R^{S+}_{DU_i\ with\ J} - R^{S+}_{DU_i\ without\ J}\right]^+ \tag{33}$$

where $\Delta R^{S+}_{DU_i}$ is greater than zero. □

Rearranging Eq. (33), we get

$$\Delta R_{D_i}^{S+} = \left\{ W\left(\log_2\left(1+\frac{P_{D_i}h_{D_i}}{N}\right) - \log_2\left(1+\frac{P_{D_i}h_{DE_i}}{N+P_{CJ_i}h_{CE_i}}\right)\right)^+ - W\left(\log_2\left(1+\frac{P_{D_i}h_{D_i}}{N}\right) - \log_2\left(1+\frac{P_{D_i}h_{DE_i}}{N}\right)\right)^+ \right\}^+$$

$$\Delta R_{D_i}^{S+} = \left\{ W\left(\log_2\left(1+\frac{P_{D_i}h_{DE_i}}{N}\right) - \log_2\left(1+\frac{P_{D_i}h_{DE_i}}{N+P_{CJ_i}h_{CE_i}}\right)\right)\right\}^+ \tag{34}$$

Notice that for any $P_{CJ_i} > 0$, $\Delta R_{DU_i}^{S+} > 0$ is always tenable. However, for practical purposes, $\Delta R_{DU_i}^{S+}$ gets a minimum threshold and Eq. (33) is revised as

$$\Delta R_{DU_i}^{S+} > \Delta R_{DU_i\ thmin}^{S+} \tag{35}$$

It is obvious that $\Delta R_{DU_i}^{S+}$ is an increasing function of P_{CJ_i}. Thus, P_{CJ_i} holds a minimum value $P_{CJ_i}^{min}$ to make the inequality to be tenable.

Meanwhile, when P_{CJ_i} tends to infinity, a limitation is given as

$$\lim_{P_{CJ_i}\to+\infty} \Delta R_{DU_i}^{S+} = W\log_2\left(1+\frac{P_{D_i}h_{DE_i}}{N}\right) \tag{36}$$

When P_{CJ_i} increases to a certain degree, $\Delta R_{D_i}^{S+}$ is almost changeless and is approximately equal to Eq. (36). That means we can acquire an approximation P_{CJi}^{appro} that satisfies the following conditions:

$$\left|\lim_{P_{CJ_i}\to+\infty} \Delta R_{DU_i}^{S+} - \Delta R_{DU_i}^{S+}(P_{CJi}^{appro})\right| < \varepsilon \tag{37}$$

where ε is a value small enough.

In addition, a DUE source shares resource with a CUE jammer in an underlay way, there is a maximum threshold of jamming power to avoid interference on D2D communications. Therefore, the maximum value is given as

$$P_{CJ_i}^{max} = min(P_{CJ_i}^{thmax},\ P_{CJi}^{appro}) \tag{38}$$

According to Eqs. (35) and (37), there is a scope of P_{CJ_i}. As being described in Theorem 1, P_{CJ_i} is a decreasing feedback function of λ_i. Unit price λ_i also has a scope.

Definition 5 Let $\lambda_i^{\max}$ represents the maximum threshold of unit price and $\lambda_i^{\min}$ is the minimum value. A new constraint condition is acquired:

$$\lambda_i^{\min} \le \lambda_i \le \lambda_i^{max} \tag{39}$$

Equation (39) is a primary condition in price bargaining game.

5.1.2 CUE jammers side

The utility function of a CUE jammer is defined in Eq. (8), differentiating this function to λ_i and setting it to zero, we will get

$$\frac{\partial U_{CJ_i}}{\partial \lambda_i} = \frac{\partial \Delta R_{CJ_i}}{\partial \lambda_i} + \beta P_{CJ_i} + \beta\lambda_i \frac{\partial P_{CJ_i}}{\partial \lambda_i} \tag{40}$$

It is difficult to calculate extreme value by using partial derivative directly, but we can initiate a bargaining game to get the solutions with Eq. (39).

5.2 Evaluation function

As considering the benefits and fairness of both sides at the same time, we proposed an Evaluation Function to describe the utility diversity of a DUE source and a CUE jammer in each pair, which is similar to the variance. This function is aimed to guarantee the fairness of the buyer and the seller, and control the utility gap in a reasonable range. The Evaluation Function is a criterion for design a Comprehensive Utility Function in the next subsection. The two heuristic algorithms proposed in this paper are also comprised of this concept.

5.3 Comprehensive utility function

In a bargaining game, the total revenue under an agreement is greater than the sum of proceeds without an agreement. In order to reach an agreement on the price as soon as possible, the total revenue called comprehensive utility function needs to be designed. This function should meet following properties:

1. The function is a composite function on utilities of a buyer and a seller, which is increased with either side.
2. Under an agreement, the value of function is always grater that out of the agreement. The agreement can be a specific constraint.
3. The value of function is finite in domain and the function holds at least on peak point. The monotonousness and concavity are not rigidly restricted as long as this function is able to filter one or more extreme value cooperated with the Evaluation Function mentioned above.
4. It is also possible that points on two sides of the domain reach the maximum value.

The comprehensive utility function can be designed in different forms to meet above requirements. In this paper, we propose a simple H-formula of this function which is defined as

$$H(U_{DU_i}, U_{CJ_i}) = \delta U_{DU_i} + (1-\delta) U_{CJ_i} \quad (0 \le \delta \le 1) \tag{41}$$

where the agreement constraint is given as

$$\underset{agree}{H}(U_{DU_i}, U_{CJ_i}) > \underset{disagree}{U_{DU_i}} + \underset{disagree}{U_{CJ_i}} \tag{42}$$

Theorem 4 *The above H-formula is a comprehensive utility function.*

Proof To property (1), it is obvious tenable.

To property (2), the H-formula is linear to both sides. As δ changing from 0 to 1, the utility of H-formula changes from DUE sources to CUE jammers. When a buyer and a seller cannot reach an agreement, one of the sides will quit the bargain and the utility function is not taken into consideration. Thus, Eq. (42) is tenable.

To property (3), the H-formula can be revised as

$$H(U_{DU_i}, U_{CJ_i}) = K_1 U_{DU_i} + K_2 U_{CJ_i}, (K_1 + K_2 = 1) \tag{43}$$

As being described in Theorem 1, U_{DU_i} holds a peak point in real scene and is upward convex to P_{CJ_i} in its domain. According to Theorem 2, the strategy of a CUE jammer is to raise unit price as much as possible and it do not know the strategy of the corresponding DUE source. Therefore, U_{CJ_i} can be simplified as an increasing function to λ_i. Although the increase–decrease characteristics to unit price of the two utility functions is different, an extreme value still exists in each domain. In addition, the two curvilinear figures are not in the same shape, it is obvious that the linear composite function holds at least one maximum value points.

To property (4), in practical scene, the endpoints represent minimum and maximum threshold of unit price and it is rarely to meet the requirements of Evaluation Function at these two points. Therefore, the acceptable maximum value will not exist at endpoints in this model. □

5.4 Algorithm

We proposed an algorithm for calculating optimal unit price under a bargaining game. As a bargain, each DUE source bids from a low unit price. And the corresponding CUE jammer bids from a high unit price. Two initial prices are represented by $\lambda_i^{\min}$ and $\lambda_i^{\max}$, respectively. In the subsequent process, the buyer increases the unit price with a small value ε and seller decreases the unit price with ε. This process continues until they reach an agreement when the value of comprehensive utility function is maximal or is approximate to maximum value in an acceptable range. In addition, the requirements of Evaluation Function should be always satisfied. And we can get Nash Bargaining Solution: $U_{NBS}(\lambda_i^*,\ P_{CJ_i}^*(\lambda_i^*))$.

The algorithm is written in pseudocode as:

Algorithm 1 Procedure of λ_i^* in Non-Step Scheme.

Input: $\lambda_{\min}, \lambda_{\max}$ $(\lambda_{\min} < \lambda_{\max})$
Output: λ_i^*

$\lambda_{DU_i} \leftarrow \lambda_{\min}$;
$\lambda_{CJ_i} \leftarrow \lambda_{\max}$;
$H^* \leftarrow \max(H(\lambda_{DU_i}), H(\lambda_{CJ_i}))$;
$\lambda_i^* \leftarrow H^{-1}(H^*)$;
while $\lambda_{DU_i} \le \lambda_{CJ_i}$ **and** EF$(\lambda_{DU_i}, \lambda_{CJ_i})$ **do**
    $\lambda_{DU_i} \leftarrow \lambda_{DU_i} + \varepsilon$;
    $\lambda_{CJ_i} \leftarrow \lambda_{CJ_i} - \varepsilon$;
    if $\max(H(\lambda_{DU_i}), H(\lambda_{CJ_i})) > H^*$ **then**
        $H^* \leftarrow \max(H(\lambda_{DU_i}), H(\lambda_{CJ_i}))$;
        $\lambda_i^* \leftarrow H^{-1}(H^*)$;
    end if
end while
function EF$(\lambda_{DU_i}, \lambda_{CJ_i})$
    if $U_{DU_i} > U_{DU_i}^{threshold}$ **and** $U_{CJ_i} > U_{CJ_i}^{threshold}$ **then**
        if $|U_{DU_i} - U_{CJ_i}| < \varepsilon$ **then**
            return TRUE;
        end if
    end if
    return FALSE;
end function

6 Bargaining game under steps-contained model

In most of the game theory model, they do not consider the time factor, in fact, many of them deed consider the time. However, the bargaining game cannot iterate infinitely which means the process should be completed in finite steps. The number of steps can be defined factitiously in order to finish the iteration process within the prescribed period of time. In a real scene, the utility function is affected by time and we can use iteration steps to represents the time factor. The more steps the bargain proceeds in, the less utility will be at last.

6.1 Attenuation function

The property of affection with time can be defined as an attenuation function. This function can also be designed in different forms to describe the above characteristic. In this paper, we propose a sample based on exponential function and logarithmic function. The sample is given as

$$f(N) = \theta^{\log_2 N} (0 < \theta < 1,\ N \ge 1) \tag{44}$$

where θ is slightly less than 1 and Eq. (44) meets following properties:

1. Equation (44) is a decreasing function of N, and satisfies $\lim_{N \to +\infty} f(N) = 0$.
2. When the step of iteration is one, the attenuation function should have no affection on final utility. That is to say, $f(1) = 1$.

6.2 Comprehensive Utility Function

With the attenuation function, we can analyze the bargaining game under steps-contained model. The modified comprehensive utility function of Step-Contained is defined as

$$H_m = H \cdot f(N) \tag{45}$$

where H is the original comprehensive utility function proposed in Sect. 5. Note that CUE and DUE have different attenuation function which decide by θ. So $f(N)$ contains two parts that $f_{\theta_1}^{DU}(N)$ and $f_{\theta_2}^{CJ}(N)$, then Eq. (45) can be revised as

$$H_m = H \cdot f_{\theta_1}^{DU}(N) + H \cdot f_{\theta_2}^{CJ}(N) \tag{46}$$

The attenuation functions will take part in iteration process in a new algorithm.

6.3 Algorithm

In steps-contained model, Eq. (46) is affected by step of iteration. The strategy of each DUE source and CUE jammer are same as that mentioned in Sect. 4. But both sides need to reach an agreement as soon as possible because of the time attenuation of utility. The optimal unit price will be acquired earlier.

Considering the following problem, at the beginning of process, both buyer and seller do not know whether there will be a better result in the follow-up iterations. However, with the optimal unit price λ_i^* achieved in Sect. 4, it is positive that Eq. (46) will not increase when λ_i has already reached λ_i^*. Therefore, we can complete the iteration process early and take λ_i^* as a termination condition. The Nash Bargaining Solution is acquired as $U_{NBS}(\lambda_i^*, P_{CJ_i}^*(\lambda_i^*), N^*)$.

The algorithm is given as:

Algorithm 2 Procedure of $\lambda_i^{*\,new}$ in Step-Contained Scheme.

Input: $\lambda_{\min}$, $\lambda_{\max}$, $N_{threshold}$ ($\lambda_{\min} < \lambda_{\max}$)
Output: $\lambda_i^{*\,new}$, N^*

$\lambda_{DU_i} \leftarrow \lambda_{\min}$;
$\lambda_{CJ_i} \leftarrow \lambda_{\max}$;
$H^* \leftarrow \max(H(\lambda_{DU_i}), H(\lambda_{CJ_i}))$;
$\lambda_i^{*\,new} \leftarrow H^{-1}(H^*)$;
$N^* \leftarrow 1$;
while $\lambda_{DU_i} \le \lambda_{CJ_i}$ **and** $\mathrm{EF}(\lambda_{DU_i}, \lambda_{CJ_i})$ **do**
  if $N^* \ge N_{threshold}$ **or** $\lambda_{DU_i} \ge \lambda_i^*$ **or** $\lambda_{CJ_i} \le \lambda_i^*$ **then**
    break;
  end if
  $\lambda_{DU_i} \leftarrow \lambda_{DU_i} + \varepsilon$;
  $\lambda_{CJ_i} \leftarrow \lambda_{CJ_i} - \varepsilon$;
  if $\max(H(\lambda_{DU_i}), H(\lambda_{CJ_i})) > H^*$ **then**
    $H^* \leftarrow \max(H(\lambda_{DU_i}), H(\lambda_{CJ_i}))$;
    $\lambda_i^{*\,new} \leftarrow H^{-1}(H^*)$;
    $N^* \leftarrow N^* + 1$;
  end if
end while

7 Simulations

In this section, we illustrate system properties and demonstrate the performance of proposed algorithm with numerical results. All of our simulations are compiled and built in MATLAB R2017b.

7.1 Simulation setup

To simplify simulation model, we assume that each DUE-to-CUE pair is under the same environment condition and we concentrate on the analysis of a specific pair.

For basic non-steps model, DUE source transmission power is 0.7, the bandwidth is set as 1. Using channel gain to background noise ratio to improve computational efficiency, the ratio γ_{D_i}, γ_{CE_i}, γ_{DE_i} is given as 10, 5 and 1 respectively. The original CUE jammer transmission power is defined as 0.7 and the corresponding ratio γ_{C_i} is 5. The cost factor α and income factor β of unit price is both set as 1. We assume that system model transmission is in additive white Gaussian noise channel.

For advanced steps-contained model, the attenuation factor θ of a DUE source and a CUE jammer is given as 0.95 and 0.8 respectively. The priority of both sides is 0.5, which means buyer and seller are in the equal state. Thus, the fairness is guaranteed in a price bargain.

Firstly, we introduce the figures about optimal jamming power P_{CJ_i} to unit price λ_i and analyze the characteristics.

Secondly, we illustrate the utility function of DUE source and CUE jammer in a three-dimensional view. The extreme points are highlighted for describe the relationship of utility function, jamming power and unit price.

Thirdly, efficiency functions of buyer and seller are presented for demonstrate the strategy space of both sides.

At last, the existence of unit price threshold is illustrated. On the basis of these restrictions, we simulate the attenuation function and compare the performance of comprehensive utility function under two proposed models.

7.2 Numerical analysis

Figure 2 shows Eq. (21) is always greater than zero with threshold of unit price from 0.8 to 2.0. Therefore, the optimal jamming power is in solutions of a quadratic equation and as shown in Fig. 3, the optimal jamming power is a decreasing function to unit price. When the unit price is raised, a rational DUE source will reduce the amount of jamming power bought from a CUE jammer.

Figure 4 shows the utility function of DUE source in a three-dimensional view. Given a fixed unit price, the utility is an upward convex function to jamming power, the series of peak points are highlighted in a red line. It is obvious that the optimal jamming power is decreasing when the unit price increases for maximizing the utility function of DUE source.

Figure 5 illustrates this feature more intuitively. With four specific unit prices, four upward convex curves are presented together. The peak points marked in black solid triangles gradually moves to the left side in the horizontal direction.

As shown in Fig. 6 with a pink line, when the jamming power is fixed, the optimal utility function of CUE jammer

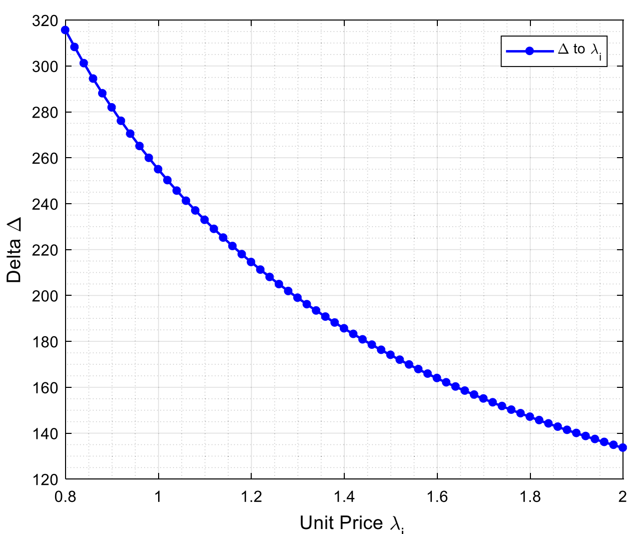

Fig. 2 Equation (21) to unit price with optimal jamming power

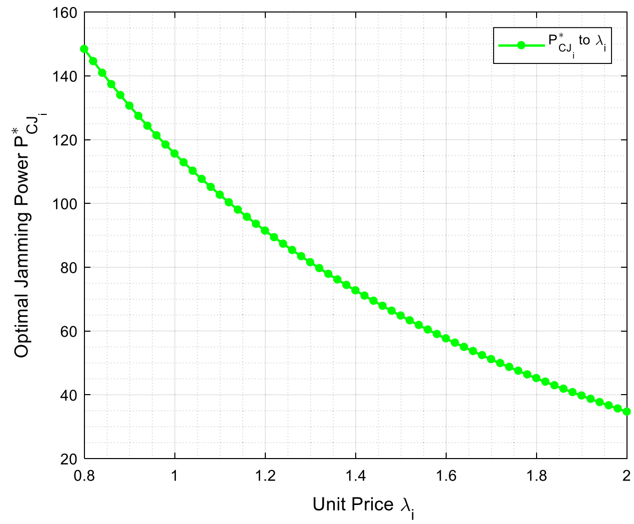

Fig. 3 Optimal jamming power to unit price

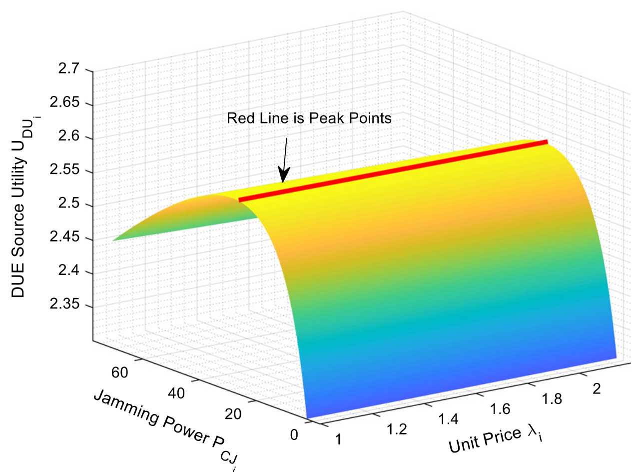

Fig. 4 DUE source utility to jamming power and unit price

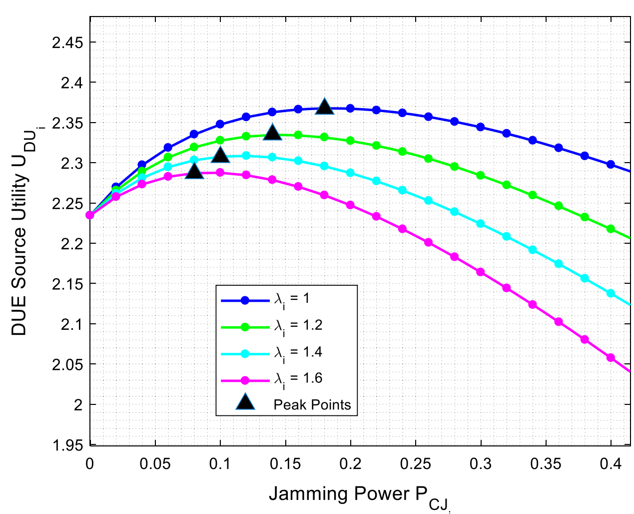

Fig. 5 DUE source utility to jamming power with different unit price

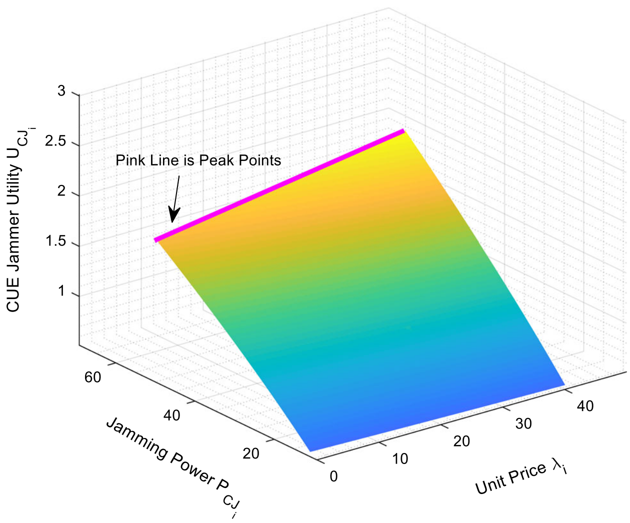

Fig. 6 CUE jammer utility to jamming power and unit price

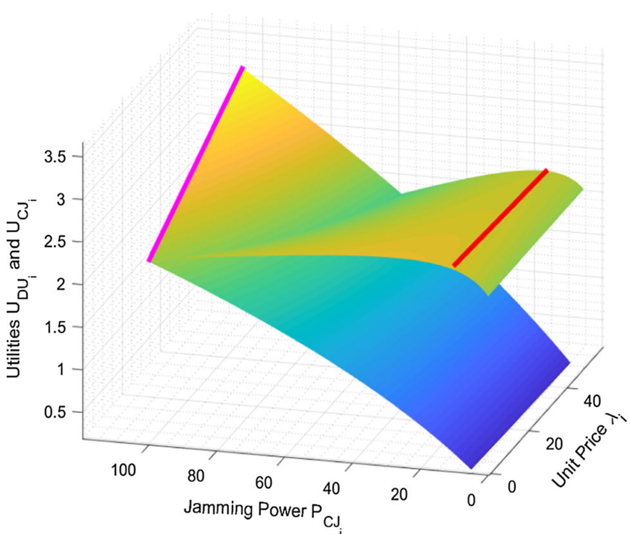

Fig. 7 Optimal utility of DUE source and CUE jammer

is increased with unit price. Combining both DUE and CUE, Fig. 7 shows that there are no intersections of the two optimal utility functions. Therefore, it is difficult to optimize both sides at the same time.

Figures 8 and 9 shows the efficiency functions of DUE source and CUE jammer. With a series fixed jamming power, the maximum value of DUE source efficiency function is illustrated in a red line and the CUE jammer side is in a pink line. It is obvious that the DUE source efficiency is decreased with the unit price while CUE jammer is opposite. Thus, Theorem 2 is demonstrated.

As shown in Figs. 10 and 11, both $R^{S+}_{DU_i}$ and $\Delta R^{S+}_{DU_i}$ are almost changeless and are approximately evolve into parallel lines when P_{CJ_i} increases to a certain degree. Thus,

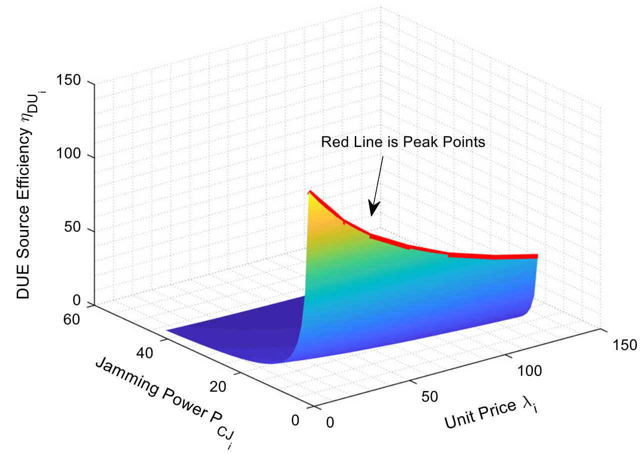

Fig. 8 DUE source efficiency to jamming power and unit price

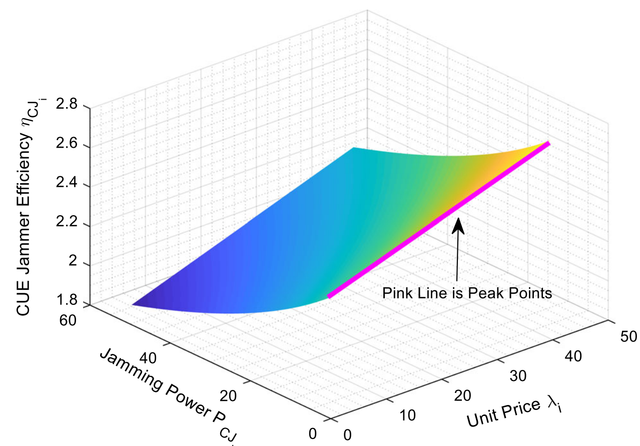

Fig. 9 CUE jammer efficiency to jamming power and unit price

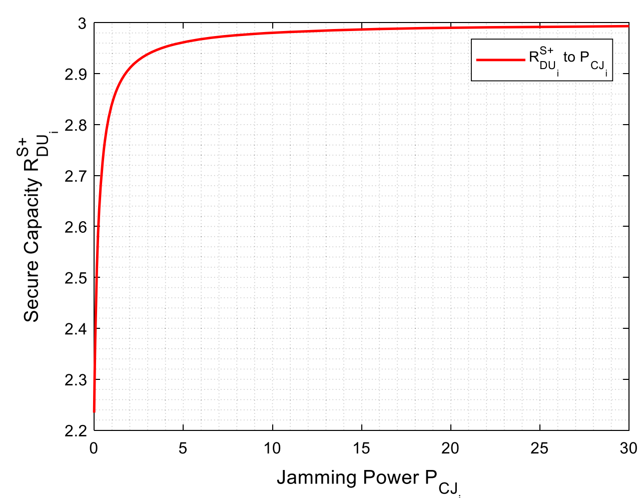

Fig. 10 DUE source secure capacity to jamming power

Eq. (37) is reasonable and Eq. (39) in Definition 5 is tenable.

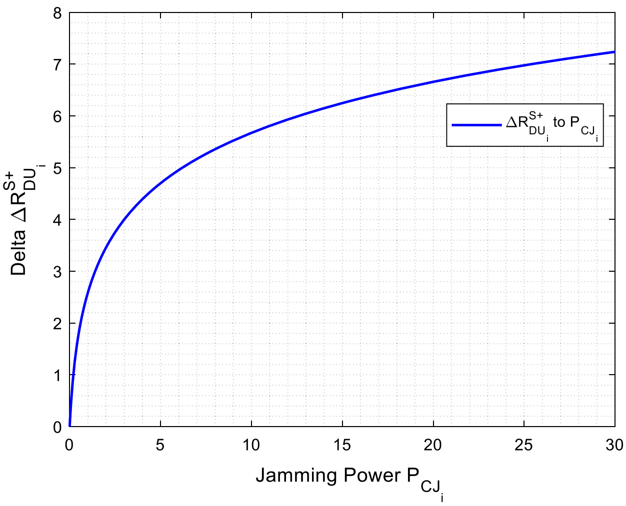

Fig. 11 Delta of DUE source secure capacity to jamming power

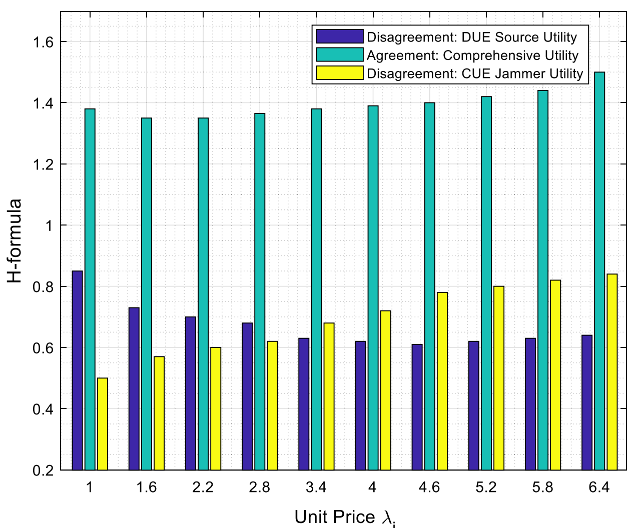

Fig. 12 Non-steps comprehensive utility function to unit price

Figures 12 and 13 shows the trend of comprehensive utility function in non-steps model and steps-contained model respectively. The green bar represents the total profit under an agreement. The blue bar and yellow bar respectively represents the profit of DUE source and CUE jammer when they do not reach an agreement. In our bargaining game model, buyer start the bargain from the left endpoint of unit price while the seller start from the right endpoint. The equilibrium point under an agreement will be reached somewhere in the domain. In Fig. 12, the equilibrium point of unit price is reached at x axis of 3.4. At this point, the non-steps comprehensive utility function is approximate to the maximum value and the utility functions of both sides are close to each other. In Fig. 13, the equilibrium point is reached at x axis of 5.8 for the evaluation criterion mentioned in Evaluation Function.

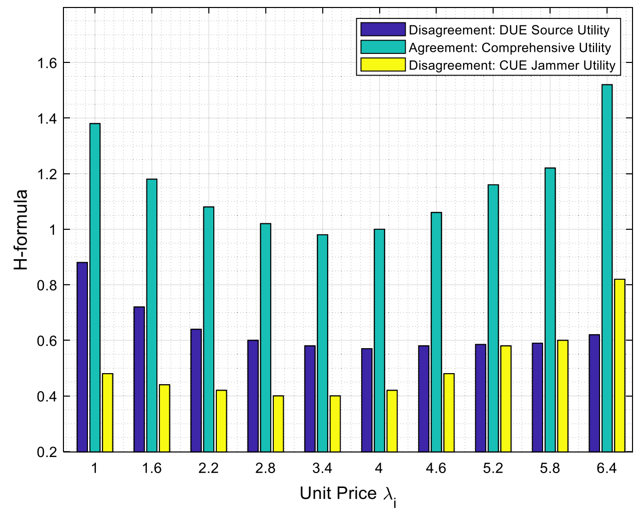

Fig. 13 Steps-contained comprehensive utility function to unit price

Notice that, the step number of iteration in Fig. 12 is five and in Fig. 13 is two. Therefore, the equilibrium point will be reached more early in steps-contained model.

8 Conclusions

In this paper, we investigate the security and efficiency problem of device-to-device underlay communication in a base station cell area with the presence of malicious eavesdroppers. Fairness of both DUE and CUE are taken into consideration by maximizing their utility as far as possible. Problems are modeled into a series of utility functions related to jamming power and unit price. A price bargaining game is proposed to solve these problems by reaching an agreement of unit price. For the non-steps model, an Evaluation Function and a Comprehensive Utility Function are demonstrated to analyze the bargain process. For steps-contained model, the step number of iteration is involved and an attenuation function is introduced to modify the bargaining game. Algorithms of two models are proposed to derive the equilibrium point for reaching an agreement.

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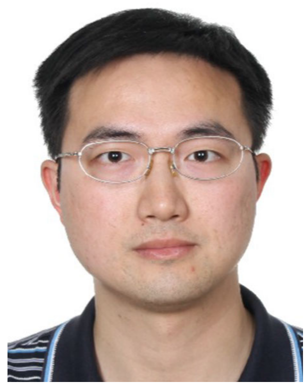
References

1. Gandotra, P., Jha, R. K., & Jain, S. (2017). A survey on device-to-device (D2D) communication: architecture and security issues. *Journal of Network & Computer Applications, 78*, 9–29.
2. Chen, X., Hu, R. Q., & Jeon, J., et al. (2015). Optimal resource allocation and mode selection for D2D communication underlaying Cellular Networks. In *IEEE global communications conference* (pp. 1–6).
3. Zappone, A., Matthiesen, B., & Jorswieck, E. A. (2017). Energy efficiency in MIMO underlay and overlay device-to-device communications and cognitive radio systems. *Mathematics, 65*(4), 1026–1041.
4. Yang, K., Martin, S., & Xing, C., et al. (2014). Energy-efficient power control for device-to-device communications. In *IEEE international conference on communications workshops* (pp. 483–488).
5. Huang, B. Y., Su, S. T., Wang, C. Y., Yeh, C. W., Wei, H. Y. (2016). Resource allocation in D2D communication-a game theoretic approach. *IEEE Wireless Communications Letters, PP*(99), 1–1.
6. Liu, J., Kato, N., Ujikawa, H., et al. (2016). Device-to-device communication for mobile multimedia in emerging 5G networks. *ACM Transactions on Multimedia Computing Communications & Applications, 12*(5s), 75.
7. Liu, Y., Chen, H. H., & Wang, L. (2017). Physical layer security for next generation wireless networks: theories, technologies, and challenges. *IEEE Communications Surveys & Tutorials, 19*(1), 347–376.
8. Huss, M., Waqas, M., Ding, A. Y., et al. (2017). Security and privacy in device-to-device (D2D) communication: a review. *IEEE Communications Surveys & Tutorials, 19*(2), 1054–1079.
9. Xu, J., Xiang, J., & Yang, D. (2015). Incentive mechanisms for time window dependent tasks in mobile crowdsensing. *IEEE Transactions on Wireless Communications, 14*(11), 6353–6364.
10. Shannon, C. E. (1949). Communication theory of secrecy systems. *Bell Labs Technical Journal, 28*(4), 656–715.
11. Xu, J., Xiang, J., & Li, Y. (2017). Incentivize maximum continuous time Interval coverage under budget constraint in mobile crowd sensing. *Wireless Networks, 23*(5), 1549–1562.
12. Xu, J., Li, H., & Li, Y., et al. (2017). Incentivizing the biased requesters: Truthful task assignment mechanisms in crowdsourcing. In *2017 14th annual IEEE international conference on sensing, communication, and networking* (pp. 1–9). IEEE.
13. Wyner, A. D. (1975). The wire-tap channel. *Bell System Technical Journal, 54*(8), 1355–1387.
14. Leung-Yan-Cheong, S., & Hellman, M. E. (1978). The gaussian wire-tap channel. *IEEE Transactions on Information Theory, 24*(4), 451–456.
15. Zhang, H., Yang, N., Long, K., Pan, M., Karagiannidis, G. K., & Leung, V. C. M. (2018). Secure communications in NOMA system: Subcarrier assignment and power allocation. *IEEE Journal on Selected Areas in Communications*. https://doi.org/10.1109/JSAC.2018.2825559.
16. Zhang, H., Xing, H., Cheng, J., Nallanathan, A., & Leung, V. (2016). Secure resource allocation for OFDMA two-way relay wireless sensor networks without and with cooperative jamming. *IEEE Transactions on Industrial Informatics, 12*(5), 1714–1725.
17. Negi, R., Goel, S. (2005). Secret communication using artificial noise. In *IEEE 62nd vehicular technology conference* (pp. 1906–1910).
18. Kashyap, A., Basar, T., & Srikant, R. (2004). Correlated jamming on MIMO gaussian fading channels. *IEEE Transactions on Information Theory, 50*(9), 2119–2123.
19. Zhang, H., Liu, N., Long, K., Cheng, J., Leung, V. C. M., & Hanzo, L. (2018). Energy efficient subchannel and power allocation for the software defined heterogeneous VLC and RF networks. *IEEE Journal on Selected Areas in Communications*. https://doi.org/10.1109/JSAC.2018.2815478.
20. Chen, S., Wang, K., Zhao, C., Zhang, H., & Sun, Y. (2017). Accelerated distributed optimization design for reconstruction of big sensory data. *IEEE Internet of Things Journal, 4*(5), 1716–1725.
21. Han, Z., Marina, N., & Debbah, M., et al. (2009). Physical layer security came: How to date a girl with her boyfriend on the same table. In *International conference on game theory for networks*: IEEE (pp. 287–294).
22. Yang, H., Xie, X., & Vasilakos, A. V. (2016). A robust Stackelberg game based uplink power control for device-to-device communication with channel uncertainty and outage probability constraints. *Wireless Personal Communications, 90*(2), 551–573.
23. Kebriaei, H., Maham, B., & Niyato, D. (2016). Double sided bandwidth-auction game for cognitive device-to-device communication in cellular networks. *IEEE Transactions on Vehicular Technology, 65*(9), 7476–7487.
24. Lin, Y. D., & Hsu, Y. C. (2000). Multihop cellular: A new architecture for wireless communications. In *Nineteenth joint conference of the IEEE computer and communications societies proceedings* (pp. 1273–1282).
25. Asadi, A., Wang, Q., & Mancuso, V. (2014). A survey on device-to-device communication in cellular networks. *IEEE Communications Surveys & Tutorials, 16*(4), 1801–1819.
26. Tehrani, M. N., Uysal, M., & Yanikomeroglu, H. (2014). Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions. *IEEE Communications Magazine, 52*(5), 86–92.
27. Feng, D., et al. (2016). Device-to-device communications in cellular networks. *IEEE Communications Magazine, 52*(4), 49–55.
28. Wen, S., et al. (2013). Distributed resource management for device-to-device (D2D) communication underlay cellular networks. In *IEEE international Symposium on personal indoor and mobile radio communications* (pp. 1624–1628).
29. Wang, Mingjun, & Yan, Z. (2017). A survey on security in D2D communications. *Mobile Networks & Applications, 22*(2), 195–208.
30. Jung, M., Hwang, K., & Choi, S. (2012). Joint mode selection and power allocation scheme for power-efficient device-to-device (D2D) communication. In *IEEE vehicular technology conference* (pp. 1–5).
31. Zhou, Z., et al. (2014). Energy efficiency and spectral efficiency tradeoff in device-to-device (D2D) communications. *IEEE Wireless Communications Letters, 3*(5), 485–488.
32. Ghavimi, Fayezeh, & Chen, Hsiao-Hwa. (2015). M2M communications in 3GPP LTE/LTE-A networks: Architectures, service requirements, challenges, and applications. *IEEE Communications Surveys & Tutorials, 17*(2), 525–549.
33. Huang, Hong, Ahmed, N., & Karthik, P. (2011). On a new type of denial of service attack in wireless networks: the distributed jammer network. *IEEE Transactions on Wireless Communications, 10*(7), 2316–2324.
34. Mascetti, S., Bertolaja, L., & Bettini, C. (2013). A practical location privacy attack in proximity services. In *IEEE international conference on mobile data management* (pp. 87–96).
35. Shirvanian, M., & Saxena, N. (2014). Wiretapping via mimicry: Short voice imitation man-in-the-middle attacks on crypto phones. In *ACM Sigsac conference on computer and communications security* (pp. 868–879).

36. Gandotra, P., Jha, R. K., & Jain, S. (2017). A survey on device-to-device (D2D) communication: Architecture and security issues. *Journal of Network & Computer Applications, 78*(C), 9–29.
37. Sudarsono, A., & Nakanishi, T. (2014). An implementation of secure data exchange in wireless delay tolerant network using attribute-based encryption. In *Second international Symposium on computing and networking* (pp. 536–542). IEEE Computer Society.
38. Shen, W., et al. (2014). Secure key establishment for device-to-device communications. In *IEEE global communications conference* (pp. 336–340).
39. Tata, C., & Kadoch, M. (2014). Secure multipath routing algorithm for device-to-device communications for public safety over LTE heterogeneous networks. In *International conference on information & communication technologies for disaster management* (pp. 1–7).
40. Zhang, H., et al. (2014). Radio resource allocation for physical-layer security in D2D underlay communications. In *2014 IEEE international conference on communications* (pp. 2319–2324).
41. Zheng, C., et al. (2015). Robust secrecy rate optimizations for multiuser multiple-input-single-output channel with device-to-device communications. *IET Communications, 9*(3), 396–403.
42. Chen, S., Zhao, C., Wu, M., Sun, Z., Zhang, H., & Leung, V. C. M. (2016). Compressive network coding for wireless sensor networks: spatio-temporal coding and optimization design. *Computer Networks, 108,* 345–356.
43. Chen, S., Wu, M., Wang, K., & Sun, Z. (2014). Compressive network coding for error control in wireless sensor networks. *Wireless Networks, 20*(8), 2605–2615.
44. Luo, Y., et al. (2015). Power control and channel access for physical-layer security of D2D underlay communication. In *IEEE international conference on wireless communications & signal processing* (pp. 1–5).
45. Wang, B., Wu, Y., & Liu, K. J. R. (2010). Game theory for cognitive radio networks: An overview. *Computer Networks, 54*(14), 2537–2561.
46. Pei, Yiyang, & Liang, Ying-Chang. (2013). Resource allocation for device-to-device communications overlaying two-way cellular networks. *IEEE Transactions on Wireless Communications, 12*(7), 3611–3621.
47. Chen, Xu, Song, Lingyang, Han, Zhu, Zhao, Qun, Wang, Xiaoli, Cheng, Xiang, et al. (2013). Efficiency resource allocation for device-to-device underlay communication systems: a reverse iterative combinatorial auction based approach. *IEEE Journal on Selected Areas in Communications, 31*(9), 348–358.
48. Zhang, R., Song, L., Han, Z., Cheng, X., & Jiao, B. (2013). Distributed resource allocation for device-to-device communications underlaying cellular networks. In *IEEE international conference on communications (ICC)* (pp. 1889–1893).
49. Kapetanovic, D., Zheng, G., & Rusek, F. (2015). Physical layer security for massive MIMO: An overview on passive eavesdropping and active attacks. *IEEE Communications Magazine, 53*(6), 21–27.



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