Economic-Robust Transmission Opportunity Auction for D2D Communications in Cognitive Mesh Assisted Cellular Networks

Ming Li, *Member, IEEE*, Weixian Liao, *Student Member, IEEE*, Xuhui Chen, *Student Member, IEEE*, Jinyuan Sun, *Member, IEEE*, Xiaoxia Huang, *Member, IEEE*, and Pan Li, *Member, IEEE*

Abstract—Device-to-device (D2D) communications can potentially alleviate cellular network congestion by utilizing local available links, and have attracted intensive attention recently. Cognitive radio (CR) allows users to opportunistically access unused licensed spectrums. It thus serves as a great candidate technology for D2D communications, but has not been widely employed in cellular networks due to hardware development limitations. In this paper, we propose a new architecture, called cognitive mesh assisted cellular network (CMCN), in which several secondary service providers (SSPs) deploy CR routers to facilitate D2D communications among wireless users. To address the competition among the SSPs, we further construct a secondary spectrum auction market. Although a few works have studied spectrum auctions, most of them are designed for single-hop communications, and it is usually not clear whom a winning user communicates with. Uncertain spectrum availability is not considered in previous schemes either. In this paper, we propose a transmission opportunity auction scheme, called TOA, which can address these problems. Extensive simulations are conducted to validate the efficiency of the CMCN architecture and that of the TOA scheme.

Index Terms—Device-to-device communications, cognitive mesh assisted cellular network, transmission opportunity auction

1 Introduction

The exploding growth of wireless devices like smartphones and tablets has driven the emergence of various applications, such as location-based social networking, mobile gaming, and mobile video services[1], but on the other hand, has exaggerated the congestion in wireless cellular networks. Device-to-device (D2D) communications deliver data traffic by utilizing local available links and bypassing the base stations (BSs), and hence can potentially alleviate network congestion, improve network capacity, coverage, and robustness, enable new services, etc. Besides, recent studies show that many licensed spectrum blocks are not used in certain geographical areas and are idle most of the time [2], [3]. Since Federal Communications Commission (FCC) opens the discussions on intelligently sharing licensed spectrum, there has been a surge of research activities on cognitive radios (CRs), which can be allowed to opportunistically access the unused licensed spectrum as long as they abide by the rules and regulations for such a usage. Thus, by integrating CR techniques, nodes under the D2D communication mode can borrow idle radio spectrums from other networks without interrupting communications among the licensed users. In such a way, the capacity of D2D communications in cellular networks can be largely increased by improved spectrum efficiency. There have been some existing research exploring the resource allocation, connectivity and energy efficiency for CR-enabled D2D communication systems [4], [5], [6].

However, we notice that most previous works commonly assume that a CR can operate across a wide spectrum range (e.g., from MHz to GHz [7]). This may be possible in theory, but in practice it is very difficult to implement such high cognitive capability in light-weight radios. In other words, wireless users may not be able to directly benefit from the CR technology due to hardware development limitations. Therefore, how to leverage CR technologies to support D2D communications practically is still an open and challenging problem, which deserves thorough investigation.

In this paper, we propose a new network architecture, called cognitive mesh assisted cellular network (CMCN), which allows wireless users to take advantage of CR technologies while minimizing the complexity of their devices. Specifically, in a CMCN, several secondary service providers (SSPs) deploy their own CR routers, which together form a cognitive mesh, to facilitate D2D communications. CR routers are equipped with multiple CR radios that can operate over a wide spectrum range. A wireless user

- *M. Li is with the Department of Computer Science and Engineering, University of Nevada, Reno, NV 89557. E-mail: mingli@unr.edu.*
- *W. Liao, X. Chen, and P. Li are with the Department of Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, OH, 44106. E-mail: {wxl393, xxc296, lipan}@case.edu.*
- *J. Sun is with the Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville, TN 37996. E-mail: jysun@eecs.utk.edu.*
- *X. Huang is with the Shenzhen Institutes of Advanced Technology, Chinese Academy of Science, Shenzhen, Guangzhou 510070, China. E-mail: xx.huang@siat.ac.cn.*

Manuscript received 10 Dec. 2016; revised 3 Oct. 2017; accepted 16 Nov. 2017. Date of publication 4 Dec. 2017; date of current version 29 June 2018.
(Corresponding author: Pan Li.)
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TMC.2017.2779488

accesses CMCN via a CR router nearby using either Wi-Fi or cellular radio. In such a way, no specific requirement is imposed on users' devices. They could be either laptops using Wi-Fi, cell phones using GSM/GPRS, or smart phones using 3G/4G/LTE, etc. Thus the CR capability requirement is offloaded from wireless users to CR routers.

For the data transmission among CR routers, rather than connecting them via the base station, we propose to leverage the short-range D2D communication. In so doing, we can further take advantage of local available channels and frequency reuse to provide higher network capacity. Since CR routers could be multihop away from each other, we adopt multihop D2D communications herein, i.e., an end-to-end connection for two CR routers may consist of multiple D2D links in between. The idea of multihop D2D communications in cellular networks was first proposed in [8] and has recently been discussed for its application in content downloading and sharing [9], [10], [11], [12]. It is expected to be a key feature supported by next-generation cellular networks [13].

For spectrums utilized by CR routers, they are leased from the primary cellular service provider (PSP), and can either be PSP's vacant licensed spectrums or some unused licensed spectrums harvested/purchased from other spectrum license holders, such as TV white space. Since wireless users pay to SSPs who deliver their data traffic, SSPs are motivated in renting spectrums from the PSP. To account for the competition among SSPs, we further construct a secondary spectrum auction market, where the PSP acts as the auctioneer and SSPs ask their CR routers to participate in the auction as bidders. The PSP determines the winning CR routers and optimizes the D2D communications by joint scheduling and routing. Note that the winning CR routers could belong to different SSPs. Each source user finally pays all the SSPs whose CR routers have helped relay its traffic with the help of (or through) the PSP, who has full knowledge of which SSPs have participated and how much each of them should earn.

In the literature, there have been some works studying spectrum auctions in wireless networks. However, most of them [14], [15], [16], [17], [18], [19], [20], [21], [22], [23] were designed for single-hop data transmission. In particular, each user bids and is allowed to use the purchased spectrum for communications if it wins. There are two problems: First, this is unsuitable for D2D communications; and second, it is not clear whom a winner communicates with (the receiver is not clearly specified). Thus, the network performance can be poor due to collisions. Li et al. [24], [25] discussed spectrum auctions for multi-hop data delivery. But they assumed that each secondary network only has one flow, and did not consider time domain scheduling when utilizing the spectrums. Our previous work [26] studied spectrum auctions for multi-hop wireless networks without exploring the diversity brought by multi-radio nodes. In addition, due to the unpredictable activities from other license holders, the harvested/purchased spectrum at the PSP is dynamic in nature. Unfortunately, uncertain spectrum availability was not considered by previous auction schemes. Moreover, in addition to fulfilling cellular users' traffic demands, auction schemes need to satisfy some critical economic properties.

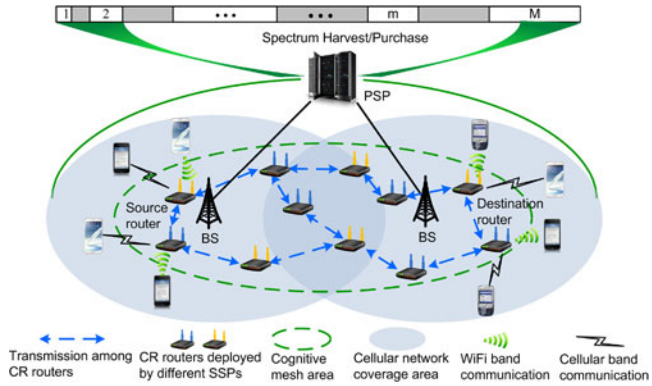


Fig. 1. The architecture of our proposed cognitive mesh assisted cellular network (CMCN).

In light with all these observations, we propose a transmission opportunity auction scheme, called TOA, for the proposed CMCN. Specifically, in TOA we model spectrum bandwidths as random variables. Instead of spectrums as in traditional spectrum auction schemes, CR routers bid for transmission opportunities (TOs). A TO is defined as the permit of data transmission on a specific link between a transmitter and a receiver using certain radios on a specific band, i.e., a link-radio-channel (LRC) tuple. The TOA scheme is mainly composed of three procedures: TO allocation, TO scheduling, and pricing. These three procedures are performed sequentially and iteratively until the aforementioned goals are reached. Particularly, in TO allocation, in each iteration the auctioneer solves a TO allocation (TO-AL) optimization problem to find out the LRC tuples (i.e., TOs) that can be active at the same time and have the highest total bid. *It considers the set of the transmitters in these TOs as a winning virtual bidder group (VBG).* In TO scheduling, the auctioneer formulates a minimum length scheduling problem, called TO scheduling (TO-SC), to see if the winning VBGs found so far can support the users' traffic in the network by exploring scheduling (in both time and frequency domains) and routing. If the minimum scheduling length is larger than 1, it means that the current winning VBGs cannot support the users' traffic, and the auctioneer needs to find another VBG through TO-AL again. Otherwise, the auctioneer can then determine the clearing price for each winning VBG and CR router.

The rest of this paper is organized as follows. The system models are described in Section 2. We detail the proposed TOA scheme in Section 3, and prove the economic-robustness of TOA in Section 4, respectively. We conduct simulations in Section 5 to evaluate the performance of the CMCN architecture and of the TOA scheme. We present extensive related work in Section 6. We finally conclude this paper in Section 7.

2 SYSTEM MODELS

2.1 Network Model

We consider a novel cognitive mesh assisted cellular network in this paper, as shown in Fig. 1. Specifically, several secondary service providers deploy their own CR routers in a cellular network to facilitate D2D communications, which together form a cognitive mesh. The primary cellular service provider leases its own idle spectrums, and if necessary, some unused licensed spectrums harvested/purchased from the corresponding spectrum license holders, such as TV white space, to the SSPs for their CR routers' communications. Thus, our proposed CMCN falls in the category of outband D2D communications [29], [30], [31], where the communications carried over cellular spectrums are not affected by D2D communications. Since users pay to SSPs who successfully deliver their data traffic, SSPs compete with each other in winning spectrums to support as much as traffic. Specifically, they ask their deployed CR routers to bid.[1] Meanwhile, the PSP determines the winning routers and arranges them to carry out D2D communications for the users. In addition, to exchange control messages with the PSP, SSPs can either let the CR routers utilize some of the PSP's common signaling control channels to communicate with the PSP's base stations in one hop, or communicate with the PSP on behalf of their routers via a wired connection. Moreover, as most wireless devices are not equipped with cognitive radios, they connect to the cognitive mesh, i.e., the CR router nearby, using the cellular or WiFi band to enjoy the high data rate brought by CR technologies. Since the first-hop and last-hop communications can be easily carried out, we focus on how to deliver D2D traffic in the cognitive mesh.

Suppose there are a set of $\mathcal{L} = \{1, 2, \ldots, L\}$ uni-cast D2D sessions in a CMCN. Let $s(l)$, $d(l)$, and $r(l)$ denote the source router, destination router, and traffic demand of session $l \in \mathcal{L}$, respectively.[2] Denote by $\mathcal{N} = \{1, 2, \ldots, N\}$ the set of all the routers. Since each CR router may be equipped with multiple radios, we denote the set of radios at CR router $i \in \mathcal{N}$ by $\mathcal{R}_i = \{1, 2, \ldots, R_i\}$. In addition, we let $\mathcal{M} = \{1, 2, \ldots, M\}$ denote the harvested/purchased spectrum bands by the PSP.

2.2 Dynamic Spectrum Availability and Link Capacity

Due to the unpredictable activities of other license holders, the availability of the harvested/purchased spectrums is highly dynamic. Based on the statistical characteristics of spectrum bands obtained from observations and experiments in [2], [32], [33],[3] we model the secondary spectrum bandwidths as random variables. In particular, we denote by W^b the bandwidth of band $b \in \mathcal{M}$, which is a random variable following a certain distribution.

Suppose the power spectral density of node i on band b is a constant and denoted by P_i^b. A widely used model [34], [35], [36], [37], [38], [39] for power propagation gain between node i and node j, denoted by g_{ij}, is $g_{ij} = C \cdot [d(i,j)]^{-\gamma}$, where i and j also denote the positions of node i and node j, respectively, $d(i,j)$ refers to the euclidean distance between i and j, γ is the path loss factor, and C is a constant related to the antenna profiles of the transmitter and the receiver, wavelength, and so on. In this work, we employ the protocol model [34], [35], [36], [37], [38], [39] to characterize interference relationships among transmissions. Specifically, the above data transmission is successful only if the received power spectral density at the receiver exceeds a threshold P_T^b. Meanwhile, we assume interference becomes non-negligible only if it produces a power spectral density over a threshold of P_I^b ($P_I^b \leq P_T^b$) at the receiver. We denote the transmission range and interference range of node i on band b by $R_T^{i,b}$ and $R_I^{i,b}$, respectively. Obviously, we have $R_I^{i,b} \geq R_T^{i,b}$. Besides, different nodes may have different transmission ranges/interference ranges on different channels with different transmission power.

Moreover, similar to that in [35], [38], [40], according to the Shannon-Hartley theorem, if node i transmits to node j on band b, using radios m ($m \in \mathcal{R}_i$) and n ($n \in \mathcal{R}_j$), respectively, the capacity of this transmission is

$$r_{ij,mn}^b = W^b \log_2\Big(1 + \frac{g_{ij} P_i^b}{\eta}\Big), \tag{1}$$

where η is the thermal noise at the receiver. Note that the denominator inside the log function only contains η. This is because of one of our interference constraints, i.e., when node i is transmitting to node j on band b, all the other neighbors of node j within its interference range are prohibited from using this band. We will address the interference constraints in detail in the following section. Notice that since we consider W^b's as random variables, the transmission capacity $r_{ij,mn}^b$'s are also random variables.

2.3 Auction Model

In a CMCN, the PSP acts as the auctioneer, while SSPs ask their CR routers to participate in the auction as bidders. Instead of spectrum bands as in previous auction schemes, the CR routers bid for transmission opportunities. A TO is defined as the permit of data transmission between a transmitter and a receiver using certain radios on a certain spectrum band, which we call a link-radio-channel tuple. *Compared with spectrum in traditional spectrum auctions, a TO in our proposed TO auction not only specifies the allocated spectrum, but also the specific transmitter and receiver as well as their radios using this spectrum.* The PSP then determines the winning CR routers (actually the winning TOs) and optimizes the D2D data traffic delivery by joint scheduling and routing. Note that the winning CR routers could belong to different SSPs. Each source user finally pays all the SSPs, whose deployed CR routers have helped relay its traffic, with the help of (or through) the PSP, who has full knowledge of which SSPs have participated and how much each of them should earn. Note that routers are the real bidders in TO auctions instead of wireless users.

In order to participate in spectrum auctions, all the SSPs submit the locations of their routers to the PSP, who can then determine the topology of the entire CR mesh. Based on that, the PSP constructs a conflict graph denoted by $G(V, E)$, where V is the vertex set and E is the edge set. In particular, each vertex corresponds to a LRC tuple denoted by $((i,j),(m,n),b)$, where $i, j \in \mathcal{N}$, $j \in \mathcal{T}_i^b$, $m \in \mathcal{R}_i$, $n \in \mathcal{R}_j$,

1. In this paper, we only discuss the bidding activities of CR routers. For how much users pay to SSPs for delivering their data, it is not the focus here. A necessary condition is that the charge to SSPs during an auction should be no larger than their collected payment from users.

2. Source router and destination router can be easily determined, for example, according to the signal strength.

3. For example, Yin et al. [2] carried out a set of spectrum measurements in the 20 MHz to 3 GHz spectrum bands at four locations concurrently in the Guangdong Province of China. They conducted a set of detailed analysis of the first and second order statistics of the collected data.

and $b \in \mathcal{M}_i \bigcap \mathcal{M}_j$. Here, $\mathcal{T}_i^b$ is the set of nodes[4] within node i's transmission range on band b, and $\mathcal{M}_i$ is the set of spectrum bands available at node i. The LRC tuple indicates that node i transmits to node j on channel b with radio m and radio n, respectively. Besides, two vertices in V are connected with an undirected edge if the corresponding LRC tuples interfere with each other, i.e., if any of the following conditions is true:

- The receiving node in one LRC tuple is within the interference range of the transmitting node in another LRC tuple, given that the both of them are using the same band;
- The two tuples use the same radio at one or two nodes.

In this conflict graph, an independent set (IS) is a set in which each element is a LRC tuple for a transmission, and all the elements (or transmissions) can be carried out successfully at the same time. If adding any more LRC tuple into an IS results in a non-independent one, this IS is defined as a maximum independent set (MIS). We denote the set of all the MISs by $\mathcal{I} = \{\mathcal{I}_1, \mathcal{I}_2, \ldots \mathcal{I}_q, \ldots, \mathcal{I}_Q\}$, where $Q = |\mathcal{I}|$, and $\mathcal{I}_q \subseteq V$ for $1 \leq q \leq Q$. We will show later that we do not really need to find all the MISs, which is in fact an NP-complete problem. We denote the MIS $\mathcal{I}_q$'s time share (out of unit time 1) to be active by λ_q ($\lambda_q \geq 0$). Therefore, if all the data traffic in the network can be supported, we have $\sum_{q=1}^{Q} \lambda_q \leq 1$. Besides, we let $r_{ij,mn}^b(\mathcal{I}_q)$ be the instantaneous transmission rate of the LRC tuple $((i,j),(m,n),b)$ when the MIS $\mathcal{I}_q$ is active. Then, $r_{ij,mn}^b(\mathcal{I}_q)$ is equal to 0 if the LRC tuple $((i,j),(m,n),b) \notin \mathcal{I}_q$, and the capacity of $((i,j),(m,n),b)$, i.e., $r_{ij,mn}^b$, otherwise, as calculated in (1).

We denote node i's real valuation and bid price for a TO by v_i and c_i, respectively. In an auction, nodes submit their bids c_i's in a sealed manner, so that no one has access to any information about others' bids. After the auctioneer receives all the bids, it divides the bidders into different virtual bidder groups (VBGs), each of which is a set of transmitters of all LRC tuples in one MIS. We denote the set of all the VBGs by $\mathcal{G}$. The auctioneer considers each VBG as a virtual bidder with its group bid being the sum of all nodes' bids in that group, and determines the winning VBGs denoted by $\mathcal{G}_W$. We denote each winning VBG in $\mathcal{G}_W$ by $\mathcal{G}_{W,t}$ $(1 \leq t \leq |\mathcal{G}_W|)$, and the set of indices of the winning VBGs containing node i by H_i, respectively. We also denote the clearing price for node i in a winning VBG containing i, say $\mathcal{G}_{W,t}$ $(t \in H_i)$, by p_i^t.

2.4 Objective of Auction Design

The design of auction schemes heavily depends on the desired properties. In this paper, we assume that all nodes are strategic in the sense that they may manipulate their bids to obtain favorable outcomes. We aim to design an auction scheme that can satisfy two of the most important economic requirements: Incentive Compatibility (IC) and Individual Rationality (IR), which are defined as follows:

- *Incentive Compatibility*: The utility function of node i $(i \in \mathcal{N})$, is a function of all the bids

$$u_i(c_i, \mathbf{c_{-i}}) = \begin{cases} \sum_{t \in H_i}(v_i - p_i^t), \text{if } i \text{ wins} \\ \text{with bid } c_i, \\ 0, \text{ otherwise.} \end{cases} \quad (2)$$

where $\mathbf{c_{-i}}$ denotes the vector of bids from other nodes. Thus, an auction is IC if for any node i $(i \in \mathcal{N})$ with any $c_i \neq v_i$ while others' bids are fixed, we have

$$u_i(c_i, \mathbf{c_{-i}}) \leq u_i(v_i, \mathbf{c_{-i}}). \quad (3)$$

- *Individual Rationality*: An auction is IR, if no bidder is charged higher than its bid in the auction, i.e., $c_i \leq p_i$ for all $i \in \mathcal{N}$.

We say an auction is *economic-robust* [20], [27] if it is IC and IR.

3 Transmission Opportunity Auction

In this section, we introduce our proposed transmission opportunity auction scheme, called TOA. Recall that there are a set of uni-cast D2D sessions, which need to be delivered through the CR mesh and may be across multiple hops each. Thus, the objective of TOA is to choose MISs, and hence VBGs, which can support such multi-hop sessions and generate high social utility. Meanwhile, TOA should be economic-robust. In general, the TOA scheme is composed of three closely coupled procedures: TO allocation, TO scheduling, and pricing. These three procedures are performed sequentially and iteratively until our goals are reached. In what follows, we detail the design of three procedures, respectively.

3.1 Transmission Opportunity Allocation

At the beginning of TOA, each node i $(i \in \mathcal{N})$ submits its bid c_i to the auctioneer. Then the auctioneer calculates the virtual bid from $\mathcal{G}_q$ as

$$C_q = \sum_{i \in \mathcal{G}_q} c_i. \quad (4)$$

The objective of TO allocation is to find out one winning MIS, which corresponds to a winning VBG, that maximizes the virtual bid C_q in each iteration in a monotonic manner. In particular, we find the VBG with the highest virtual bid in the first iteration, the one with the second highest virtual bid in the second iteration, and so on and so forth until the iteration ends. Such VBGs (MISs) are considered as winning VBGs (MISs) denoted by $\mathcal{G}_W$ $(\mathcal{I}_W)$. We will show in Section 4 that a monotonic TO allocation procedure is critical in achieving the IC and IR properties. Note that each element in an MIS is a TO. Since finding all the MISs and hence TOs is an NP-complete problem, our approach of finding useful MISs one by one is much more efficient.

Before formulating the optimization problem, we first list several constraints as follows.

Notice that in the procedure of TO allocation, we do not assume that we know all the MISs, finding which is in fact an NP-complete problem. We denote

$$s_{ij,mn}^b = \begin{cases} 1, \text{if } i, \text{ using radio } m, \text{ can transmit to } j, \\ \text{using radio } n, \text{ on channel } b, \\ 0, \text{ otherwise.} \end{cases}$$

4. In this paper, we consider the terms node and CR router interchangeable.

Recall that we let $\mathcal{T}_i^b$ denote the set of nodes that can access channel b and are within the transmission range of node i, and $\mathcal{R}_i$ the set of radios at node i. We can prove that a node cannot transmit to or receive from multiple nodes on the same channel due to interference, even if it has multiple radios. Thus, we have

$$\sum_{j\in\mathcal{T}_i^b}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} s_{ij,mn}^b \le 1, \sum_{\{i|j\in\mathcal{T}_i^b\}}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} s_{ij,mn}^b \le 1. \quad (5)$$

Besides, a node j cannot use the same channel or radio for transmission and reception at the same time. Therefore, we get

$$\sum_{\{i|j\in\mathcal{T}_i^b\}}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} s_{ij,mn}^b + \sum_{q\in\mathcal{T}_j^b}\sum_{y\in\mathcal{R}_j}\sum_{z\in\mathcal{R}_q} s_{jq,yz}^b \le 1. \quad (6)$$

$$\sum_{b\in\mathcal{M}_j}\sum_{\{i|j\in\mathcal{T}_i^b\}}\sum_{m\in\mathcal{R}_i} s_{ij,mn}^b + \sum_{p\in\mathcal{M}_j}\sum_{q\in\mathcal{T}_j^b}\sum_{z\in\mathcal{R}_q} s_{jq,nz}^p \le 1. \quad (7)$$

Moreover, the total number of communication links, transmitting or receiving, at any node j should be no larger than the number of radios node j has, which means

$$\sum_{b\in\mathcal{M}_j}\sum_{\{i|j\in\mathcal{T}_i^b\}}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} s_{ij,mn}^b + \sum_{p\in\mathcal{M}_j}\sum_{q\in\mathcal{T}_j^b}\sum_{y\in\mathcal{R}_j}\sum_{z\in\mathcal{R}_q} s_{jq,yz}^p \le |\mathcal{R}_j| = R_j. \quad (8)$$

In addition to the above constraints at a certain node, there are also constraints due to potential interference among the nodes. In particular, for a spectrum band b, if node i uses this band for transmitting data to a neighboring node $j\in\mathcal{T}_i^b$, then any other nodes that can interfere with node j's reception should not use this band. To model this constraint, we denote by $\mathcal{P}_j^b$ the set of nodes that can interfere with node j's reception on band b, i.e.,

$$\mathcal{P}_j^b = \{p|d(p,j)\le R_I^{p,b}, p\ne j, \mathcal{T}_p^b \ne \emptyset\}.$$

The interpretation of $\mathcal{T}_p^b \ne \emptyset$ in the above definition is that node p may interfere with the reception at node j only if there are some nodes within p's transmission range on channel b which p can transmit to. Consequently, for each $p\in\mathcal{P}_j^b$, we have

$$\sum_{\{i|j\in\mathcal{T}_i^b\}}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} s_{ij,mn}^b + \sum_{q\in\mathcal{T}_p^b}\sum_{y\in\mathcal{R}_p}\sum_{z\in\mathcal{R}_q} s_{pq,yz}^b \le 1. \quad (9)$$

Moreover, recall that we need find the tth highest virtual bid in the tth iteration. Thus, in the tth ($t\ge 2$) iteration, we need find the VBG giving the highest virtual bid with the previously found $t-1$ VBGs being excluded. Letting $\mathcal{I}_{W,t}$ and $\mathcal{G}_{W,t}$ denote the MIS and the corresponding VBG that we find in the tth iteration, respectively, we have

$$\sum_{((i,j),(mn),b)\in\mathcal{I}_{W,\tau}} s_{ij,mn}^b < |\mathcal{I}_{W,\tau}|, \quad 1\le\tau\le t-1, \quad (10)$$

$$\sum_{((i,j),(m,n),b)\notin\mathcal{I}_{W,\tau}} s_{ij,mn}^b \ge 1, \quad 1\le\tau\le t-1, \quad (11)$$

where $|\mathcal{I}_{W,\tau}|$ is the number of elements contained in $\mathcal{I}_{W,\tau}$. (10) means that all the LRC tuples in any of the previously found $t-1$ MISs cannot be selected at the same time in the tth iteration, which excludes the previous $t-1$ MISs. (11) means that the newly found MIS should contain at least one different LRC tuple from any of the previously found $t-1$ MISs.

Consequently, according to the above constraints, the TO allocation (TO-AL) optimization problem finding the VBG with the tth highest virtual bid in the tth iteration can be formulated as follows:

$$\mathbf{TO-AL: Maximize} \quad \sum_{i\in\mathcal{N}}\sum_{b\in\mathcal{M}_i}\sum_{j\in\mathcal{T}_i^b}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} s_{ij,mn}^b\cdot c_i$$
$$\mathbf{s.t.} \quad \text{Constraints } (5)-(11)$$
$$s_{ij,mn}^b = 0 \quad \text{or} \quad 1,$$

where $s_{ij,mn}^b$'s are the optimization variables. Note that (10) and (11) make sure the newly found IS in tth iteration is an MIS and different from any MIS found in previous $t-1$ iterations. Besides, (10) is in fact always satisfied as long as (11) holds. Since $s_{ij,mn}^b$ can only take value of 0 or 1, TO-AL is a binary integer programming (BIP) problem, which can be solved by applying the traditional *branch-and-bound* or *branch-and-cut* [41] approach.

Note that at the end of each round of TO-AL a winning MIS (and thus a winning VBG) is identified. However, how to allow the winning VBGs to carry out D2D sessions is not clear. In another word, although the spectrum has been allocated to winning VBGs, it is useless for data transmissions without specifying the scheduling and data routing policy.

3.2 Transmission Opportunity Scheduling

After determining some winning MISs, the auctioneer finds an optimal way to utilize them to deliver all the uni-cast sessions, by exploring joint scheduling and routing.

Denote the set of the winning MISs found up to the tth iteration by $\mathcal{I}_W^t = \cup_{\tau=1}^t \mathcal{I}_{W,\tau}$. Note that $|\mathcal{I}_W^t| = t$. Letting $f_{ij}(l)$ denote the flow rate of traffic l over link (i,j), where $i\in\mathcal{N}$, $j\in\mathcal{T}_i$ ($\mathcal{T}_i = \cup_{b\in\mathcal{M}_i}\mathcal{T}_i^b$), and $l\in\mathcal{L}$, the scheduling of MISs should satisfy the following:

$$\sum_{l\in\mathcal{L}} f_{ij}(l) \le \sum_{q=1}^t \lambda_q \sum_{b\in\mathcal{M}_i\cap\mathcal{M}_j}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} r_{ij,mn}^b(\mathcal{I}_q). \quad (12)$$

Note that (12) is a probabilistic constraint since $r_{ij,mn}^b(\mathcal{I}_q)$'s are random variables. Inspired by the concept of value at risk (VaR) in [42], we leverage a parameter $\beta\in[0,1]$ to define the spectrum availability at confidence level β, and denote it by $X_\beta(W)$ as follows:

$$\begin{cases} H_W(t) = \int_t^\infty h_W(w)dw, & t\in\mathcal{R} \\ X_\beta(W) = \sup\{t : H_W(t)\ge\beta\}, & \beta\in[0,1]. \end{cases}$$

Based on the above definition, we can reformulate (12) as

$$\sum_{l\in\mathcal{L}} f_{ij}(l) \le \sum_{q=1}^t \lambda_q X_\beta\left(\sum_{b\in\mathcal{M}_i\cap\mathcal{M}_j}\sum_{m\in\mathcal{R}_i}\sum_{n\in\mathcal{R}_j} r_{ij,mn}^b(\mathcal{I}_q)\right). \quad (13)$$

We then give routing constraints in the following. Recall that a source node may need a number of relay nodes to relay its data packets toward the intended destination node.

Since routing packets along a single path may not be able to fully take advantage of the local available channels, in this study, we employ multi-path routing to deliver packets more effectively and efficiently.

In particular, if node i is the source of session l, i.e., $i = s(l)$, then we have the following constraints:

$$\sum_{j \neq s(l), s(l) \in \mathcal{T}_j} f_{js(l)}(l) = 0, \tag{14}$$

$$\sum_{j \neq s(l), j \in \mathcal{T}_{s(l)}} f_{s(l)j}(l) = r(l). \tag{15}$$

The first constraint means that the incoming data rate of session l at its source node is 0. The second constraint means that the traffic for session l may be delivered through multiple nodes on multiple paths, and the total data rate on all outgoing links is equal to the corresponding average end-to-end session data rate $r(l)$.

If node i is an intermediate relay node for session l, i.e., $i \neq s(l)$ and $i \neq d(l)$, then

$$\sum_{j \neq s(l), j \in \mathcal{T}_i} f_{ij}(l) = \sum_{p \neq d(l), i \in \mathcal{T}_p} f_{pi}(l), \tag{16}$$

which indicates that the total incoming data rate at a relay node is equal to its total outgoing data rate for the same session.

Moreover, if node i is the destination node of session l, i.e., $i = d(l)$, then we have

$$\sum_{j \neq d(l), j \in \mathcal{T}_{d(l)}} f_{d(l)j}(l) = 0, \tag{17}$$

$$\sum_{p \neq d(l), d(l) \in \mathcal{T}_p} f_{pd(l)}(l) = r(l). \tag{18}$$

The first constraint means the total outgoing data rate for session l at its destination $d(l)$ is 0, while the second constraint indicates that the total incoming data rate for session l at the destination $d(l)$ is equal to the corresponding average end-to-end session data rate $r(l)$.

Based on the constraints mentioned above, the TO scheduling (TO-SC) optimization problem in the tth iteration is formulated as follows:

$$\begin{aligned} \mathbf{TO-SC:}\quad & \mathbf{Minimize} \quad \sum_{q=1}^{t} \lambda_q \\ & \mathbf{s.t.} \quad \text{Constraints } (13) - (18) \\ & \lambda_q \geq 0 \ (1 \leq q \leq t) \\ & f_{ij}(l) \geq 0 \ (i \in \mathcal{N}, j \in \mathcal{T}_i, l \in \mathcal{L}). \end{aligned}$$

Its objective is to minimize the active transmission time of all winning MISs to support all the D2D sessions, such that a feasible solution, i.e., $\sum_{q=1}^{t} \lambda_q \leq 1$, can be found fast. Denoting by $F_W(w)$ the cumulative distribution function (CDF) of the random variable W, we can get $X_\beta(W) = F_W^{-1}(1-\beta)$. Thus, (13) can be further reformulated as

$$\sum_{l \in \mathcal{L}} f_{ij}(l) \leq \sum_{q=1}^{t} \lambda_q F^{-1}_{W_{ij}(\mathcal{I}_q)}(1-\beta), \tag{19}$$

where $W_{ij}(\mathcal{I}_q)$ is defined as $\sum_{b \in \mathcal{M}_i \cap \mathcal{M}_j} \sum_{m \in \mathcal{R}_i} \sum_{n \in \mathcal{R}_j} \sum_{((i,j),(m,n),b) \in \mathcal{I}_q} W^b s^b_{ij,mn} \log_2(1 + \frac{g_{ij} P_i^b}{\eta})$. Thus, given the distributions of random variables W^b's, and the decision variables $s^b_{ij,mn}$'s obtained in the TO-AL procedure, (19) is a linear constraint regarding variables $f_{ij}(l)$'s. After replacing (13) with (19), the formulated TO-SC problem is a linear programming (LP) problem, which can be easily solved by the simplex method [43]. The optimal result of TO-SC indicates whether the current winning MISs are enough to support all the uni-cast sessions. Specifically, if the optimal result is no larger than 1, then all sessions can be supported. The solution also shows how to schedule the MISs and route the traffic. Then, the auctioneer continues to perform pricing as introduced next. Otherwise, it means that the current winning MISs cannot satisfy the sessions. Thus, the auctioneer does not need to perform pricing and another winning MIS is generated from TO-AL.

Note that TO-SC is an indispensable procedure for our proposed TOA. First, it tells how the winning VBGs utilize their obtained spectrum to deliver D2D sessions. Second, the derived minimum scheduling length $\sum_{q=1}^{t} \lambda_q$ is critical for pricing, which determines if the economic-robustness can be achieved in TOA. More details will be provided next.

3.3 Iteration Termination and Pricing

Before describing the pricing scheme, we would like to discuss the iteration termination condition. As mentioned above, a minimum scheduling length $\sum_{q=1}^{t} \lambda_q$ over all selected VBGs is derived via TO-SC in tth iteration. If $\sum_{q=1}^{t} \lambda_q > 1$, it indicates the traffic load cannot be supported by current winning VBGs and another round of iteration is needed to identify more winning VBG(s). In this paper, we set the termination condition as the iteration when $\sum_{q=1}^{t} \lambda_q \leq 1$ is reached for the first time. As we will show later in the proof of Theorem 1, this termination condition plays a critical role in guaranteeing economic-robustness of our scheme.

After fixing the iteration number, i.e., the number of winning VBGs, we set the charging price for each winning node following the basic idea of VCG auction pricing [44]. Recall that H_i represent the set of indices of winning VBGs containing node i. The clearing price for i is

$$p_i = \sum_{t \in H_i} p_i^t = \sum_{t \in H_i} \big(C_{t,-\mathbf{i}} - (C_t - c_i)\big), \tag{20}$$

where $C_{t,-\mathbf{i}}$ stands for the tth highest group bid when node i is excluded from the tth iteration and $C_t - c_i$ is the sum of bids from the tth highest group bid except c_i. Clearly, the clearing price for winner i is irrelevant to its bid. Based on the proposed spectrum allocation and pricing procedure, we are able to prove this spectrum auction framework is economic-robust. We leave its discussion and proof in Section 4.

3.4 Computation Efficiency Analysis

Recall that our TOA scheme consists of three procedures: TO allocation (solving TO-AL), TO scheduling (solving TO-SC), and pricing, out of which TO-SC (an LP problem) and pricing can be efficiently computed while TO-AL (a BIP problem) may take some computation efforts. A new round of TOA might be triggered by the update of traffic demand. Fortunately, in most cases the PSP does not have to conduct a new TOA entirely, as long as the CR routers' bids and the CR mesh topology do not change. The objective of TO-AL is to find out winning VBGs that have the highest virtual bids. In particular, a winning VBG that maximizes the virtual bid C_q is selected in each iteration in a monotonic manner. Note that a VBG's virtual bid is only dependent on the CR routers' bids and their topology (as it determines their interference relations). If these two factors do not change, the order of winning VBGs selected via TO-AL of two TOAs (for different traffic demand) will be identical. That is, the formulation and solution of TO-AL is irrelevant to the traffic demand. Besides, these two factors are considered stable for a relatively long time period,[5] say one hour or even longer. Therefore, even if the traffic demand changes, it is quite possible that the PSP does not need to compute TO-AL, but only TO-SC and pricing based on the existing winning VBGs, unless the existing winning VBGs cannot support the new traffic demand. In this case, more new winning VBGs are required. Thus, several more rounds of TO-AL will be conducted. Still, it does not need to re-compute the entire TOA. We provide more discussion in the simulation part.

4 Proof of Economic Properties

In this section, we will demonstrate that our proposed auction scheme TOA is economic-robust. However, proof procedures from existing works cannot be directly applied. And it is a non-trivial task. In addition to spectrums, the outcome of a TOA further determines how to utilize them to support multihop data sessions via the link scheduling and routing policy. All of them play important role in achieving the economic-robustness. However, traditional spectrum auction schemes only focus on spectrum allocation. Neither link scheduling nor routing is considered. Hence their factors to take into account for the proof are much simpler.

To prove the economic-robustness of the proposed spectrum auction scheme, we first have the following lemma:

Lemma 1. *When the other nodes' bids, i.e., $\mathbf{c_{-i}}$, are fixed, if a VBG that contains node i with bid c_i wins in the tth iteration, it also wins by the tth iteration when node i bids $c_i' > c_i$.*

Proof. Let the winning VBG in the tth iteration containing node i with bid c_i be $\mathcal{G}_{W,t}(c_i)$. When node i bids with c_i', denote by t' and t^* the iterations at which this VBG wins and TOA terminates, respectively. It is possible that $t^* < t$ or $t^* \geq t$. In order to prove this lemma, we discuss under these two scenarios.

We first consider the scenario where $t^* \geq t$. For the winning VBG $\mathcal{G}_{W,t}(c_i)$, its group bid is $C_t = c_{-i}^t + c_i$, where $c_{-i}^t = \sum_{j\in\{\mathcal{G}_{W,t}\setminus\{i\}\}} c_j$. When node i bids $c_i' > c_i$, this VBG's new group bid, denoted by $C_{t'}'$, is $C_{t'}' = C_t - c_i + c_i' > C_t$.

The VBGs losing in all t iterations when i bids with c_i can be divided into two classes, i.e., the VBGs do not contain node i and the VBGs contain node i. For any VBG in the first class, we denote its group bids when node i bids with c_i and with c_i' by C_s and C_s', respectively. Since the other nodes' bids remain the same, we have $C_s' = C_s \leq C_t < C_{t'}'$. Therefore, the VBGs which do not contain i and lose in all t iterations when i bids with c_i will still lose in all t' iteration when i bids c_i'. For any VBG in the second class, it won't beat $C_{t'}'$ as well, since the bids from VBGs containing node i will increase by the same amount. Therefore, the number of losing VBGs in the t'th iteration when node i bids c_i' won't be less than that in the tth iteration when node i bids c_i and thus $t' \leq t$. As $t^* \geq t$, we have $t' \leq t \leq t^*$, i.e., the VBG wins by tth iteration when node i bids c_i'.

For the second scenario where $t^* < t$, we can prove $t' \leq t$ following the similar approach above. Besides, we need further prove the VBG wins before TOA termination. From the results above, we have $\{\mathcal{G}_{W,k}(c_i')|1 \leq k \leq t'\} \subset \{\mathcal{G}_{W,k}(c_i)|1 \leq k \leq t\}$, i.e., all winning VBGs up to t'th iterations when node i bids c_i' is a subset of all winning VBGs up to tth iterations when node i bids c_i. Since $\sum_{q=1}^{t-1} \lambda_q > 1$ with the winning VBG set $\{\mathcal{G}_{W,k}(c_i)|1 \leq k \leq t\}$, we have $\sum_{q=1}^{t'-1} \lambda_q > 1$ with the winning VBG set $\{\mathcal{G}_{W,k}(c_i')|1 \leq k \leq t'\}$, and thus $t' < t^*$ according to our iteration termination condition.

In all, we prove the lemma under both scenarios. □

Using the above lemma, we can arrive at the following theorem.

Theorem 1. *The proposed TOA is incentive compatibility.*

Proof. We need to show that for any node i with any $c_i \neq v_i$ while the others' bids are fixed, the condition in (3) holds. Let $u_i(c_i, \mathbf{c_{-i}})$ and $u_i(v_i, \mathbf{c_{-i}})$ denote node i's utility when it bids c_i and v_i, respectively. We first consider the scenario where $c_i > v_i$.

- *Case 1*: *node i loses with both v_i and c_i*. In this case, $u_i(c_i, \mathbf{c_{-i}}) = u_i(v_i, \mathbf{c_{-i}}) = 0$ according to our definition in (2). Thus, (3) holds.
- *Case 2*: *node i loses with v_i but wins with c_i*. Obviously, we have $u_i(v_i, \mathbf{c_{-i}}) = 0$. Considering a VBG $\mathcal{G}_{W,t}(c_i)$ containing node i with bid c_i wins in the tth iteration, we can infer that $\sum_{k=1}^{t-1} \lambda_k > 1$ according to our pricing scheme. Therefore, when node i is excluded from the tth iteration, the VBG with the group bid of $C_{t,-\mathbf{i}}$ wins as well. Since node i loses when it bids v_i, we have $C_t - c_i + v_i < C_{t,-\mathbf{i}}$. Thus, $u_i(c_i, \mathbf{c_{-i}})$ is calculated by

$$u_i(c_i, \mathbf{c_{-i}}) = \sum_{t\in H_i} \left(v_i - C_{t,-\mathbf{i}} + (C_t - c_i)\right) = \sum_{t\in H_i} \left((C_t - c_i + v_i) - C_{t,-\mathbf{i}}\right) < 0.$$

- *Case 3*: *node i wins with v_i and loses with c_i*. Since $c_i > v_i$, according to Lemma 1, this will not happen.
- *Case 4*: *node i wins with both v_i and c_i*. We denote the set of the indices of the iterations where i wins by bidding c_i and v_i by H_i and H_i', respectively.

5. For the topology, once CR routers are deployed by their SSPs, they are fixed and static. For a CR router's bid c_i, we have $c_i = v_i$ under IC property. As v_i stands for the router's real valuation towards a TO, it is reasonable to assume that it does not change frequently.

This case can be further divided into two subcases. In the first subcase, the set of winning VBGs when node i bids c_i and that when node i bids v_i, denoted by $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$, respectively, are the same. In the second one, $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ are different, it means at least one of the winning VBGs when node i bids v_i loses when i bids c_i according to Lemma 1. Since the first subcase can be treated as a special instance for the latter, we focus on the IC proof for the second subcase in the following.

When node i bids c_i, denote its utility attributed to the common VBGs between $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ by $u_i^1(c_i, \mathbf{c_{-i}})$ and the utility attributed to the other VBGs by $u_i^2(c_i, \mathbf{c_{-i}})$. When node i bids v_i, denote its utility attributed to the common VBGs between $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ by $u_i^1(v_i, \mathbf{c_{-i}})$ which is exactly $u_i(v_i, \mathbf{c_{-i}})$. Then, we have the following results.

First, for those common VBGs between $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$

$$\begin{aligned}&u_i^1(c_i, \mathbf{c_{-i}}) - u_i^1(v_i, \mathbf{c_{-i}})\\&= \sum_{t\in(H_i\cap H_i')} \big(v_i - C_{t,-\mathbf{i}} + C_t - c_i\big)\\&\quad - \sum_{t'\in(H_i\cap H_i')} \big(v_i - C_{t',-\mathbf{i}} + C_{t'} - v_i\big).\end{aligned}$$

Since $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ are identical, we have $\sum_{t\in(H_i\cap H_i')} v_i = \sum_{t'\in(H_i\cap H_i')} v_i$. In addition, since the bids from any VBG that does not include node i when i bids either c_i or v_i are the same, the exclusion of node i from the auction won't change their relative relationships as well. Therefore, we have $C_{t,-\mathbf{i}} = C_{t',-\mathbf{i}}$ and thus $\sum_{t\in(H_i\cap H_i')} C_{t,-\mathbf{i}} = \sum_{t'\in(H_i\cap H_i')} C_{t',-\mathbf{i}}$. In all, we arrive at $u_i^1(c_i, \mathbf{c_{-i}}) = u_i^1(v_i, \mathbf{c_{-i}})$.

Second, for any VBG in $\mathcal{G}_W(c_i)$ but not in $\mathcal{G}_W(v_i)$, since $v_i + C_t - c_i < C_{t,-\mathbf{i}}$, we have

$$u_i^2(c_i, \mathbf{c_{-i}}) = \sum_{t\in H_i\setminus(H_i\cap H_i')} \big(v_i - C_{t,-\mathbf{i}} + (C_t - c_i)\big) < 0.$$

As a result, we can get

$$\begin{aligned}&u_i(c_i, \mathbf{c_{-i}}) - u_i(v_i, \mathbf{c_{-i}})\\&= u_i^1(c_i, \mathbf{c_{-i}}) - u_i^1(v_i, \mathbf{c_{-i}}) + u_i^2(c_i, \mathbf{c_{-i}}) < 0.\end{aligned}$$

We then consider the scenario where $v_i > c_i$.

- *Case 1*: *node i loses with both v_i and c_i*. In this case, $u_i(c_i, \mathbf{c_{-i}}) = u_i(v_i, \mathbf{c_{-i}}) = 0$ according to our definition in (2). Thus, (3) holds.
- *Case 2*: *node i loses with v_i but wins with c_i*. Since $v_i > c_i$, according to Lemma 1, this will not happen.
- *Case 3*: *node i wins with v_i and loses with c_i*. In this case, we have $u_i(c_i, \mathbf{c_{-i}}) = 0$ and

$$\begin{aligned}u_i(v_i, \mathbf{c_{-i}}) &= \sum_{t\in H_i'} \big(v_i - C_{t,-\mathbf{i}} + (C_t - v_i)\big)\\&= \sum_{t\in H_i'} (C_t - C_{t,-\mathbf{i}}) > 0.\end{aligned}$$

- *Case 4*: *node i wins with both v_i and c_i*. Similarly, this case can be further divided into two subcases. In the first subcase, $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ are the same. In the second one, $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ are different, it means at least one of the winning VBGs when node i bids v_i loses when i bids c_i according to Lemma 1. Since the first subcase can be treated as a special instance for the latter, we focus on the IC proof for the second subcase in the following.

When node i bids v_i, denote its utility attributed to the common VBGs between $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ by $u_i^1(v_i, \mathbf{c_{-i}})$ and the utility attributed to the other VBGs by $u_i^2(v_i, \mathbf{c_{-i}})$. When node i bids c_i, denote its utility attributed to the common VBGs between $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$ by $u_i^1(c_i, \mathbf{c_{-i}})$ which is exactly $u_i(c_i, \mathbf{c_{-i}})$. Then, we have the following results.

First, for those common VBGs between $\mathcal{G}_W(c_i)$ and $\mathcal{G}_W(v_i)$, we have $u_i^1(c_i, \mathbf{c_{-i}}) = u_i^1(v_i, \mathbf{c_{-i}})$ following the same approach above.

Second, for any VBG in $\mathcal{G}_W(v_i)$ but not in $\mathcal{G}_W(c_i)$, we have

$$u_i^2(v_i, \mathbf{c_{-i}}) = \sum_{t\in H_i'\setminus(H_i'\cap H_i)} \big(v_i - C_{t,-\mathbf{i}} + (C_t - v_i)\big) > 0.$$

As a result, we can get

$$\begin{aligned}&u_i(c_i, \mathbf{c_{-i}}) - u_i(v_i, \mathbf{c_{-i}})\\&= u_i^1(c_i, \mathbf{c_{-i}}) - u_i^1(v_i, \mathbf{c_{-i}}) - u_i^2(v_i, \mathbf{c_{-i}}) < 0.\end{aligned}$$

In all, $u_i(c_i, \mathbf{c_{-i}}) \le u_i(v_i, \mathbf{c_{-i}})$ always hold, and hence the spectrum auction is IC. □

Theorem 2. *The proposed TOA is individual rationality.*

Proof. For a winning node i, its utility is expressed as

$$\begin{aligned}u_i(c_i, \mathbf{c_{-i}}) &= \sum_{t\in H_i} (v_i - C_{t,-\mathbf{i}} + (C_t - c_i))\\&= \sum_{t\in H_i} (-C_{t,-\mathbf{i}} + C_t) > 0.\end{aligned}$$

For a losing node i, its utility is 0. In all, node i always gets non-negative utility. □

With Theorems 1 and 2, we conclude that the proposed spectrum auction scheme is economic-robust.

5 Simulation Results

In this section, we conduct simulations to evaluate the performance of our proposed auction scheme TOA under the novel CMCN architecture. Specifically, we consider a CMCN consisting of two adjacent hexagonal cellular cells with radius of 500m. Suppose that there are four basic cellular bands available at the PSP, which have the same bandwidth of 5 MHz and are shared by both cells. A total number of $|\mathcal{N}| = 30$ CR routers are randomly deployed in the network, forming a cognitive mesh, to facilitate D2D communications. Each CR router is equipped with 2 radios. Assume that the PSP has $|\mathcal{M}| = 4$ secondary spectrum bands which it can lease to the CR routers, and that all the spectrum bands' bandwidths follow the same normal distribution. Unless otherwise specified, the default value of the mean (μ) and that of the standard deviation (σ) of the spectrum are 5 and 1 MHz, respectively. We assume that each CR router's true valuation of (and hence its bid for) unit expectation transmission rate is uniformly distributed over $[10^{-6}, 10^{-5}]$. Some other important simulation parameters are listed as follows. The path loss exponent is 4 and $C = 62.5$. The noise power spectral density is $\eta = 3.34 \times 10^{-18}\mathrm{W/Hz}$ at all nodes. The transmission power spectral density of nodes is $8.1 \times 10^{9}\eta$, and the reception threshold and interference threshold are both 8.1η on each spectrum band. All simulations are carried out in CPLEX 12.4 on a computer with a 2.27 GHz CPU and 24 GB RAM.

5.1 Performance of the CMCN Architecture

In this section, we compare the maximum throughput of our proposed CMCN architecture with that of another two architectures, i.e., cellular network (CN) architecture and mesh network assisted cellular network (MNCN) architecture. In particular, in the CMCN architecture, we first utilize the cellular bands to carry users' traffic. Then, after all the cellular bands are exhausted, we employ the cognitive mesh to further support users' traffic demand. We assume that the CN architecture works in FDMA/FDD mode, i.e., each cellular band is exclusively allocated to one user for either upstream or downstream data transmissions in one cell, and each session requires two cellular bands, one for upstream transmissions and the other for downstream transmissions. In addition, MNCN works in a similar way to that of CMCN, except that the mesh network in the MNCN only uses the cellular bands that are available locally. As we focus on the performance comparison among these three architectures, we do not employ the TOA scheme to allocate the spectrums in CMCN. Instead, we explore the joint scheduling and routing to find the maximum throughput of these three architectures.[6]

Simulation results when the number of sessions L ranges from 3 to 10 are shown in Fig. 2. We find that the maximum throughput of the CN architecture is the lowest among the three. The maximum throughput of the MNCN architecture is up to 130 percent larger than that of the CN architecture. The performance gain is because the MNCN can utilize the available cellular bands for local transmissions. Moreover, comparing the performance of the CMCN architecture and that of the MNCN architecture, we can see that the average throughput of CMCN is much larger, i.e., up to 63 percent more, due to the utilization of secondary spectrum bands.

Besides, we compare in Fig. 3 the total spectrum resources utilized by the three architectures when they achieve their maximum throughput shown in Fig. 2. The total spectrum resources are defined as the effective spectrums utilized in

6. Specifically, we formulate one optimization problem under each architecture with the objective of maximizing the total throughput of all the sessions, considering link scheduling and routing constraints.

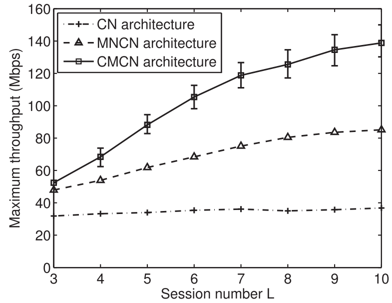


Fig. 2. Maximum throughput comparison among three architectures.

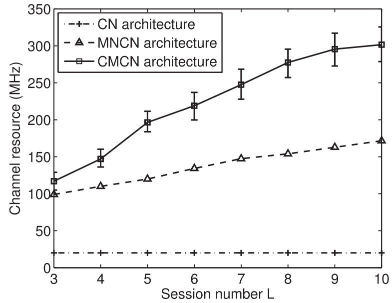


Fig. 3. Spectrum resources utilized by the three different architectures.

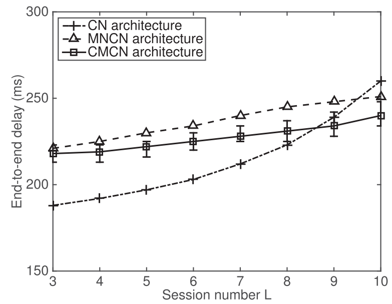


Fig. 4. End-to-end delay comparison among three architectures.

the whole network, i.e., $\sum_{q=1}^{t'} \lambda_q \sum_{((i,j),(m,n),b)\in\mathcal{I}_q} s_{ij,mn}^{b} \cdot W^{b}$, where t' is the total number of MISs used to support the maximum throughput. We find that the total spectrum resources utilized by our CMCN architecture are much larger than those by the CMCN and the CN architectures. For example, when $L = 10$, the average total spectrum resources used by the CMCN architecture are 301.5 MHz, which are 1.8 times and 15.1 times as large as those by MNCN (171.6 MHz) and those by CN (20.0 MHz), respectively. The total spectrum resources utilized by the CN architecture are the lowest and remain constant as L increases, because this architecture does not explore spectrum reuse for communications.

We further evaluate the end-to-end delay performance of the three architectures. By applying the *Little's theorem*, the average delay a session experiences at a single node could be approximated by the ratio between the average queue length at that node and its average transmission rate. Then, for each session we count the number of hops/nodes it passes through from the source to the destination. Accordingly, the average delay of all sessions can be readily derived. The result is shown in Fig. 4. First, we find that the CN architecture has the lowest delay when $L < 9$. This is because all sessions in CN are carried out in two hops, one as the uplink connection and the other as the downlink

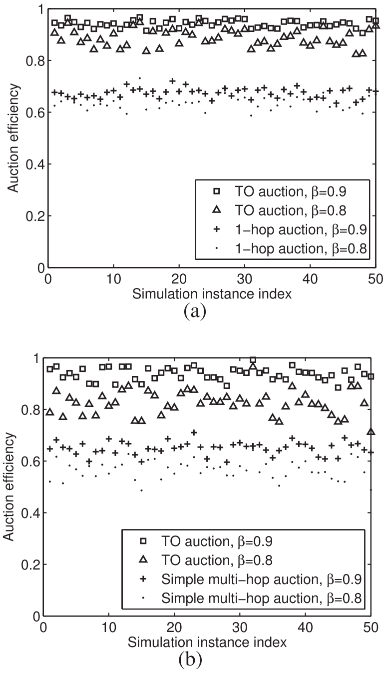


Fig. 5. Auction efficiency comparison with a 1-hop auction scheme and a simple multi-hop auction scheme. (a) Single-hop data transmission scenario. (b) Multi-hop data transmission scenario.

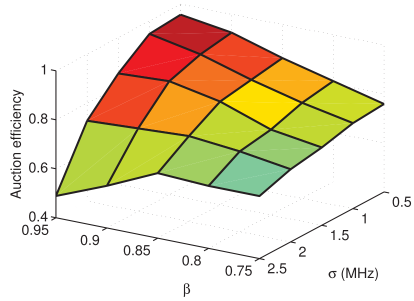


Fig. 6. Auction efficiency under different confidence level β and spectrum standard deviation σ.

connection. When $L \geq 9$, its delay surpasses that of CMCN. It accounts to the fact that when the network becomes crowded, the base station becomes the bottleneck of data delivery, which causes some extra queuing delay, while CMCN can explore local links to accommodate more traffic. Besides, part of sessions in CMCN can be delivered within a single hop with D2D communications, if the destination is within the transmission range of the source. We also find that the delay of MNCN is larger than that of CMCN, since CMCN also leverages secondary spectrums for data delivery which leads to a higher network capacity.

5.2 Performance of the TOA Scheme

Next, we demonstrate the performance of the TOA scheme. Since we have proved that our auction scheme is economic-robust in the previous section, we focus on the *auction efficiency*, the auctioneer's revenue and computation complexity of the TOA scheme in what follows. Note that *auction efficiency is defined as the ratio of the number of finally successfully delivered traffic flows to the total number of traffic flows demanded by the cellular users*. Besides, in this simulation, we assume that there are 5 sessions in the network which are all carried by the cognitive mesh, and that the same as before, there are four secondary spectrum bands available.

We first compare the auction efficiency of the proposed TOA scheme with those of two other auction schemes: one for single-hop data transmission [22], and the other for multi-hop data transmission [24] which greedily assigns spectrum bands to links. We call these two schemes 1-hop auction and simple multi-hop auction, respectively, in our simulations. To make fair comparisons, we compare TOA with these two schemes in single-hop and multi-hop scenarios, respectively. In addition, for each confidence level β, we employ 50 simulation instances, each with the newly generated bandwidths for all the 4 spectrum bands according to their distributions. For each simulation instance, we regenerate the network topology and source/destination pairs of the session and take the average value as the result.

In single-hop scenarios, each source node can reach its intended destination node in one hop, and hence the data traffic can be delivered in one-hop as well. Fig. 5a compares the auction efficiency under our proposed TOA scheme and that under the 1-hop auction scheme, when β is equal to 0.8 and 0.9. We can find that TOA can achieve much higher auction efficiency than 1-hop auction. As we mentioned before, this is because in 1-hop auction, it is not clear whom a winning node communicates with and there can be a lot of collisions in the network. Besides, we find the auction efficiency achieved when $\beta = 0.8$ is lower than that achieved when $\beta = 0.9$ under both auction schemes. This is because a larger β implies that the probability that transmissions can be carried out successfully on the chosen links is higher. Thus, the sessions can be supported with a higher probability and the auction efficiency is higher as well.

In multi-hop scenarios, each source node needs to deliver data to its destination via multiple hops. The auction efficiency of TOA and that of the simple multi-hop auction scheme are compared in Fig. 5b. We can also find that TOA can achieve much higher auction efficiency than the simple multi-hop auction scheme. This is because we consider transmission opportunities in auctions as well as spectrum scheduling in both frequency and time domains, while the simple multi-hop auction scheme greedily assigns one spectrum for each session without much coordination or interference control. Moreover, comparing Figs. 5a and 5b, we notice that the auction efficiency of TOA in single-hop scenarios is on average slightly larger than that in multi-hop scenarios with the same β. This is intuitively true since the probability that packets can be successfully delivered from source nodes to destination nodes is lower in multi-hop scenarios than in single-hop scenarios.

We further demonstrate in Fig. 6 the auction efficiency of TOA under different confidence levels (β's) and different standard deviations (σ's) of secondary spectrum's bandwidth distributions. We can find that the auction efficiency increases as σ decreases, since the spectrum supply becomes more stable and the PSP's probabilistic constraint (12) can be satisfied more easily. On the other hand, we notice that a larger β does not necessarily lead to a higher auction efficiency, which is more obvious when σ is larger. For instance, when $\sigma = 0.5$ MHz, the auction efficiency of TOA when $\beta = 0.75$ is 0.76, which is smaller than that when $\beta = 0.95$, i.e., 0.96. However, when $\sigma = 2.5$ MHz, the auction

TABLE 1
Computation Performance of TOA When New Sessions Join

Index	1	2	3	4	5	6	7	8
Session	1	2	3	4	5	6	7	8
Iteration	464	34	29	52	27	0	38	16
Time (s)	146.2	9.2	8.5	13.4	8.1	0.1	11.4	4.9
Time (s)	0.9	0.9	1.2	1.3	1.5	1.6	1.6	1.7

TABLE 2
Computation Performance of TOA When Sessions Leave

Index	1	2	3	4	5	6	7	8
Session	8	7	6	5	4	3	2	1
Iteration	488	0	0	0	0	0	0	0
Time (s)	153.3	0.11	0.10	0.10	0.09	0.09	0.09	0.08
Time (s)	1.7	1.6	1.6	1.5	1.3	1.2	0.9	0.9

efficiency of TOA when $\beta = 0.75$ is 0.66, which is nevertheless larger than that when $\beta = 0.95$, i.e., 0.49. The maximum auction efficiency is achieved when β is about 0.85. This interesting result is due to the following reason. When σ is large, it means that the spectrum bandwidth gets very dynamic. In this case, when β first increases but is still a small value, the auction efficiency increases because the PSP can easily find links or schedules that satisfies its probabilistic constraint (12) while the probability that transmissions can be carried out successfully on the chosen links gets higher. However, when β further increases, e.g., becomes a large value, the auction efficiency can decrease because the PSP may not be able to find many links or schedules that can satisfy its probabilistic constraint with high confidence (or probability). Therefore, based on this observation, the PSP needs to jointly consider the secondary spectrum's bandwidth distributions and its confidence level β to achieve a high auction efficiency.

We finally study the computation performance of TOA, in terms of iteration number in TO-AL and computation time for the entire TOA, under traffic dynamics. Recall that TOA scheme consists of three procedures: TO-AL, TO-SC, and pricing, out of which TO-SC (an LP problem) and pricing can be efficiently computed while TO-AL (a BIP problem) may take some computation efforts.

Table 1 is for the case that each session joins the network one by one. The third row is the number of additional iterations needed for TO-AL to find new VBGs and the fourth row is the computation time for the entire TOA. The joining of a new session triggers the calculation of TOA. We can see that the number of iterations needed for the first index (there is only one session) is the highest, 464, leading to the highest computation time 146.2s. This is mainly due to the computation of TO-AL. After that, when a new session joins, only a small amount of additional iterations are needed since many winning VBGs have been identified already in previous iterations. We also notice that when the 6th session joins, no iteration is needed. It means that the current winning VBGs can support all 6 sessions. The computation time, 0.1s, counts for the computation of TO-SC and pricing.

We further show in Table 2 the computation performance of TOA when sessions leave. Similar to Table 1, they leave one by one and, each triggering the calculation of TOA. It shows that the number of iterations needed for the first index (when there are eight sessions) is the highest, 488, leading to the highest computation time 153.3s. However, as sessions leave, the iteration involved in TO-AL keeps as 0. Their time consumption all comes from TO-SC and pricing.

From Tables 1 and 2, we conclude that our proposed TOA can efficiently handle the traffic dynamics when sessions leave the network and the case when sessions join the network in an intermittent manner (or the session intervals are relatively large). In order to tackle the case of high session arrival rate, one possible solution is to just run TOA once for a batch of new sessions, instead of running it every time a new session joins.

The last row of Tables 1 and 2 also show the computation time when utilizing non-auction approach for resource management in CMCN. As that in Section 5.1, we formulate an optimization problem with the objective of maximizing the total end-to-end data rate of all the sessions, considering link scheduling and routing constraints. We notice that the computation time of non-auction approach is less than that of TOA when new sessions join. However, the former is larger than the latter when sessions leave. This is because the optimization problem needs to be recalculated when a new session leaves. However, TOA only needs to recalculate TO-SC, which is an LP problem with much smaller size.

6 Related Work

6.1 D2D Communications in Cellular Networks

The concept of D2D communications as an underlay to an LTE-Advanced cellular network is first introduced in [1]. After that, a few works have studied resource allocation and power control which aim to mitigate mutual interference between D2D and cellular connections. For example, Kaufman et al. [45] proposed a route discovery scheme for D2D users, which keeps the interference to cellular users below an allowed threshold. However, the interference from cellular users to D2D users is not considered. To address this problem, Min et al. [46], [47] proposed interference management strategies to enhance the reliability of D2D communications or the overall capacity of D2D underlaying cellular networks. Besides, Yu et al. [48] studied a resource sharing mode selection problem, which decides whether the network shall assign D2D communication mode or not to a user pair and whether a pair of D2D users shall share resources with cellular users or use dedicated resources instead. Niu et al. [49] discussed popular content downloading in mmWave small cells. Both D2D transmission in close proximity and concurrent transmissions are exploited to improve transmission efficiency. Meng et al. [50] investigated a dynamic social-aware peer selection problem for cooperative D2D communications. Mozaffari et al. [51] studied the performance of a UAV that acts as a flying base station in an area in which users are engaged in the D2D communication. Tractable expressions for the coverage probabilities are derived.

Notice that none of the above work is similar to ours, which discusses how a PSP offloads cellular users' data traffic to a cognitive mesh via a constructed spectrum auction market.

6.2 Game Theory in D2D Communications

There are some works utilizing Auction Theory for resource management and load balancing in D2D communications. A two-phase auction based resource allocation was developed for underlaying D2D communications in [52]. It aims at minimizing interference while maximizing fairness in the allocation. However, the economic properties are not discussed. Hasan et al. [53] proposed an auction-based distributed resource allocation scheme in D2D-enabled multi-tier cellular networks. The goal is to allocate transmit power to D2D UEs to maximize spectral efficiency without causing significant interference to macro UEs. Reverse auction mechanisms are applied in [54], [55] for D2D load balancing in cellular networks. D2D users sell their transmission capabilities to offload some traffic from a cellular network. The problem discussed therein is totally different from ours.

In addition, to characterize the interactive power control and resource management in D2D communications, game theory has been extensively used in the literature. In particular, game theory has been used to model competition among transmitters and interference coordination, analyze the strategic behavior of transmitters, and design distributed algorithms. Both cooperative game and non-cooperative game theory have been utilized [56], [57], [58], [59].

Note that none of above works considers multi-hop D2D communications in their auction design. Besides, link scheduling and routing are not taken into account for resource allocation and load balancing.

6.3 Spectrum Auction in Wireless Networks

Auction has been employed by the Federal Communications Commission to efficiently allocate spectrum resources [60]. Based on this idea, some works propose to apply auction to spectrum sharing in wireless networks. Kloeck et al. [14] considered a multi-unit sealed-bid auction for efficient spectrum allocation. Huang et al. [23] proposed an auction mechanism which allows users to bid for their transmission power to efficiently share the spectrum. Gandhi et al. [15] designed an auction scheme considering spectrum reuse in wireless networks. Zhou et al. [22] proposed a spectrum auction scheme VERITAS with greedy channel assignment and critical value based pricing. Jia et al. [16] discussed how to generate maximum expected revenue, which is an alternate goal of maximum social welfare in spectrum auction. In order to further improve the expected revenue, Al-Ayyoub et al. [18] designed a color-based channel allocation scheme. Taking fairness in channel allocation into account, Gopinathan et al. [19] developed a spectrum auction protocol by applying linear programming techniques to balance the social welfare and max-min fairness in secondary spectrum markets. In addition to single-sided auction, some works employ double auction in spectrum market, where multiple spectrum owners compete with each other to sell idle spectrums for profit. Zhou and Zheng [20] proposed a framework TRUST for double spectrum auction enabling spectrum reuse. Wang et al. [21] designed a double auction scheme considering that spectrums are tradable only within their licensed areas. However, these two works assume each seller can only sell one channel and each buyer can buy one channel at most. This limits the utility of both buyers and sellers, as well as the revenue of the auctioneer. Most importantly, all these works are only suitable for single-hop data transmission. Although Zhu et al. [24], [25] discussed spectrum auctions for multi-hop data delivery, they assume that each secondary network only has one flow, and do not consider time domain scheduling when utilizing the spectrums. Our previous work [26] studied spectrum auctions for multi-hop wireless networks without exploring the diversity brought by multi-radio nodes. In addition, dynamic spectrum availability is not taken into consideration by the above auction schemes.

7 Conclusions

In this paper, we have proposed a novel architecture, called cognitive mesh assisted cellular network, to enable D2D communications and alleviate congestion in cellular networks. A transmission opportunity auction scheme, called TOA, has been developed for carrying out spectrum auctions in CMCNs, which has been proved to be economic-robust. Moreover, we have found through simulations that the proposed CMCN architecture can achieve much higher throughput than the traditional cellular network architecture and the mesh network assisted cellular network architecture. Extensive simulation results also show that TOA can lead to higher spectrum utilization under uncertain spectrum supply than other auction schemes.

Acknowledgments

The work of Ming Li was supported by the US National Science Foundation under grants CNS-1566634 and ECCS-1711991. The work of Jinyuan Sun is partially supported by the US National Science Foundation under grant 1642590 and the Army Research Office under grant 66270-CS. The work of Xiaoxia Huang was supported by the NSFC-Guangdong Joint Program under grant No. U1501255 and Guangdong Special Support Plan for Young Talents in Science and Technology under grant No. 2016TQ03X279. The work of Pan Li was partially supported by the US National Science Foundation under grants CNS-1602172 and CNS-1566479.

References

[1] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42–49, Dec. 2009.

[2] S. Yin, D. Chen, Q. Zhang, M. Liu, and S. Li, "Mining spectrum usage data: A large-scale spectrum measurement study," *IEEE Trans. Mobile Comput.*, vol. 11, no. 6, pp. 1033–1046, Jun. 2012.

[3] S. M. Mishra, et al., "A real time cognitive radio testbed for physical and link layer experiments," in *Proc. IEEE Int. Symp. New Frontiers Dyn. Spectr. Access Netw.*, Nov. 2005, pp. 562–567.

[4] H. Kebriaei, B. Maham, and D. Niyato, "Double-sided bandwidth-auction game for cognitive device-to-device communication in cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7476–7487, Sep. 2016.

[5] M. G. Khoshkholgh, Y. Zhang, K.-C. Chen, K. G. Shin, and S. Gjessing, "Connectivity of cognitive device-to-device communications underlying cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 81–99, Jan. 2015.

[6] A. Zappone, B. Matthiesen, and E. A. Jorswieck, "Energy efficiency in MIMO underlay and overlay device-to-device communications and cognitive radio systems," *IEEE Trans. Signal Process.*, vol. 65, no. 4, pp. 1026–1041, Feb. 2017.

[7] J. H. Reed, *A Modern Approach to Radio Engineering*. New York, NY, USA: Prentice Hall, 2002.
[8] Y.-D. Lin and Y.-C. Hsu, "Multihop cellular: A new architecture for wireless communications," in *Proc. IEEE Int. Conf. Comput. Commun.*, 2000, pp. 1273–1282.
[9] M. A. Alim, T. Pan, M. T. Thai, and W. Saad, "Leveraging social communities for optimizing cellular device-to-device communications," *IEEE Trans. Wireless Commun.*, vol. 16, no. 1, pp. 551–564, Jan. 2017.
[10] L. Militano, A. Orsino, G. Araniti, A. Molinaro, and A. Iera, "A constrained coalition formation game for multihop D2D content uploading," *IEEE Trans. Wireless Commun.*, vol. 15, no. 3, pp. 2012–2024, Mar. 2016.
[11] Y. Zhao, Y. Li, H. Mao, and N. Ge, "Social-community-aware long-range link establishment for multihop D2D communication networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9372–9385, Nov. 2016.
[12] I. O. Nunes, P. O. V. de Melo, and A. A. Loureiro, "Leveraging D2D multihop communication through social group meeting awareness," *IEEE Wireless Commun.*, vol. 23, no. 4, pp. 12–19, Aug. 2016.
[13] L. Wei, R. Hu, Y. Qian, and G. Wu, "Enable device-to-device communications underlaying cellular networks: Challenges and research aspects," *IEEE Commun. Mag.*, vol. 52, no. 6, pp. 90–96, Jun. 2014.
[14] C. Kloeck, H. Jaekel, and F. K. Jondral, "Dynamic and local combined pricing, allocation and billing system with cognitive radios," in *Proc. IEEE Int. Symp. New Frontiers Dyn. Spectr. Access Netw.*, Nov. 2005, pp. 73–81.
[15] S. Gandhi, C. Buragohain, L. Cao, H. Zheng, and S. Suri, "A general framework for wireless spectrum auctions," in *Proc. IEEE Int. Symp. New Frontiers Dyn. Spectr. Access Netw.*, Apr. 2007, pp. 22–33.
[16] J. Jia, Q. Zhang, Q. Zhang, and M. Liu, "Revenue generation for truthful spectrum auction in dynamic spectrum access," in *Proc. 10th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2009, pp. 3–12.
[17] L. Gao, X. Wang, Y. Xu, and Q. Zhang, "Spectrum trading in cognitive radio networks: A contract-theoretic modeling approach," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 4, pp. 843–855, Apr. 2011.
[18] M. Al-Ayyoub and H. Gupta, "Truthful spectrum auctions with approximate revenue," in *Proc. IEEE Int. Conf. Comput. Commun.*, Apr. 2011, pp. 2813–2821.
[19] A. Gopinathan, Z. Li, and C. Wu, "Strategyproof auctions for balancing social welfare and fairness in secondary spectrum markets," in *Proc. IEEE Int. Conf. Comput. Commun.*, Apr. 2011, pp. 3020–3028.
[20] X. Zhou and H. Zheng, "TRUST: A general framework for truthful double spectrum auctions," in *Proc. IEEE Int. Conf. Comput. Commun.*, Apr. 2009, pp. 999–1007.
[21] W. Wang, B. Li, and B. Liang, "District: Embracing local markets in truthful spectrum double auctions," in *Proc. IEEE Commun. Soc. Conf. Sensor Ad Hoc Commun. Netw.*, Jun. 2011, pp. 521–529.
[22] X. Zhou, S. Gandhi, S. Suri, and H. Zheng, "eBay in the sky: Strategy-proof wireless spectrum auctions," in *Proc. 14th ACM Int. Conf. Mobile Comput. Netw.*, Sep. 2008, pp. 2–13.
[23] J. Huang, R. A. Berry, and M. L. Honig, "Auction-based spectrum sharing," *J. Mobile Netw. Appl.*, vol. 11, no. 3, pp. 405–418, 2006.
[24] Y. Zhu, B. Li, and Z. Li, "Truthful spectrum auction design for secondary networks," in *Proc. IEEE Int. Conf. Comput. Commun.*, Mar. 2012, pp. 873–881.
[25] Z. Li, B. Li, and Y. Zhu, "Designing truthful spectrum auctions for multi-hop secondary networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 2, pp. 316–327, Feb. 2015.
[26] M. Li, P. Li, M. Pan, and J. Sun, "Economic-robust transmission opportunity auction in multi-hop wireless networks," in *Proc. IEEE Int. Conf. Comput. Commun.*, 2013, pp. 1842–1850.
[27] M. Babaioff and W. E. Walsh, "Incentive-compatible, budget-balanced, yet highly efficient auctions for supply chain formation," *Decision Support Syst.*, vol. 39, no. 1, pp. 123–149, 2004.
[28] P. Klemperer, "What really matters in auction design," *J. Econ. Perspectives*, vol. 16, no. 1, pp. 169–189, 2002.
[29] X. Shen, "Device-to-device communication in 5G cellular networks," *IEEE Netw.*, vol. 29, no. 2, pp. 2–3, Mar./Apr. 2015.
[30] S. Andreev, O. Galinina, A. Pyattaev, K. Johnsson, and Y. Koucheryavy, "Analyzing assisted offloading of cellular user sessions onto D2D links in unlicensed bands," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 67–80, Jan. 2015.
[31] X. Lin, R. Ratasuk, A. Ghosh, and J. G. Andrews, "Modeling, analysis, and optimization of multicast device-to-device transmissions," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4346–4359, Aug. 2014.
[32] M. Mchenry, *Spectrum White Space Measurements*. New America Foundation Broadband Forum, Jun. 2003.
[33] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C. S. Hood, "Chicago spectrum occupancy measurements and analysis and a long-term studies proposal," in *Proc. 1st Int. Workshop Technol. Policy Accessing Spectrum*, Aug. 2006, Art. no. 1.
[34] Y. T. Hou, Y. Shi, and H. D. Sherali, "Optimal spectrum sharing for multi-hop software defined radio networks," in *Proc. IEEE Conf. Comput. Commun.*, May 2007, pp. 1–9.
[35] Y. T. Hou, Y. Shi, and H. D. Sherali, "Spectrum sharing for multi-hop networking with cognitive radios," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 146–155, Jan. 2008.
[36] W. Wang, X. Liu, and D. Krishnaswamy, "Robust routing and scheduling in wireless mesh networks under dynamic traffic conditions," *IEEE Trans. Mobile Comput.*, vol. 8, no. 12, pp. 1705–1717, Dec. 2009.
[37] H. Li, Y. Cheng, C. Zhou, and P. Wan, "Multi-dimensional conflict graph based computing for optimal capacity in MR-MC wireless networks," in *Proc. IEEE Int. Conf. Distrib. Comput. Syst.*, Jun. 2010, pp. 774–783.
[38] Z. Feng and Y. Yang, "Joint transport, routing and spectrum sharing optimization for wireless networks with frequency-agile radios," in *Proc. IEEE Conf. Comput. Commun.*, Apr. 2009, pp. 1665–1673.
[39] J. Tang, S. Misra, and G. Xue, "Joint spectrum allocation and scheduling for fair spectrum sharing in cognitive radio wireless networks," *Comput. Netw. J.*, vol. 52, no. 11, pp. 2148–2158, Aug. 2008.
[40] M. Pan, C. Zhang, P. Li, and Y. Fang, "Spectrum harvesting and sharing in multi-hop CRNs under uncertain spectrum supply," *IEEE J. Sel. Areas Commun. - Special Issue Cooperative Netw. Challenges Appl.*, vol. 30, no. 2, pp. 369–378, Feb. 2012.
[41] Y. Pochet and L. Wolsey, *Production planning by mixed integer programming*. Springer Science & Business Media, 2006.
[42] G. Holton, *Value-at-Risk: Theory and Practice*. Cambridge, MA, USA: Academic Press, 2003.
[43] G. B. Dantzig, *Linear Programming and Extensions*. Princeton, NJ, USA: Princeton Univ. Press, 1963.
[44] W. Vickrey, "Counterspeculation, auctions, and competitive sealed tenders," *J. Finance*, vol. 16, no. 1, pp. 8–37, 1961.
[45] B. Kaufman, J. Lilleberg, and B. Aazhang, "Spectrum sharing scheme between cellular users and ad-hoc device-to-device users," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, pp. 1038–1049, Mar. 2013.
[46] H. Min, W. Seo, J. Lee, S. Park, and D. Hong, "Reliability improvement using receive mode selection in the device-to-device uplink period underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 2, pp. 413–418, Feb. 2011.
[47] H. Min, W. Seo, J. Lee, S. Park, and D. Hong, "Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 3995–4000, Dec. 2011.
[48] C.-H. Yu, K. Doppler, C. B. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2752–2763, Aug. 2011.
[49] Y. Niu, L. Su, C. Gao, Y. Li, D. Jin, and Z. Han, "Exploiting device-to-device communications to enhance spatial reuse for popular content downloading in directional mmWave small cells," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5538–5550, Jul. 2016.
[50] Y. Meng, C. Jiang, Q. D. La, T. Q. Quek, and Y. Ren, "Dynamic social-aware peer selection scheme for cooperative device-to-device communications," in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2017, pp. 1–6.
[51] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 3949–3963, Jun. 2016.
[52] M. T. Islam, A.-E. M. Taha, S. Akl, and S. Choudhury, "A two-phase auction-based fair resource allocation for underlaying D2D communications," in *Proc. IEEE Int. Conf. Commun.*, 2016, pp. 1–6.
[53] M. Hasan and E. Hossain, "Distributed resource allocation in D2D-enabled multi-tier cellular networks: An auction approach," in *Proc. IEEE Int. Conf. Commun.*, 2015, pp. 2949–2954.

[54] M. H. Hajiesmaili, L. Deng, M. Chen, and Z. Li, "Incentivizing device-to-device load balancing for cellular networks: An online auction design," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 2, pp. 265–279, Feb. 2017.
[55] Y. Zhu, J. Jiang, B. Li, and B. Li, "Rado: A randomized auction approach for data offloading via D2D communication," in *Proc. IEEE Int. Conf. Mobile Ad Hoc Sensor Syst.*, 2015, pp. 1–9.
[56] Y. Xiao, K.-C. Chen, C. Yuen, Z. Han, and L. A. DaSilva, "A Bayesian overlapping coalition formation game for device-to-device spectrum sharing in cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 4034–4051, Jul. 2015.
[57] L. Song, D. Niyato, Z. Han, and E. Hossain, "Game-theoretic resource allocation methods for device-to-device communication," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 136–144, Jun. 2014.
[58] J. Huang, Y. Yin, Y. Zhao, Q. Duan, W. Wang, and S. Yu, "A game-theoretic resource allocation approach for intercell device-to-device communications in cellular networks," *IEEE Trans. Emerging Topics Comput.*, vol. 4, no. 4, pp. 475–486, Oct.–Dec. 2016.
[59] K. Zhu and E. Hossain, "Joint mode selection and spectrum partitioning for device-to-device communication: A dynamic stackelberg game," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1406–1420, Mar. 2015.
[60] P. Cramton, "Spectrum auctions," *Handbook of telecommunications economics*, pp. 605–639, 2002.

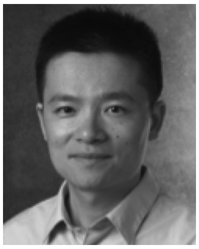
Ming Li received the BE degree in electrical engineering from Sun Yat-sen University, China, in 2007, the ME degree in electrical engineering from the Beijing University of Posts and Communications, China, in 2010, and the PhD degree in electrical and computer engineering from Mississippi State University, Starkville, in 2014, respectively. She is currently an assistant professor in the Department of Computer Science and Engineering, University of Nevada, Reno. Her research interests include wireless security, privacy-preserving data analysis, resource management, and network optimization in cyber-physical systems and wireless networks.

Weixian Liao received the BE degree in information engineering from Xidian University, Xi'an, China, in 2012, and the ME degree in electrical and computer engineering from Mississippi State University, Starkville, in 2015, respectively. He is currently pursuing the PhD degree in the Department of Electrical Engineering and Computer Science, Case Western Reserve University. His current research interests include network optimization, cybersecurity in wireless networks, cyber-physical systems, and big data.

Xuhui Chen received the BE degree in information engineering from Xidian University, Xi'an, China, in 2012, and the ME degree in electrical and computer engineering from Mississippi State University, Starkville, in 2015, respectively. She is currently pursuing the Ph.D. degree in the Department of Electrical Engineering and Computer Science, Case Western Reserve University. Her current research interests include machine learning, smart health, security, and privacy.

Jinyuan Sun received the BSc degree in computer information systems from Beijing Information Technology Institute, China, in 2003, the MASc degree in computer networks from Ryerson University, Canada, in 2005, and the PhD degree in electrical and computer engineering from the University of Florida, in 2010. She is currently an associate professor with the Department of Electrical Engineering and Computer Science at the University of Tennessee, Knoxville. She was a network test developer at RuggedCom Inc., ON, Canada, 2005-2006. Her research interests include the security protocol and architecture design of wireless networks. She is a member of the IEEE and ACM.

Xiaoxia Huang received the BE and ME degrees in electrical engineering from the Huazhong University of Science and Technology, China, in 2000 and 2002, respectively, and the PhD degree in electrical and computer engineering from the University of Florida in 2007. She is a professor at the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences. She is the deputy director of the Center for Real-Time Monitoring and Communications Technologies (RTT). Her research interests include cognitive radio networks, energy harvesting, smart phone applications, wireless sensor networks, and wireless communications.



Pan Li received the BE degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2005, and the PhD degree in electrical and computer engineering from the University of Florida, Gainesville, in 2009, respectively. He is currently an associate professor with the Department of Electrical Engineering and Computer Science at Case Western Reserve University. He was an assistant professor in the Department of Electrical and Computer Engineering at Mississippi State University between August 2009 and August 2015. His research interests include network science and economics, energy systems, security and privacy, and big data. He has been serving as an editor for *IEEE Wireless Communications Letters*, *IEEE Journal on Selected Areas in Communications—Cognitive Radio Series and IEEE Communications Surveys and Tutorials*, a feature editor for *IEEE Wireless Communications*, a general chair for IEEE SmartData 2017, and a technical program committee (TPC) co-chair for the Ad-hoc, Mesh, Machine-to-Machine and Sensor Networks Track, IEEE VTC 2014, Physical Layer Track, Wireless Communications Symposium, WTS 2014, and Wireless Networking Symposium, IEEE ICC 2013. He received the NSF CAREER Award in 2012 and is a member of the IEEE and the ACM.