Two-Tier Architecture for Spectrum Auction in SDN-Enabled Cloud Radio Access Network

Ajmery Sultana, Isaac Woungang, Lian Zhao, *Senior Member, IEEE*, and Alagan Anpalagan, *Senior Member, IEEE*

***Abstract*—The demand for mobile services is growing aberrantly, which provides both challenges and opportunities for wireless networks. Wireless network virtualization is suggested as a key progression path for enhancing the capacity and resource utilization in the forthcoming fifth-generation mobile networks. In this paper, a software-defined network (SDN) enabled cloud radio access network (C-RAN) framework is proposed for enabling spectrum auction with a two-tier architecture support. In Tier-I, several remote radio heads (RRHs) are introduced to act as the secondary service providers to provide services to its small cell users (SUEs) by exploiting the purchased underutilized or idle resources from the primary service provider in Tier-II. Specifically, in order to maintain quality-of-service requirements of the SUEs, the revenue maximization problem for the RRHs is formulated by considering the user association, band assignment, interference management, and budget allowance. In Tier-II, an SDN-enabled spectrum auction mechanism is proposed for maximizing the social welfare based on the SUEs' service requirements of all participating RRHs from Tier-I. In this auction mechanism, the bipartite graph is utilized to determine the socially optimal winners and the price charging scheme is proposed inspired by the well-known Vickrey–Clarke–Groves auction method. Simulation results reveal the performance and the benefits of the proposed SDN-enabled spectrum auction mechanism under different scenarios.**

***Index Terms*—Wireless network virtualization, SDN, spectrum auction, social welfare.**

I. Introduction

DUE to the explosively growing demands for mobile traffic and services, it is projected that there will be more than 50 billion smart devices connected to the Internet of Things (IoT) [1] within the coming decade. Wireless network virtualization [2] is suggested as a key progression path for enhancing the capacity and resource utilization in the forthcoming fifth generation (5G) mobile networks. In order to allow different services to share the same infrastructure, wireless virtualization has been utilized to decouple the infrastructure from the services it offers. Another emerging technology referred to as software defined networking (SDN) [3] has been proposed as a key driver in the design of the 5G network architecture. SDN technology promotes innovations in constructing communication networks by enabling the separation of control and data planes, and by allowing networks to be programmed using open interfaces. With the blossoming of wirelss network virtualization and SDN, mobile network operators (MNOs) are able to improve their resource usage efficiency [4], as well as significantly reduce the capital expenses (CapEx) [5] and operation expenses (OpEx) [6]. MNOs are also able to enhance the network flexibility and scalability, and to shorten the time-to-market of new services and applications [7]. Therefore, in this paper, a framework with SDN-enabled virtualized cloud radio access network (C-RAN) is proposed for enabling spectrum auction with a two-tier architecture support. In this framework, a primary service provider (PSP), who is playing the role of a virtual infrastructure provider, leases its underutilized or idle resources to other service providers (SPs) known as secondary service providers (SSPs). This allows SPs to increase their resource utilization and gain extra profit at the same time. This underutilized resource ulilization approach is similar to the cognitive radio technology [8].

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A. Sultana, L. Zhao, and A. Anpalagan are with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON M1P 4T7, Canada (e-mail: ajmery.sultana@ryerson.ca; l5zhao@ryerson.ca; alagan@ryerson.ca).

I. Woungang is with the Department of Computer Science, Ryerson University, Toronto, ON, M5B 2K3, Canada (e-mail: iwoungan@ryerson.ca).

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II. Related Work and Contributions

In wireless networks, auction mechanisms can be applied efficiently to allocate radio resources (e.g., spectrum) among users and wireless service providers. By utilizing the auction properties, users and wireless service providers can acquire the required performance guarantee as well as optimize the overall network utility [9]. For dynamic spectrum allocation, auction-based schemes have attracted much attention in the research community. There have been several burgeoning research efforts found in the literature for wireless spectrum sharing in various settings [10]–[24]. As pioneers in spectrum auction design, Zhou *et al.* [10] proposed VERITAS which is the first truthful spectrum auction that considers spectrum reusibility and computation efficiency. Then, they further proposed TRUST [11] that considers multiple sellers as well. A truthful multichannel auction scheme (TMCA) is designed in [12] for spectrum allocation under interference constraints. A spectrum double auction is presented in [13] by incorporating locality in spectrum markets while another auction scheme is developed in [14] for markets with communication constraints. In [15], Chen and Zhong proposed a truthful auction for continuous spectrum with variable bandwidths. A feasible auction scheme named as FlexAuc is presented in [16] to enable flexible demands in a spectrum trading market with polynomial time complexity. In [17], a dynamic index auction called ADAPTIVE is designed for spectrum sharing with time evolving values. A multi-round service-oriented combinatorial spectrum auction with two-tier framework support is proposed in [18] considering the interference management, spectrum uncertainty, flow routing, and budget allowance.

As an online truthful double auction, Chen *et al.* [18] designed LOTUS by considering buyers' location information into account. A multi-flow transmission based double auction mechanism is presented in [19] by considering the transaction cost. Truthful mechanisms are studied for a general network utility maximization model in [20], in which incentive compatible mechanisms that can be applied to coordinate spectrum auctions are proposed. An auction mechanism for the cloudlet scenario is designed in [21] to satisfy the service demands of mobile devices and determine the pricing.

As of now, from the literature review, it is found that the existing studies have investigated spectrum auction in terms of several parameters such as variable bandwith, flexible demands, time evolving values, communication constraints, location information, transaction cost, etc. However, none of the existing work incorporates wireless network virtualization, especially SDN-enabled C-RAN architecture to design the spectrum auction. In this paper, a SDN-enabled C-RAN framework is proposed for enabling spectrum auction with a two-tier architecture support. Different from [18] in Tier-I, several remote radio heads (RRHs) are introduced to act as secondary service providers (SSPs) to provide services to its small cell users (SUEs). This is achieved by exploiting the purchased underutilized or idle resources from the primary service provider (PSP) in Tier-II. Specifically, in order to maintain QoS requirements of the SUEs, the revenue maximization problem for the RRHs is formulated as an optimization problem, considering the user association, band assignment, interference management, and budget allowance, which are different from the constraints considered in [18]. In Tier-II, a SDN-enabled spectrum auction mechanism (SDN-SAM) is proposed for maximizing the social welfare based on the SUEs' service requirements of all participating RRHs from Tier-I. In our auction mechanism, the bipartite graph is utilized to determine the socially optimal winners and a price charging scheme is proposed inspired by the well-known Vickrey-Clarke-Groves (VCG) auction method. In this two-tier framework support, since the bidders are RRHs, the information exchange can be performed easily and the number of participants in the auction is decreased significantly, which leads to a much more practical spectrum auction.

The main contributions of this paper are summarized as follows:

- A SDN-enabled wireless network structure is designed to perform spectrum auction in the C-RAN architechture. The functions of the data plane and control planes, decoupled in SDN, are described and a wireless network vertualization scheme is designed to enable a multi-round spectrum auction mechanism. More specifically, a SDN-enabled C-RAN framework is proposed with a two-tier architecture support. In Tier-I, several RRHs are introduced to act as SSPs to provide services to its SUEs by exploiting the purchased underutilized resources from the PSP in Tier-II. In order to maintain QoS requirements of the SUEs, the revenue maximization problem for the RRHs is formulated as an optimization problem, considering the user association, band assignment, interference management, and budget allowance. In Tier-II, a spectrum auction mechanism is proposed for maximizing the social welfare based on the SUEs' service requirements of all participating RRHs from Tier-I.
- A SDN-enabled C-RAN framework is proposed for enabling spectrum auction with a two-tier architecture support. In this framework, each SUE only needs to provide its service request and bidding value to its RRH who is acting as an agent and performs the bidding for the required bands to support the requested services. This transfers the complexity from the SUEs' part to the SPs side which have more resources to fulfil the bidding goal. Moreover, since the resource allocation controller executes the Algorithm 1 (band identification for RRH) and the Algorithm 2 (winner determination) to perform the spectrum auction, the computational complexity of the proposed scheme is no longer a concern and can be easily managed by the SDN controller.
- In order to consider spectrum heterogeneity, a fine-grained idle spectrum map and a data table are incorporated to represent a multi-dimensional information for each band. This offers the following. First, it provides more information to the RRHs who are acting as bidders, to take decision regarding purchasing which bands to bid in order to meet its SUEs' QoS requirements. Second, it makes easier for the SDN controller who is acting as auctioneer to determine the conflict relationship among the bidders.
- A multi-round SDN-enabled spectrum auction mechanism (named as SDN-SAM) is proposed to accomplish more transactions at each auction round, where losing RRHs at each round can continue to participate in the following rounds until there are no bands available to support the requested services for any RRH. In this auction mechanism, bipartite graph is utilized to determine the socially optimal winners, and the price charging scheme is proposed inspired by the renowned VCG auction method. This offers the best match between the random service demands and random spectrum resource availability.

The rest of the paper is organized as follows. Section II describes the software defined network architechture and virtualized scheme. Section III presents the proposed spectrum auction mechanism design with a two-tier architechture support. The performance evaluations of this spectrum auction mechanism are described in Section IV. Finally Section V concludes the paper.

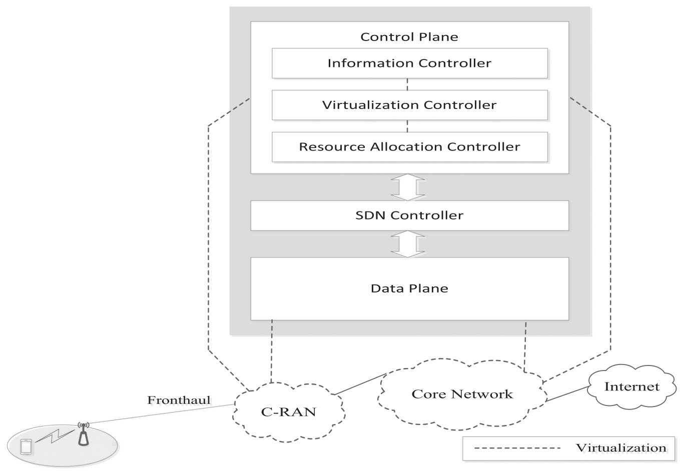

Fig. 1. A SDN-enabled wireless network architechture.

III. Software Defined Network Architecture and Virtualized Scheme

A. SDN-Enabled Wireless Network Architecture

A SDN-enabled wireless network architecture offers the ability to virtualize and slice the wireless network by separating the control and data planes in C-RAN [9]. A general C-RAN architecture by applying SDN is illustrated in Fig. 1. In this figure, the SDN controller acts as the hypervisor to host the network virtualization on a programmable platform. The hypervisor uses a-priori knowledge about wireless links and traffic status, users QoS requirements, and other service level agreements among different SPs. By applying SDN to C-RANs, many benefits can be realized; for instance, the software defined fronthaul can achieve a flexible mapping for all RRHs, which adapts the network to traffic volume and user mobility [25]. The functions of the data plane and control plane, decoupled in SDN, are described as follows:

Thus, auction-based schemes for virtualization can operate in the SDN controller.

- *Data plane:* The data plane or forwarding plane is responsible for the proper transit of the user traffic via virtual networks. Wireless resources, including the infrastructure and radio resources are sliced according to the instructions signalled by the central controller.
- *Control plane:* The SDN controller, along with its interfaces constitutes the control plane that serves as a logically centralized intelligent entity having a global view of the network and the ability to dynamically reconfigure it [3]. There are many different controllers in the designed control plane. Among them, three main controllers are considered in our SDN-enabled C-RAN architechture as shown in Fig. 1 are listed below:
  1) *Information Controller:* It keeps track of all the network status, potential participating PSP, SSPs and their users' QoS services requirements. These information are then transmitted to the desired controllers, namely: the virtualization controller and the resource allocation controller.

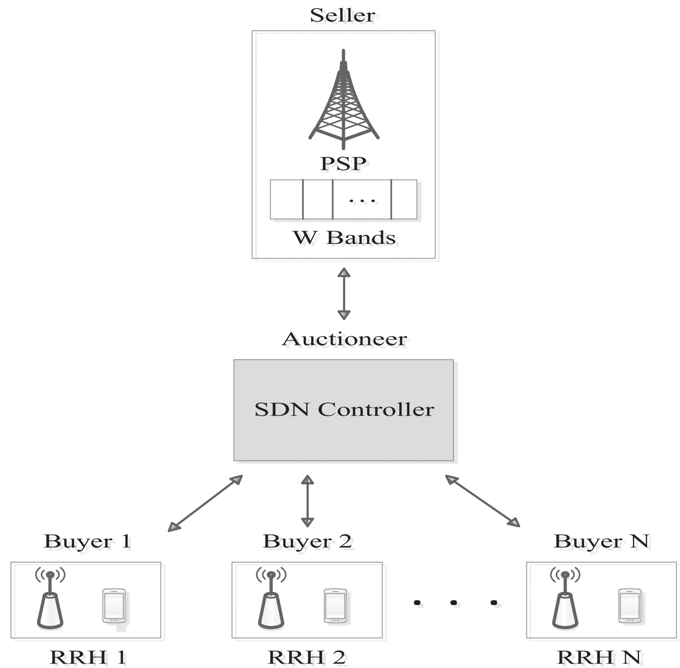

Fig. 2. A multi-round spectrum auction mechanism for SDN-enabled C-RAN.

  2) *Virtualization Controller:* It dynamically and flexibly generates the virtual slices of the infrastructure and radio resources based on the current status of the network. All virtual slices are independent and interference free.
  3) *Resource Allocation Controller:* Based on the demand and supply information of the users from the information controller, it executes the resource allocation algorithms to achieve a globally optimized resource utilization.

B. Wireless Network Virtualization Scheme by Auction Theory

The auction theory as a branch of economics can be utilized in designing virtualization models for wireless networks. The auction based virtualization framework has a wide range of opportunities to increase the resource utilization by jointly virtualizing the infrastructure and computational resources across the access and core networks as a single service or application package [9]. The SDN-based architecture has the potential to deploy such network-wide virtualization. Thus, firstly, the resource allocation and sharing schemes are formulated as a multi-round auction under the policy of competition. One PSP is considered who wants to share its under-utilized licence bands for economic profits. The RRHs are acting as SSPs and can bid for those idle licence bands to support their wireless services by considering the essence of competition. Three logical functions are categorized after virtualization as depicted in Fig. 2 with a multi-round spectrum auction mechanism, namely: PSP, SSPs/RRHs and SDN controller:

- The PSP is the seller who owns the radio resources i.e., licensed bands, and who wants to share the idle bands based on the availability or the supply.

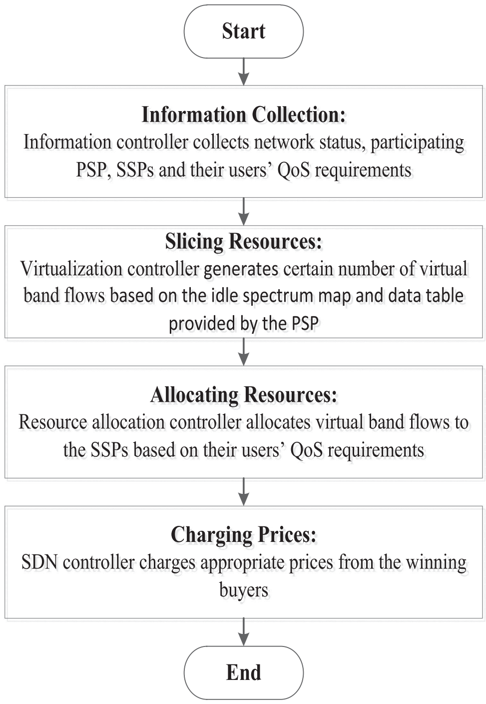

Fig. 3. Virtualization steps in the proposed SDN-enabed wireless architechture.

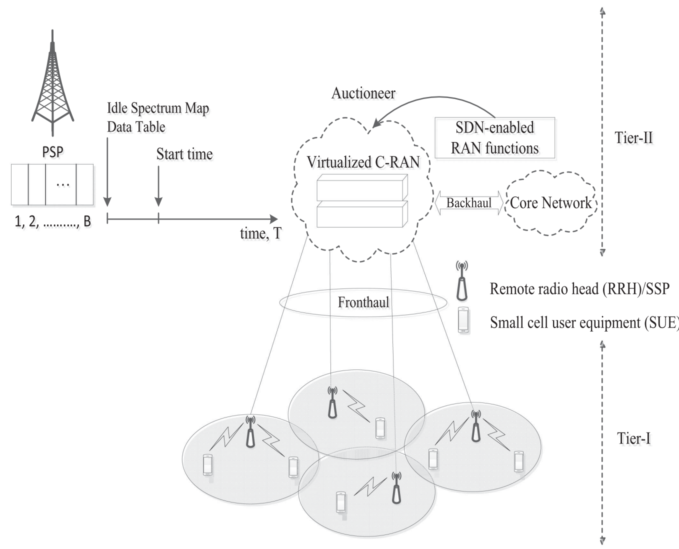

Fig. 4. Two-tier architechture for spectrum auction in SDN enabled C-RAN.

- The SSPs/RRHs are the buyers who lease the virtualized radio resources (idle licence bands) from the PSP based on their subscribed users' demands.
- The SDN controller is the auctioneer who is in charge of virtualizing the radio resources i.e., idle licence bands and make a proper balance of the demand and supply from the buyers and the seller.

Secondly, at the starting time of each auction period, the PSP provides a fine-grained idle spectrum map and a data table to let the information of the under-utilized bands be known. Then, the virtualized network resources are generated by slicing the physical radio resources i.e., idle licence bands owned by the PSP into virtual pieces. In this paper, a spectrum-level slicing [2] is considered and defined as band flow. It is a new logical element similar to the physical resource block in LTE systems. These band flows (isolated spectrum units) can be divided into packet blocks to achieve synchronization in the virtualization control plane. They are labeled with the packet blocks sequence number. Without knowing how the virtual spectrum/bands are generated and transmited, the SPSs can reconstruct these packet blocks based on the sequence number and merge them into the original service flow for guaranteeing their end users QoS requirements.

Finally, the virtualization process is well described in Fig. 3. In this paper, time is assumed to be slotted, and a single time period T is considered that comprises enough slots for the proposed method to converge to the optimal solution. At the starting time of each auction period, the seller PSP provides the idle spectrum map and a data table to allow the information controller to know about the available bands. Then, the band flows are generated by virtualization controller based on the current status of the network. At each time period T, the resource allocation controller runs the auction mechanism to identify the corresponding demand and supply. Finally, the SDN controller maps the generated band flows to certain users through the data plane and charges suitable prices from the buyers.

IV. Spectrum Auction Mechanism Design of a Two-Tier Architechture

The proposed two-tier system architecture to perform spectrum auction in SDN-enabled C-RAN is shown in Fig. 4.

A. *Small Cell Network Acting as SSP in Tier-I*

Tier-I is between RRHs and their end-users i.e., SUEs, where the RRHs are acting as SSPs. For SUEs, they do not know any information regarding the spectrum bands, but they only know about their requested services and affordable transaction costs. All RRHs form an evolved system paradigm: C-RAN where SDN-enabled virtualized structures are considered in a centralized location. In this SDN-enabled C-RAN architecture, $\mathcal{R}$ number of RRHs, where $i \in \mathcal{R} = \{1, 2, ..., R\}$, are deployed to serve $\mathcal{S}$ number of SUEs, where $s \in \mathcal{S} = \{1, 2, ..., S\}$. Each RRH receives the service requests from its SUEs and transmits the users' requests to the SDN controller for baseband processing. According to the aggregated service requests from the SUEs, each RRH bids for their required bands during the auction in an all-or-none approach, e.g., either fully acquired or rejected.

B. *SDN-Enabled Spectrum Auction in Tier-II*

In Tier-II, multi-round auctions are performed by the resource allocation controller who acts as an auctioneer every time period T. As shown in Fig. 4, at the starting time of each auction period, the seller PSP supplies a fine-grained idle spectrum map and a data table [18] to release the information regarding the available bands in the next period T. Let's assume there are W bands available, where each band $w \in \mathcal{W} = \{1, 2, ..., W\}$ covers K_w available blocks and block $\forall k \in \mathcal{K}_w$ is denoted as w_k. If $RRH_i, \forall i \in \mathcal{R}$, wants to bid for certain band $w \in \mathcal{W}$, it has to bid for a band with all required blocks, denoted as K_w^i, which includes the band's index. The purchase of all the desired bands for each RRH is performed in an all-or none approach, i.e., any partial purchase is unacceptable. As multiple rounds are running, rich information might be revealed in previous rounds, which increases the success rates of cheating and challenges truthfulness. The SDN-based virtualization controller can provide a trusted encryption platform for communication between the PSP and the RRHs. The SDN-controller is able to protect bidders private bidding information and locations so that other participating bidders cannot rig the information and manipulate the auction outcome.

A data table is provided by the PSP along with the idle spectrum map which contains the specific spectrum range and the available blocks' information. The data table also includes the information regarding the reserved price P_{w_k} for each available block $k, k \in \mathcal{K}_w$, which is required by the PSP.

For all competing RRHs, they need to provide the information regarding the bands with required blocks and the bidding value to the auctioneer before the auction starts. When the auction begins, the resource allocation controller who is acting as auctioneer, determines the winners and their charging prices. After that, the blocks of the bands which have been already claimed, will be deleted from the idle spectrum map and each losing RRH can bid in the next auction round. The auction continues multiple rounds until no participating RRH is left, or no available bands on idle spectrum map, or the auction period is over.

C. Economic Properties and Preliminaries for Auction Design

An economic-robust auction design mechanism needs to satisfy the following economic properties [9]:

- *Individual rationality:* Each player needs to receive a non-negative utility, i.e., a buyer will be charged according to the bidding price where a seller will get a maximum revenue equivalent to the asking price.
- *Truthfulness/Incentive compatibility:* Every bidder gets the maximum utility from its true valuation, and there is no strategic advantage to be gained by being dishonest.
- *Budget-balance:* The auctioneer's predicted payoff is non-negative, i.e., there is no deficit for the auctioneer between the charged price from the winning buyers' and the revenues of the seller(s).
- *Efficiency:* The total social welfare, i.e., the sum of the values of all winning bids needs to be maximized.

Now, some preliminaries are introduced that are utilized to design the auction mechanism:

Bidding Value: At round t, RRH_i, $\forall i \in \mathcal{R}$, has a bidding value, which is the maximum price it would like to pay, is denoted as B_t^i.

True Valuation: At round t, suppose that RRH_i want to admit a set of SUEs denoted as $\mathcal{S}_t^i \subseteq \mathcal{S}_i$. Thus, its true valuation is equal to the sum of all amount budgeted by all its SUEs, i. e., $V_t^i = \sum_{s \in \mathcal{S}_t^i} P_s^i$.

Clearing Price: At round t, a winner set, denoted as $\mathcal{R}_t^*$, is determined by the auctioneer (SDN controller) and the winning RRH_i, $\forall i \in \mathcal{R}_t^*$ is charged a certain price denoted as $\bar{P}_t^i$.

Utility Function: For the seller PSP at round t, the utility function is the difference between the total revenue and the total reserve price of the sold entities (band-block pairs). Thus, the utility function for the PSP can be written as:

$$U_t^{PSP} = \sum_{i \in \mathcal{R}_t^*} \bar{P}_t^i - \sum_{w \in \mathcal{W}_t} \sum_{k \in \mathcal{K}_{t,w}} P_{w_k}, \tag{1}$$

where at round t, the sold bands and the sold blocks of $w \in \mathcal{W}_t$ are denoted as $\mathcal{W}_t \subseteq \mathcal{W}$ and $\mathcal{K}_{t,w} \subseteq \mathcal{K}_w$ respectively.

For the buyer RRH_i, $\forall i \in \mathcal{R}$, at round t, the utility function is defined as

$$U_t^{RRH,i} = \begin{cases} V_t^i - \bar{P}_t^i = \sum_{s \in \mathcal{S}_t^i} P_s^i - \bar{P}_t^i, & \text{if RRH } i \text{ wins at round } t, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Social Welfare: The social welfare of an auction can not only stimulate the resource sharing, but also improve certain economic performance, which can be denoted as the aggregated utilities of all players, i.e., buyers and sellers. Thus, at round t, the social welfare of the auction can be written as:

$$SW_t = U_i^{PSP} + \sum_{i \in \mathcal{R}_t^*} U_t^{RRH,i} = \sum_{i \in \mathcal{R}_t^*} V_t^i - \sum_{w \in \mathcal{W}_t} \sum_{k \in \mathcal{K}_{t,w}} P_{w_k} \tag{3}$$

V. System Model and Problem Formulation

A. Modeling the Small Cell Network

In this section, the constraints considered in the modeling and scheduling of the small cell network are described.

Let binary variable α_s^i be a user association indicator, indicating whether a SUE $s \in \mathcal{S}_i$ is associated or not with RRH i, i.e.,

$$\alpha_s^i = \begin{cases} 1, & \text{if SUE } s \text{is associated with RRH} i, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Let another binary variable β_w^i be a band allocation indicator, defined as

$$\beta_{s,w}^i = \begin{cases} 1, & \text{if band } w \text{ is allocated to RRH } i \text{ for SUE} s, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

For simplicity, let's assume that each SUE associates with only one RRH, i.e.,

$$\sum_{i=1}^{R} \alpha_s^i = 1, \forall s \in \mathcal{S}, \tag{6}$$

and each SUE and RRH connection uses one band for its data transmission, i.e.,

$$\sum_{w=1}^{W} \alpha_s^i \beta_{s,w}^i \leq 1, \forall s \in \mathcal{S}, \forall i \in \mathcal{R}. \tag{7}$$

In order to avoid co-tier interference, we also assume that each RRH selects seperate bands for its SUEs, i.e.,

$$\alpha_{s_1}^i \beta_{s_1,w}^i + \alpha_{s_2}^i \beta_{s_2,w}^i \leq 1, \forall (s_1, s_2) \in \mathcal{S}_i, \forall w \in \mathcal{W}. \tag{8}$$

Now, the signal-to-interference-plus-noise ratio (SINR) achieved by the SUE s connected to the RRH i on band w is written as

$$\Upsilon^i_{s,w} = \frac{|h^i_{s,w}|p^i_{s,w}}{\sum_{s\neq s',i\neq i'}|h^{i'}_{s',w}|p^{i'}_{s',w} + \sigma_0}, \tag{9}$$

where $h^i_{s,w}$ is the channel gain from RRH i to SUE s on band w, $p^i_{s,w}$ is the allocated power from RRH i to SUE s on band w and σ_0 represents the zero mean and unit variance additive Gaussian noise (AWGN) power. In order to verify the SINR threshold value for the allocated band, the following condition must hold:

$$\alpha^i_s \beta^i_{s,w} \Upsilon^i_{s,w} > \Upsilon^{th};\ \forall s \in \mathcal{S}, \forall i \in \mathcal{R}, \forall w \in \mathcal{W}. \tag{10}$$

In order to balance the bugdet, when the resource allocation controller schedules its network transmissions to generate certain bunch of the required blocks, it needs to guarantee that the total bidding price from all the SUEs can be higher than the total reserve price. Let a binary variable γ^i_w be used to describe whether RRH_i bids for $\mathcal{K}^i_w$ i.e.,

$$\gamma^i_w = \begin{cases} 1, & \text{if RRH } i \text{ bids for the block } \mathcal{K}^i_w, \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

Now, the budget balance constraint can be written as

$$\sum_{s\in\mathcal{S}^i} P^i_s.\alpha^i_s \geq \sum_{w\in\mathcal{W}^i}\sum_{k\in\mathcal{K}^i_w} P_{w_k}.\gamma^i_w \tag{12}$$

B. Objective Function of Tier-I

For $RRH_i, \forall i \in \mathcal{S}$, the revenue can be calculated by

$$\sum_{s\in\mathcal{S}^i} P^i_s.\alpha^i_s - \sum_{w\in\mathcal{W}^i}\sum_{k\in\mathcal{K}^i_w} P_{w_k}.\gamma^i_w \tag{13}$$

Now, considering the aforementioned set of constraints, the objective function for RRHs can be formulated as maximizing its revenue, i.e.,

$$\mathbf{OP1}: \max \sum_{s\in\mathcal{S}^i} P^i_s.\alpha^i_s - \sum_{w\in\mathcal{W}^i}\sum_{k\in\mathcal{K}^i_w} P_{w_k}.\gamma^i_w \tag{14}$$

subject to:

$$\begin{aligned}
&C1: \sum_{i=1}^{R} \alpha^i_s = 1;\ \forall s \in \mathcal{S},\\
&C2: \sum_{w=1}^{W} \alpha^i_s \beta^i_{s,w} \leq 1;\ \forall s \in \mathcal{S}, \forall i \in \mathcal{R},\\
&C3: \alpha^i_{s_1}\beta^i_{s_1,w} + \alpha^i_{s_2}\beta^i_{s_2,w} \leq 1;\ \forall (s_1,s_2) \in \mathcal{S}_i, \forall w \in \mathcal{W},\\
&C4: \alpha^i_s \beta^i_{s,w} \Upsilon^i_{s,w} > \Upsilon^{th};\ \forall s \in \mathcal{S}, \forall i \in \mathcal{R}, \forall w \in \mathcal{W},\\
&C5: \sum_{s\in\mathcal{S}^i} P^i_s.\alpha^i_s \geq \sum_{w\in\mathcal{W}^i}\sum_{k\in\mathcal{K}^i_w} P_{w_k}.\gamma^i_w;\\
&C6: \alpha^i_s, \beta^i_{s_1,w}, \gamma^i_w \in \{1,0\};\ \forall s \in \mathcal{S}, \forall i \in \mathcal{R}, \forall w \in \mathcal{W},
\end{aligned} \tag{15}$$

where constraints C1 to C5 refer to in (6) to (8), (10) and (12) respectively. The constraint C6 represents the descision variable described in (4), (5) and (11). The objective function in (14) turns the problem **OP1** into a mixed integer non-linear programming (MINLP) problem. The optimization problem **OP1** is computionally intractable and is generally a NP-hard problem [26]. Several solutions can be found in the literature [9]; for instance, greedy method, branch and bound algorithm, dual decomposition, and more generally Lagrangian relaxation.

VI. SDN-Enabled Spectrum Auction Mechanism (SDN-SAM) for Social Welfare Maximization

Social welfare is the most commonly used metric for auction mechanism which comprehensively considers the benefit from both sides (seller and buyer) [9]. It represents the total profit earned in the market, leading to an efficient spectrum allocation. In our proposed auction mechanism, the social walfare (given by (3)) represents the aggregated utilities of both the seller and the buyer. Here, the PSP is the seller, the RRHs are the bidding agents and the SDN controller (a combination of information controller, virtualization controller and resource allocation controller) is the auctioneer that controls the overall auction process. All SUEs and RRHs within the C-RAN are always connected to the SDN controller through the control plane. The exchange of the bidding information and the step-by-step auction mechanism are captured in Fig. 5, and described as follows:

Step 1: The seller PSP generates a bid information and sends this information to the information controller of the SDN controller. This bid information contains two types of information, i.e., I^1_{PSP} and I^2_{PSP}. The I^1_{PSP} represents a fine-grained idle spectrum map that releases the information of the available blocks in the bands, i.e., $I^1_{PSP} = K_w$. The I^2_{PSP} contains the information about the corresponding reserved prices of the blocks, i.e., $I^2_{PSP} = P_{w_k}$.

Step 2: Whenever a SUE s receives the pilot signal from the RRHs, it requests one service to the RRHs. The information (I_s) of the service requests contains the information about the candidate RRH list. A RRH becomes a candidate for its SUEs when the following condition is satisfied :

$$\begin{aligned}
&I^1_s = \{\alpha^i_s\} = [\boldsymbol{\alpha}_s] = \boldsymbol{\alpha}_s;\ \forall i \in \mathcal{R}\\
&\alpha^i_s = 1 \text{ when } \frac{\pi {d^i_s}^2}{\pi {D_i}^2} \leq 1;
\end{aligned} \tag{16}$$

where d^i_s represents the distance between the SUE s and RRH i and D_i denotes the radius of the RRH i.

The information controller of the SDN controller receives the service requests from all the SUEs and generates the information (I^2_i) about the initial user association for the RRH i, i.e.,

$$I^2_i = \{\alpha^i_s\} = [\boldsymbol{\alpha}^i] = \boldsymbol{\alpha}^i,\ \forall s \in \mathcal{S}. \tag{17}$$

Based on the information of I^1_s and I^2_i, the information controller of the SDN controller has the complete information of the user association matrix $\boldsymbol{\mathcal{A}}$.

Step 3: Based on the information of the seller PSP provided by the information controller, the virtualization controller of the

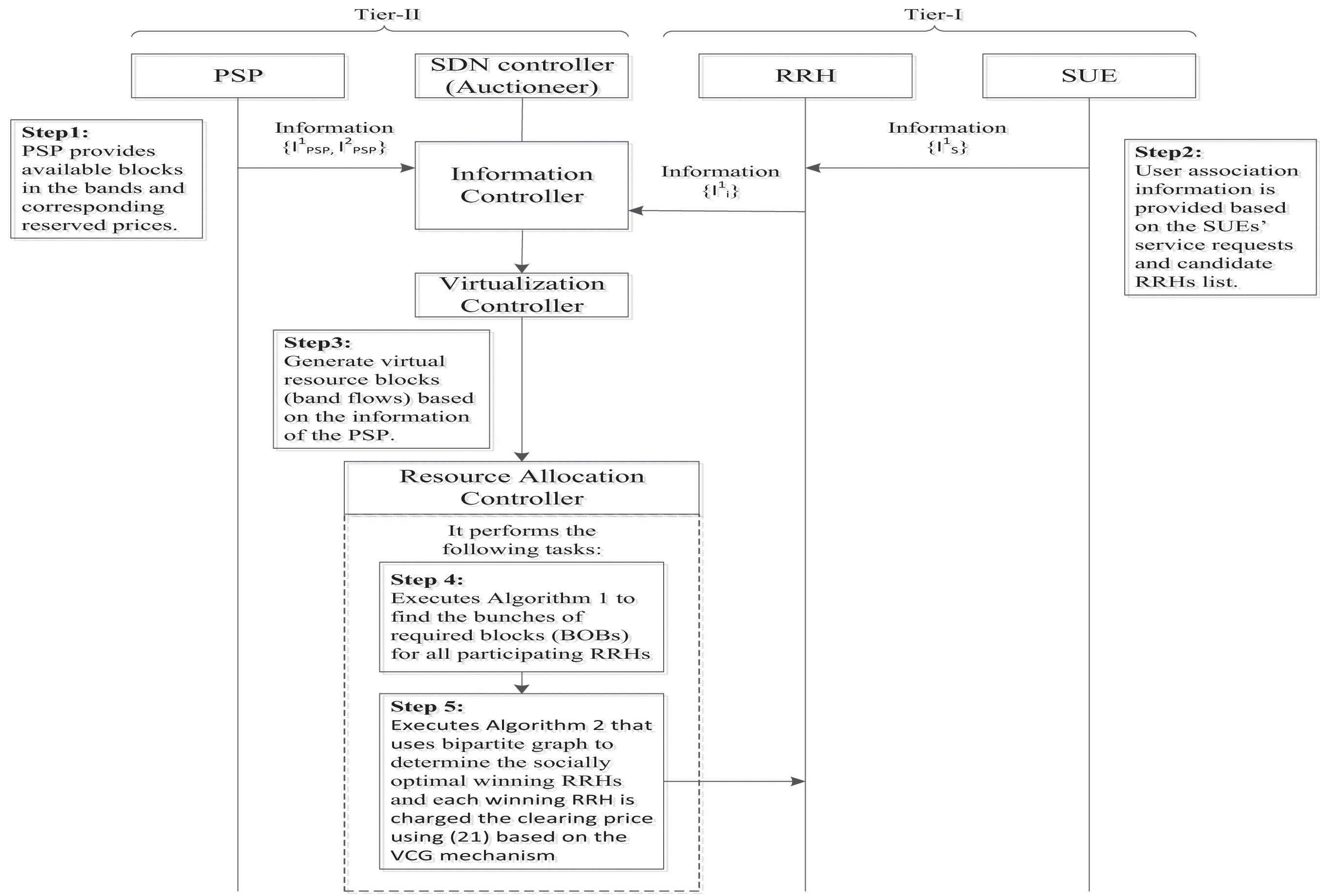

Fig. 5. SDN-enabled Spectrum Auction Mechanism (SDN-SAM).

SDN controller generates the band flows which are the logical elements similar to the physical resource blocks. Each band flow can be divided into packet block containing the sequence number to achieve synchronization in the virtualization control plane.

Step 4: The resource allocation controller executes Algorithm 1 to determine the band assignment (w, l) (i.e. band w and power l) and the outcome of using this assignment. Algorithm 1 satisfies all the constraints of the problem **OP1** to determine a stable allocation of the band assignment for guaranteeing the SUEs' service requirements and maximizing the revenue of the RRHs' for Tier-I. The outcome of using this band assignment is to identify the bands with required blocks for the participating RRH i and the revenue.

Proposition 1: Band assignment (w, l) performed by Algorithm 1 leads to a stable allocation.

Proof: See Appendix A. ■

Proposition 2: The band assignment (w, l) performed by Algorithm 1 terminates after some finite number of steps.

Proof: See Appendix B. ■

Step 5: The resource allocation controller then executes Algorithm 2 to determine the winning RRHs and calculate the pricing for the winners. Regarding the bands with required blocks and the bidding values from all the participating RRHs, the bipartite graph [27] is utilized to characterize the conflict relationship among different participating RRHs. It helps the SDN controller, who is acting as an auctioneer, to make the socially optimal desicion. A bipartite graph denoted by $G(\mathcal{R}, \mathcal{W}, \mathcal{E})$ can be constructed based on the information of the network topology, where the vertex set $\mathcal{R}$ denotes the set of RRHs, the vertex set $\mathcal{W}$ represents the set of bands and $\mathcal{E}$ is the edge set. At round t, for RRH i, $\forall i \in \mathcal{R}$, a vertex is introduced that includes the bands with required blocks as K_w^i, a bidding value as B_w^i and an outcome as O_w^i, which is equal to the social welfare that it provides. Since the price charging scheme is proposed based on the VCG auction, each RRH would like to consider its true value as the bidding value (this is proved later). Thus, at each round t, the outcome can be obtained as

$$O_w^i = B_w^i - \sum_{w_k \in \mathcal{K}_w^i} P_{w_k}. \tag{18}$$

Each vertex of $\mathcal{R}$ selects one of the vertex of $\mathcal{W}$ based on the edge which is the maximum outcome it provides, i.e.,

$$\mathcal{E}(i, w^*) = \max_{\forall w \in \mathcal{W}, \forall k \in \mathcal{K}_w} O_k^i.$$

Thus, each RRH i selects one band w^* based on the maximum output it provides.

Now, let's consider two arbitrary RRHs i.e., $i \neq j \in \mathcal{R}$. If both RRHs want the same band w with common required blocks, i.e., $k_w^i \cap k_w^j \neq \emptyset$, then they conflict with each other and thus, there

Algorithm 1: Spectrum (Band) Identification for RRH.

input: Initial user association information ($\boldsymbol{\alpha}^i$), available blocks ($\mathcal{K}_w$), SINR threshold value (Γ^{th}), budget by the SUEs of RRH_i (P_s^i), reserved price (P_{w_k}) by the PSP
Output: Bands with required blocks
Initialization:
Set equal power level for each SUE associated with RRH i
$\beta_{s,w}^i \leftarrow 0$
$\gamma_w^i \leftarrow 0$
for $i \in \mathcal{R}$ **do**
  for $s \in \mathcal{S}$ **do**
    if $\alpha_s^i == 1$ **then**
      for $w \in \mathcal{W}$ **do**
        if $\beta_{s,w}^i == 0$ **then** `// Check constraint C2 and C3`
          Estimate $\Upsilon_{s,w}^i$ using (9)
          if $\Upsilon_{s,w}^i >= \Upsilon^{th}$ **then** `// Check constraint C4`
            $\beta_{s,w}^i \leftarrow 1$
            $\alpha_s^i \leftarrow 1$
            if $\gamma_w^i == 1$ **then** `// Check constraint C5`
              calculate revenue using (13)
              break;
            end
          end
        end
        else
          $\alpha_s^i \leftarrow 0$
          $\gamma_w^i \leftarrow 0$
        end
      end
    end
  end
end
Return: Bands with required blocks

Algorithm 2: Winner Determination and price charging scheme.

input: Bands with required blocks (K_w^i) and bidding value (B^i) from all the participating RRHs, reserved price (P_{w_k}) by the PSP
Output: Winning RRHs and clearing price from the winners
for $i \in \mathcal{R}$ **do**
  At auction round t, use bipartite graph $G = (\mathcal{R}, \mathcal{W}, \mathcal{E})$ to represent the conflict relationship among RRHs.
  Each vertex includes K_w^i, B_w^i and O_w^i, where O_w^i can be calculated using (18).
  Identify conflict vertex $w \in \mathcal{W}$ using $deg(w) = 0$ or $deg(w) > 1$
  for *Each conflict vertex* $w \in \mathcal{W}$ *and* $deg(w) = 0$ **do**
    Set the band allocation indicator $\beta_w^i = 1$
  end
  for *Each conflict vertex* $w \in \mathcal{W}$ *and* $deg(w) > 1$ **do**
    Select $i^* \in \mathcal{R}$ when
$$\mathcal{E}(i^*, w) = \max_{\forall w \in \mathcal{W}, \forall k \in \mathcal{K}_w} O_k^i$$
  end
  Regenerate the graph for all unallocated vertices and repeat the above procedure until all vertices are allocated.
end
for *winning RRH* $i \in \mathcal{R}_t^*$ **do**
  Calculate the clearing price $\bar{P}_t^i$ using (20).
end

is an edge between the two vertices. Therefore, at the auction round t, a bipartite graph $G(\mathcal{R}, \mathcal{W}, \mathcal{E})$ can be constructed by the SDN controller based on the defined vertices and edges. The band selection and conflict resolution procedure are repeated until all the RRHs are connected to their appropriate bands. Fig. 6(a) shows an example of the bipartite graph representation for $\mathcal{R} = 8$ and $\mathcal{W} = 8$. When more than one RRH selects the same band $w^* \in \mathcal{W}$, then w^* is represented as a conflict vertex in the bipartite graph. In Fig. 6(b), all the black (dark) color vertices in the band represent the conflict vertex.

Definition 1: A vertex in $w \in \mathcal{W}$ becomes a conflict vertex when it is matched by either more than one $i \in \mathcal{R}$ or no i.

The conflict vertices ($w \in \mathcal{W}$) in bipartite graph G are identified using the degree information of the vertices; i) deg$(w) = 0$ or, ii) deg$(w) > 1$. The conflict vertex violates the constraint C2 in **OP1**. For conflict resolution, a winner determination and edge elimination method have been proposed, which is applied to all conflict vertices as long as each of the vertices $\mathcal{R}$ is connected to exactly one vertex in $\mathcal{W}$. For the winner determination method, the vertex of $i^* \in \mathcal{R}$ becomes the winner of w when its edge shows the maximum value among others. For example, conflict vertex $w \in \mathcal{W}$, selects i^* when

$$\mathcal{E}(i^*, w) = \max_{\forall i \in \mathcal{R}} O_k^i \tag{19}$$

and eliminate other edges to satisfy the condition C2 in **OP1**. This process is repeated for all other conflict vertices which have deg$(w) > 1$. Fig. 6(c) shows the graphical representation after the winner determination and edge elimination method is applied. In this paper, since the bidders are the RRHs rather than the SUEs, the total number of participating bidders is reduced drastically. This shifts the complexity from the SUEs' side to the SDN controller which has more capability to achieve the bidding goal. Moreover, Algorithm 1 (band identification for RRH) and Algorithm 2 (winner determination) are performed by the resource allocation controller under SDN, which has the necessary amount of resources for running it with a minimum complexity. Thus, these two algorithms make the **OP1** computationally tractable and the complexity of our proposed scheme is no longer a concern, which can be easily managed by the SDN controller.

Definition 2: A stable allocation is defined as no conflict vertex and each vertex $i \in \mathcal{R}$ is connected to at most one vertex in $w \in \mathcal{W}$ and vice versa.

Proposition 3: The winner determination performed by Algorithm 2 leads to a pair-stable allocation (RRH-band allocation) when the number of conflict vertices becomes zero.

Proof: See Appendix C. ■

The proposed price charging scheme for the winning RRHs is inspired by the well-known VCG auction. The pricing rule in VCG auction is based on the second highest bid which guarantees that the winning bidder pays less than its submitted

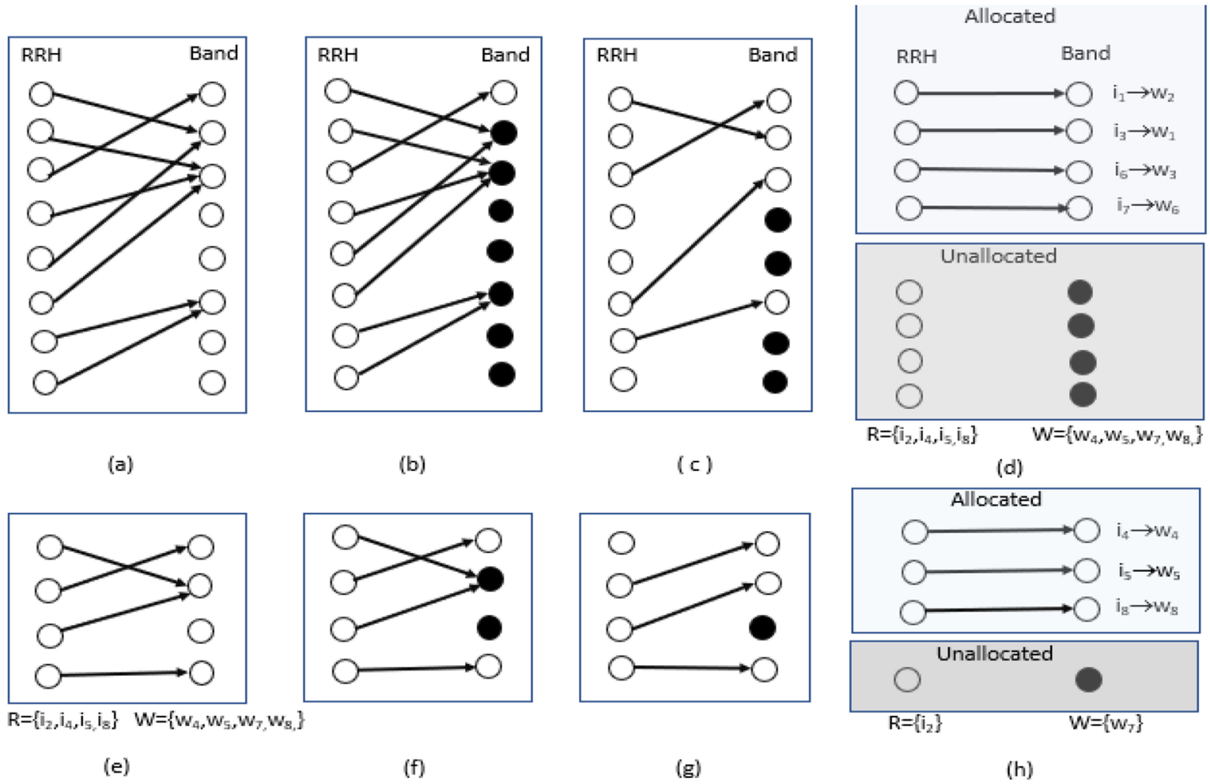

Fig. 6. (a) Bipartite graph. (b) Identifying conflict vertices. (c) Winner determination and edge elimination. (d) Allocated and unallocated vertices. (e) Repeated case of (a). (f) Repeated case of (b). (g) Repeated case of (c). (h) Repeated case of (d).

bid [9]. The VCG-based price charging scheme for bidder i is calculated by taking the difference between the optimal social welfare when i is not participating and the social welfare of the other players in the optimal allocation. At auction round t, the outcome of RRH_i, $\forall i \in \mathcal{R}_t$, can be found from (18), which represents how much higher the RRH i can bids than the reserve price required by the PSP. In order to guarantee the reserve price required by the PSP and based on the VCG auction, the clearing price to the winning RRH_i, $\forall i \in \mathcal{R}_t^*$, can be obtained as:

$$\bar{P}_t^i = \sum_{w_k \in \mathcal{K}_w^i} P_{w_k} + \left\{ \sum_{j \neq i \in \mathcal{R}_t} O_w^j \cdot h_j \left(\boldsymbol{O}_w^{-i} \right) - \sum_{j \neq i \in \mathcal{R}_t^*} O_w^j \right\} \tag{20}$$

where $\boldsymbol{O}_w^{-i} = \boldsymbol{O}_w \backslash O_w^i$ describes the situation when RRH i is not participating and $h_j \left(\boldsymbol{O}_w^{-i} \right) \in \{0, 1\}$ denotes whether RRH_j wins or not.

Proposition 4: The winner determination and the price charging scheme performed by Algorithm 2 converges to a stable allocation after a finite number of iterations.

Proof: See Appendix D. ∎

VII. Proof of Economic Properties for the Proposed Auction Mechanism

In this section, it is proven that the proposed spectrum auction mechanism SDN-SAM satisfies the properties of truthfulness, individual rationality and budget balance.

- *Truthfulness:* In order to prove the truthfulness property, we need to show that no buyer can get a higher utility by bidding other than its true valuation. For this, first we need to show that its winner determination is monotonic and then the price charging scheme is bid-independent.

(1) Monotonic winner determination

The following lemma describes the monotonicity of the winner determination.

Lemma 1: Considering a given RRH i, if it wins at any round t by bidding B_t^i, it can also win by bidding higher, i.e., $\bar{B}_t^i > B_t^i$.

Proof: Since the bidder RRH i is a winning buyer by bidding B_t^i which is not the minimum bid that it offered, the bid will not be affected if B_t^i increases to $\bar{B}_t^i$. The bidder RRH i will still be a winning buyer. ∎

Lemma 2: Considering a given RRH i, if it wins the same number of blocks at any round t by bidding B_t^i and higher $\bar{B}_t^i$, then the utility $U_t^{RRH,i}$ for RRH i is the same for both. ∎

Proof: The bids of all the winning buyers ($RRH_i, \forall i \in \mathcal{R}_t^*$) remain the same in both cases since the clearing price of the winning RRHs ($\bar{P}_t^i$) is unaffected by any of the bidding values. Thus, the utility $U_t^{RRH,i}$ for RRH i is the same for both. ∎

Now, based on the two lemmas, the following proposition holds.

Proposition 5: At each auction round t, each participating RRH would like to take the true valuation of its required bands with the required blocks as the bidding value.

TABLE I
FOUR POSSIBLE OUTCOMES WHEN BIDDING TRUTHFULLY AND UNTRUTHFULLY

Scenario	**1**	**2**	**3**	**4**
Bidding untruthfully	Lose	Lose	Win	Win
Bidding truthfully	Lose	Win	Lose	Win

Proof: Considering a certain RRH i, let the bidding value be unequal to its true valuation, i.e., $B_t^i \neq V_t^i$. Then, four possible auction outcomes exist, which are listed in the Table I when RRH i bids truthfully and untruthfully. In order to prove the truthfulness property, we need to show that in all four cases, when bidding truthfully and untruthfully, the utility of the RRH i under truthful bidding is always greater than when bidding untruthfully, i.e., $U_t^{RRH,i}(V_t^i) \geq U_t^{RRH,i}(B_t^i)$.

Now, we examine these scenarios in the case where $B_t^i > V_t^i$.

Scenario 1: For both bids, RRH i loses and is charged with zero, leading to the same utility of zero, i.e., $U_t^{RRH,i}(V_t^i) = U_t^{RRH,i}(B_t^i) = 0$.

Scenario 2: RRH i wins with V_t^i but loses with a higher bid B_t^i. According to Lemma 1, this case does not exist.

Scenario 3: RRH i loses with V_t^i but wins with a higher bid B_t^i. In the former case, the utility of RRH i is zero, i.e., $U_t^{RRH,i}(V_t^i) = 0$. In the later case, according to Lemma 2, we can write $B_t^i > \bar{P}_t^i > V_t^i$. Therefore, when bidding untruthfully, the utility of RRH i becomes negative since $V_t^i - \bar{P}_t^i < 0$. Thus, we get $U_t^{RRH,i}(V_t^i) > U_t^{RRH,i}(B_t^i)$.

Scenario 4: For both bids, RRH i wins and according to Lemma 2, RRH i will be charged the same price, leading to the same utility, i.e., $U_t^{RRH,i}(V_t^i) = U_t^{RRH,i}(B_t^i)$.

Now, we consider these scenarios in the case where $B_t^i < V_t^i$.

Scenario 1: This scenario is the same as in the scenario 1 above.

Scenario 2: RRH i wins with B_t^i, but loses with a higher bid V_t^i. According to Lemma 1, this case does not exist.

Scenario 3: RRH i loses with B_t^i but wins with a higher bid V_t^i. In the former case, the utility of RRH i is zero, i.e., $U_t^{RRH,i}(V_t^i) = 0$. In the later case, according to Lemma 2, we get $B_t^i < \bar{P}_t^i < V_t^i$. Therefore, when bidding truthfully, the utility of RRH i becomes positive since $V_t^i - \bar{P}_t^i > 0$. Thus, we get $U_t^{RRH,i}(V_t^i) > U_t^{RRH,i}(B_t^i)$.

Scenario 4: This scenario is the same as in the above scenario 4.

Therefore, in all possible scenarios, by bidding truthfully, each RRH can make a higher utility compared to that obtained by bidding untruthfully. Thus, each participating RRH will bid equal to its true valuation.

- *Individual rationality:* In this work, it is considered that the seller PSP leases its own idle or under-utilized spectrum bands by guaranteeing its own QoS requirements. According to (1), the utility function for the PSP is the difference between the total revenue and the total reserve price of the sold entities. From (20), it can be observed that the total pricing received from the winning RRHs is always greater than the reserved price by the PSP; hence, guaranteeing the non-negative utility for the seller. On the other hand, for the buyers (RRHs), it has been proved earlier that each participating RRH will bid equal to its true valuation for all possible scenarios. Thus, by bidding truthfully, each RRH can make a positive utility.
- *Budget-balance:* In our proposed SDN-SAM, the resource allocation controller who is acting as auctioneer, executes Algorithm 1 that satisfies the budget balance constraint C5. It guarantees that the total bidding price from all the participating RRHs is higher than the total reserve price, thus making the generated revenue of the auctioneer non-negative.
- *Economic Efficiency:* Because the winner determination performed by Algorithm 2 leads to a pair-stable allocation, when the number of conflict vertices becomes zero, which can yield a suitable auction outcome for maximizing the defined social welfare. Hence, SDN-SAM satisfies the property of economical efficiency. That completes the proof. ■

TABLE II
SIMULATION PARAMETERS

Parameters	**Values**
Total no. of SUEs	30-90
Total no. of RRHs	5-40
Total no. of bands	5-50
System bandwidth	10 MHz
Radius of small cell	10 m
Transmission power of RRH	20 dBm
Path loss exponent	4
Noise power	-144 dBm

VIII. PERFORMANCE EVALUATION

In this section, simulations are conducted to investigate the performance of the proposed auction scheme SDN-SAM. Below, the parameter settings and performance metrics are first introduced, and different schemes under comparison are discussed. Then, the simulation results under various settings are presented.

A. Parameter Setting

A scenario is considered where there are one PSP and several RRHs, i.e., SSPs operating within the same geographical area. The RRHs are deployed to serve a number of SUEs. They all are controlled by the SDN controller. The settings for the simulation parameters are shown in Table II. The simulation results are obtained from several independent simulation runs and then evaluated over different realizations of the proposed scenario.

B. Performance Metrics

In order to evaluate the performance of the proposed auction scheme SDN-SAM, the following metrics are considered.

- *Social Welfare/Auction Efficiency:* The sum of utilities of the auction participants, which reflects the revenue from all winning agents.

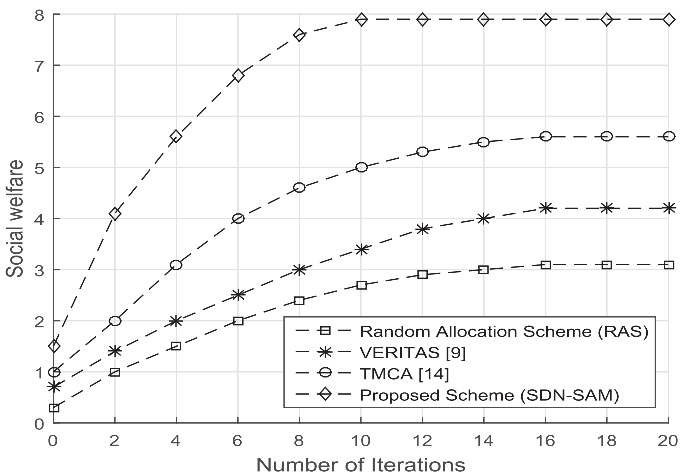

Fig. 7. The comparison of convergence process of different schemes.

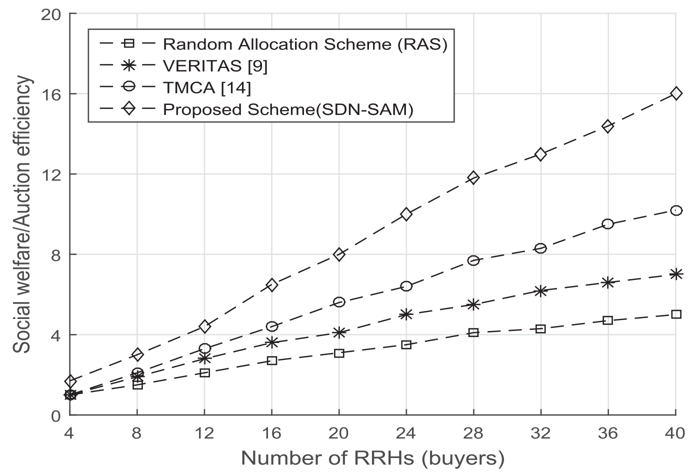

Fig. 8. Social welfare/auction efficiency versus number of RRHs (buyers) for different schemes.

- *Spectrum Utilization/Spectrum Selling Ratio:* The ratio of the number of selling bands to the total number of bands.
- *Buyer Satisfaction:* The ratio of wining agents to the total demand, which reflects the RRHs' satisfaction of spectrum services (band assignment).
- *Spectrum Reusability:* The ratio of winning agents to the total bands, which reflects spectrum efficiency.

C. Schemes Under Comparison

From the literature review, it has been noted that several spectrum auction mechanisms have been proposed for different scenarios and settings. In the following, the proposed SDN-SAM is compared with the following auction mechanisms:

1) VERITAS [10]; which is considered as the benchmark for the spectrum auction design.
2) TMCA [15]; in which the auction is designed for the allocation of wireless channels.
3) Random Allocation Scheme (RAS); in which the SDN controller randomly distributes the RRHs among the spectrums and then determines the final winning buyers.

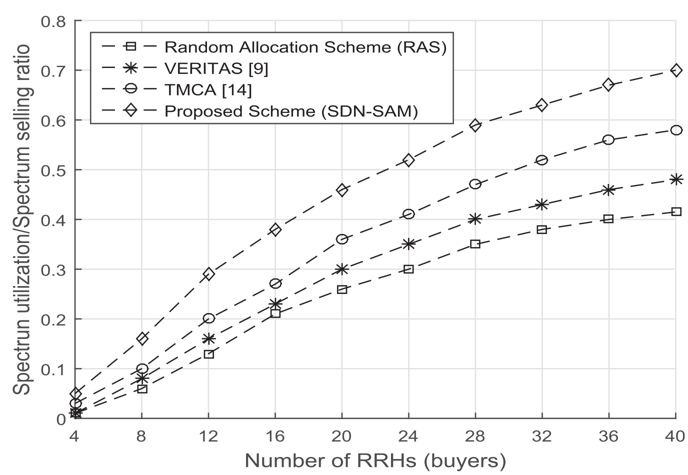

Fig. 9. Spectrum utilization/spectrum selling rario versus number of RRHs (buyers) for different schemes.

D. Simulation Results

First, the performance of the proposed auction mechanism (SDN-SAM) is evaluated against that of the different auction schemes mentioned earlier, in terms of convergence process. The results are captured in Fig. 7. From this figure, it is obvious that the proposed auction mechanism (SDN-SAM) outperforms the other three schemes and not only the overall auction welfare is higher, but also, the convergence speed is quicker.

Fig. 8 presents the performance of social welfare versus the number of RRHs (buyers) for different schemes. It is found from this figure that with the increase of the number of RRHs (buyers), the social welfare of all the schemes increases. The VERITAS's and TMCA's performances are better than that of the random allocation scheme, however these two schemes are lagging behind from the proposed SDN-SAM, since they only consider a simple spectrum allocation for nonconflict buyers and ignore the economic efficiency. The proposed SDN-SAM can significantly improve the social welfare, especially in a dense RRHs' (buyers') deployment scenario.

Fig. 9 illustrates the comparison of the spectrum utilization for different schemes. It is observed that the spectrum utilization level goes up with the increase of the numbers of RRHs (buyers) for all schemes and the proposed SDN-SAM outperforms the other schemes. Note that the spectrum utilization is the ratio of number of selling bands to the total number of bands, which is in fact the winning ratio of the whole auction. As more RRHs join the auction, they tend to produce a large size auction with higher bid, which in turn will increase the spectrum selling ratio. On the other hand, more bands sold yields a higher social welfare.

Fig. 10 shows the performance of the buyer satisfaction versus the number of RRHs (buyers) for the studied schemes. As the number of buyers increases, the buyer satisfaction increases for all schemes and the proposed SDN-SAM outperforms the other schemes. From Fig. 10, it is found that the buyer satisfaction level tends to be in saturation. The reason is that the more RRH

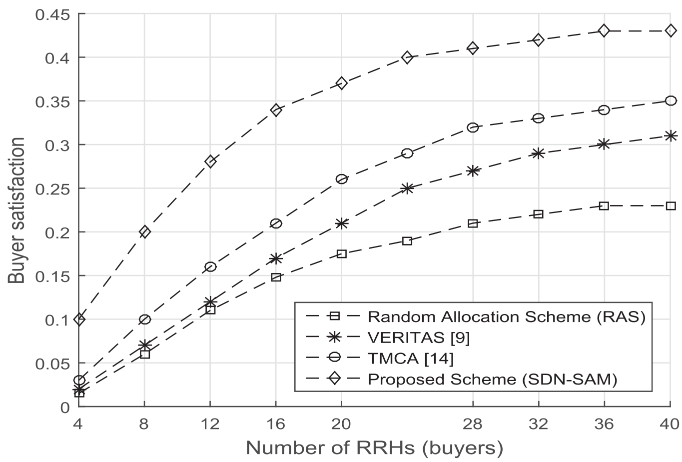

Fig. 10. Buyer satisfaction versus number of RRHs (buyers) for different schemes.

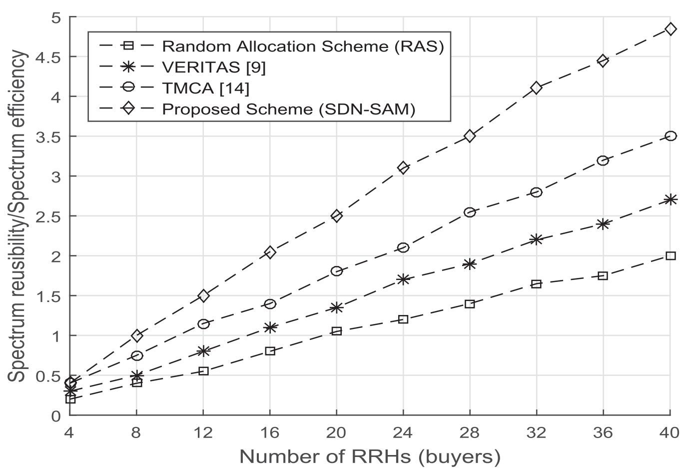

Fig. 11. Spectrum reusibility/spectrum efficiency versus number of RRHs (buyers) for different schemes.

(buyer) will lose in the auction due to the limited number of bands (spectrum) in dense RRHs' (buyers') deployment.

Fig. 11 provides the comparison of spectrum reusibility for different schemes. It is found that the spectrum reusibility degree increases with the increase of the number of RRHs (buyers) for all schemes and the proposed SDN-SAM outperforms the other schemes. Since SDN-SAM can form more winning ratio, it increases the spectrum utilization, which in turn increases the reusibility degree.

IX. Conclusion and Future Work

In this paper, a SDN-enabled C-RAN framework has been proposed for performing spectrum auction with a two-tier architecture support. In Tier-I, several RRHs are considered to act as the SSPs to provide services to its SUEs by exploiting the purchased idle resources from the PSP in Tier-II. Specifically, in order to maintain QoS requirements of the SUEs, the revenue maximization problem for the RRHs is formulated by considering the user association, band assignment, interference management, and budget allowance. In Tier-II, a SDN-enabled spectrum auction mechanism called SDN-SAM has been proposed for maximizing the social welfare based on the SUEs' service requirements of all participating RRHs from Tier-I. In order to determine the socially optimal winners, a bipartite graph is utilized and the price charging scheme is proposed based on the VCG auction scheme. Furthermore, it is proved that SDN-SAM satisfies the economic properties including truthfulness, individual rationality, budget balance, and economical efficiency. Compared with the related existing methods, it is shown that SDN-SAM yields a better auction outcome from the perspective of social welfare, spectrum utilization and buyer satisfaction. As future research directions, the auction based SDN-enabled virtualization model can be designed to have the flexibility to adopt the competetions among multiple sellers and multiple buyers i.e., double auction setting. The network-wide auction based virtualization scheme can also be implemented via a centralized SDN controller where the heterogeneous users demands can be modeled using an online combinatorial auction framework.

Appendix

A. *Proof of Proposition 1*

Depending on the initial user association information $\boldsymbol{\alpha}^i$, the total power of RRH i is equally allocated among the SUEs at the initial stage of Algorithm 1. A band $w \in \mathcal{W}$ is assigned to the SUE when it satisfies the band allocation and SINR constraints (Lines 5 and 7 in Algorithm 1). Considering that the band assignment (w, l) is allocated to the SUE s by Algorithm 1, this allocation is stable since the same band w cannot be assigned to another SUE $w^{'}$. Indeed Line 5 in Algorithm 1 prohibits the assignment of w to another user $w^{'}$. Thus, the band assignment (w, l) leads to a stable allocation. ■

B. *Proof of Proposition 2*

Let the finite set $\{\beta^i\}$ denotes all possible combinations of SUEs ($s \in \mathcal{S}$) and bands ($w \in \mathcal{W}$) matching for RRH i ($i \in \mathcal{R}$), where each element $\beta^i_{s,w} \in \{\beta^i\}$ represents the band w assigned to the SUE s in RRH i. No SUE can choose the same band w more than once since the constraints C2 and C3 of the problem **OP1** are considered in Algorithm 1. Thus, the finiteness of the set $\{\beta^i\}$ ensures the termination of Algorithm 1 in a finite number of steps. ■

C. *Proof of Proposition 3*

If any two RRHs want the same band w with common required blocks, i.e., $k^i_w \cap k^j_w \neq \emptyset$, then they conflict with each other and thus, there is an edge between the two vertices. If band w^* is selected by more than one RRH i, then the proposed winner determination method resolves the conflict by picking up the best RRH i, who will benefit the most by using the output in (18). Thus, the matches of RRH i becomes the best choice for other RRHs in the current situation. Hence, the vertex matching is pair-stable. ■

D. Proof of Proposition 4

At auction round t, there exists the finite vertex set $\{\mathcal{R}\}$ that includes all possible combinations of the participating RRHs' bands with required blocks (K_w^i), the bidding value (B_w^i) and the outcome (O_w^i) it brings. No two vertices (RRHs) can choose the same band w with common required blocks, i.e., $k_w^i \cap k_w^j = \emptyset$ since a conflict happens and there will be an edge between the two vertices. If band w^* is selected by more than one RRH, then the proposed winner determination method resolves the conflict by picking up the best RRH i with the maximum output. Thus, after each iteration, a set of vertices is generated where all the RRHs are participating successfully without having a conflict with each other. This process continues until all the participating RRHs are allocated without any conflict of choices with each other. Hence, the finiteness of the winning RRH set $\{\mathcal{R}_t^*\}$ ensures the termination of Algorithm 2 in a finite number of steps. ■

REFERENCES

[1] Ericsson White Paper, "More than 50 billion connected devices," Ericsson, Stockholm, Sweden, Tech. Rep. 284 23-3149 Uen, Feb. 2011.

[2] C. Liang and F. R. Yu, "Wireless network virtualization: A survey, some research issues and challenges," *IEEE Commun. Surv. Tut.*, vol. 17, no. 1, pp. 358–380, Jan.–Mar. 2015.

[3] J. H. Cox *et al.*, "Advancing software-defined networks: A survey," *IEEE Access*, vol. 5, pp. 25487–25526, Oct. 2017.

[4] L. Chen, F. R. Yu, H. Ji, G. Liu, and V. C. M. Leung, "Distributed virtual resource allocation in small-cell networks with full-duplex selfbackhauls and virtualization," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5410–5423, Jul. 2016.

[5] B. Naudts, M. Kind, S. Verbrugge, D. Colle, and M. Pickavet, "How can a mobile service provider reduce costs with software-defined networking?" *Int. J. Netw. Manage.*, vol. 26, no. 1, pp. 56–72, Jan. 2016.

[6] E. Hernandez-Valencia, S. Izzo, and B. Polonsky, "How will NFV/SDN transform service provider opex?" *IEEE Netw.*, vol. 29, no. 3, pp. 60–67, May/Jun. 2015.

[7] X. Zhou, R. Li, T. Chen, and H. Zhang, "Network slicing as a service: Enabling enterprises own software-defined cellular networks," *IEEE Commun. Mag.*, vol. 54, no. 7, pp. 146–153, Jul. 2016.

[8] A. Sultana, L. Zhao, and X. Fernando, "Efficient resource allocation in device-to-device communication using cognitive radio technology," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10024–10034, Nov. 2017.

[9] U. Habiba and E. Hossain, "Auction mechanisms for virtualization in 5G cellular networks: basics, trends, and open challenges," *IEEE Commun. Surv. Tut.*, vol. 20, no. 3, pp. 2264–2293, Mar. 2018.

[10] X. Zhou, S. Gandhi, S. Suri, and H. Zheng, "eBay in the sky: Strategyproof wireless spectrum auctions," in *Proc. ACM MobiCom*, New York, NY, USA, Aug. 2008, pp. 2–13.

[11] X. Zhou and H. Zheng, "TRUST: A general framework for truthful double spectrum auctions," in *Proc. IEEE INFOCOM*, Rio de Janeiro, Brazil, Apr. 2009, pp. 999–1007.

[12] J. Barrera, A. Garcia, and M. Hong, "Auction design for spectrum allocation under interference constraints," in *Proc. IEEE GLOBCOM*, Atlanta, GA, USA, Dec. 2013, pp. 3035–3041.

[13] W. Wang, B. Liang, and B. Li, "Designing truthful spectrum double auctions with local markets," *IEEE Trans. Mobile Comput.*, vol. 13, no. 1, pp. 75–88, Jan. 2014.

[14] D. S. Palguna, D. J. Love, and I. Pollak, "Secondary spectrum auctions for markets with communication constraints," *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 116–130, Jan. 2016.

[15] T. Chen and S. Zhong, "Truthful auctions for continuous spectrum with variable bandwidths," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 1116–1128, Feb. 2014.

[16] X. Feng, P. Lin, and Q. Zhang, "FlexAuc: Serving dynamic demands in a spectrum trading market with flexible auction," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, pp. 824–830, Feb. 2015.

[17] M. Khaledi and A. A. Abouzeid, "Dynamic spectrum sharing auction with time-evolving channel qualities," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 5900–5912, Nov. 2015.

[18] X. Li, H. Ding, M. Pan, Y. Sun, and Y. Fang, "Users first: Service-oriented spectrum auction with a two-tier framework support," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 11, pp. 2999–3013, Nov. 2016.

[19] Y. Chen, P. Lin, and Q. Zhang, "LOTUS: Location-aware online truthful double auction for dynamic spectrum access," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, pp. 1092–1099, Feb. 2015.

[20] D. Zhang, Z. Chang, T. Hmlinen, and F. R. Yu, "Double auction-based multi-flow transmission in software-defined and virtualized wireless networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 12, pp. 8390–8404, Dec. 2017.

[21] J. Gao, L. Zhao, and X. Shen, "Network utility maximization based on incentive mechanism for truthful reporting of local information," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7523–7537, Aug. 2018.

[22] Q. Z. Li, L. Zhao, J. Gao, H. Liang, L. Zhao, and X. H. Tang, "SMDP-based coordinated virtual machine allocations in cloud-fog computing systems," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1977–1988, Jun. 2018.

[23] A. Sultana, X. Fernando, and L. Zhao, "An overview of medium access control strategies for opportunistic spectrum access in cognitive radio networks," *Peer-to-Peer Netw. Appl.*, vol. 10, no. 5, pp. 1113–1141, Sep. 2017.

[24] A. Jin, W. Song, and W. Zhuang, "Auction-based resource allocation for sharing cloudlets in mobile cloud computing," *IEEE Trans. Emerg. Topics Comput.*, vol. 6, no. 1, pp. 45–57, Jan.–Mar. 2018.

[25] M. Peng, Y. Sun, X. Li, Z. Mao, and C. Wang, "Recent advances in cloud radio access networks: System architectures, key techniques, and open issues," *IEEE Commun. Surv. Tut.*, vol. 18, no. 3, pp. 2282–2307, Jul.–Sep. 2016.

[26] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness*. New York, NY, USA: W. H. Freeman and Company, 1979.

[27] L. F. Abanto-Leon, A. Koppelaar, and S. H. de Groot, "Graph-based resource allocation with conflict avoidance for V2V broadcast communications," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun.*, Montreal, QC, Canada, Oct. 2017, pp. 1–7.

Ajmery Sultana received the Ph.D. degree in electrical and computer engineering from Ryerson University, Toronto, ON, Canada, in 2018, and the B.Sc. and M.Sc. degrees in applied physics and electronics and communication engineering from the University of Dhaka, Dhaka, Bangladesh, in 2006 and 2008, respectively. She is currently a Postdoctoral Fellow with the Department of Computer Science, Ryerson University, Toronto, ON, Canada. Her research interests include resource allocation in cognitive and device-to-device communication and virtualization in 5G cellular networks.

Isaac Woungang received the M.Sc. degree in mathematics from the University of Aix-Marseille II, Marseille, France, in 1990, and the Ph.D. degree in mathematics from the University of South, Toulon and Var, France, 1994. Since 2002, he has been with Ryerson University, Toronto, ON, Canada, where he is currently a Professor in computer science and the Director of the Distributed Applications and Broadband (DABNEL) Lab. His current research interests include radio resource management, computer security, heterogeneous networks, computational intelligence and machine learning applications, performance modeling, analysis, and optimization.

Lian Zhao (S'99–M'03–SM'06) received the Ph.D. degree from the University of Waterloo, Waterloo, ON, Canada, in 2002. She joined the Department of Electrical, Computer & Biomedical Engineering, Ryerson University, Toronto, ON, Canada, in 2003, where she became a Professor in 2014. Her research interests are in the areas of wireless communications, radio resource management, edge computing and caching, cognitive radio and cooperative communications, and optimization for complicated systems. She was the Co-Chair for IEEE International Conference on Communications 2018 Wireless Communication Symposium, the Workshop Co-Chair for IEEE/CIC International Conference on Communications in China in 2015, the Local Arrangement Co-Chair for IEEE Vehicular Technology Conference Fall 2017 and IEEE INFOCOM in 2014, and the Co-Chair for IEEE GLOBECOM 2013 Communication Theory Symposium. She was a Committee Member for NSERC Discovery Grants Evaluation Group for Electrical and Computer Engineering during 2015–2018. She is a Licensed Professional Engineer in the Province of Ontario and a Senior Member of the IEEE Communication and Vehicular Society. She was the recipient of the Best Land Transportation Paper Award from IEEE Vehicular Technology Society in 2016, Top 15 Editor Award in 2015 from the IEEE TRANSACTION ON VEHICULAR TECHNOLOGY, the Best Paper Award from the 2013 International Conference on Wireless Communications and Signal Processing and Best Student Paper Award (with her student) from CHINACOM in 2011, the Canada Foundation for Innovation New Opportunity Research Award in 2005, She received Early Tenure and was promoted to Associate Professor in 2006.

Alagan Anpalagan (S'98–M'01–SM'04) received the B.A.Sc., M.A.Sc., and Ph.D. degrees in electrical engineering from the University of Toronto, Toronto, ON, Canada. He joined the Electrical and Computer Engineering Department, Ryerson University, Toronto, ON, Canada, in 2001, and was promoted as Full Professor in 2010. He was with the Department in administrative positions as the Associate Chair, the Program Director for electrical engineering, and the Graduate Program Director. He was an Editor for the IEEE COMMUNICATIONS SURVEYS & TUTORIALS (2012–2014), IEEE COMMUNICATIONS LETTERS (2010–2013), and EURASIP (2004–2009). He was also a Guest Editor for six special issues published in IEEE, IET, and ACM. He was the TPC Co-Chair for IEEE Vehicular Technology Conference Fall 2017 and the TPC Co-Chair for IEEE INFOCOM in 2016, IEEE GLOBECOM in 2015, and IEEE Personal Indoor Mobile Radio Communications in 2011. He was the Vice Chair for the IEEE SIG on Green and Sustainable Networking and Computing with Cognition and Cooperation (2015–2018), the IEEE Canada Central Area Chair (2012–2014), the IEEE Toronto Section Chair (2006–2007), the Communications Society Toronto Chapter Chair (2004–2005), and the IEEE Canada Professional Activities Committee Chair (2009–2011). He is a Registered Professional Engineer in the province of Ontario, Canada, and a Fellow of the Institution of Engineering and Technology and a Fellow of the Engineering Institute of Canada. He was the recipient of the IEEE Canada J. M. Ham Outstanding Engineering Educator Award (2018), the YSGS Outstanding Contribution to Graduate Education Award (2017), the Deans Teaching Award (2011), the Faculty Scholastic, Research and Creativity Award thrice from the Ryerson University. He was also the recipient of the IEEE M. B. Broughton Central Canada Service Award (2016), the Exemplary Editor Award from IEEE Communications Society (2013), and the Editor-in-Chief Top10 Choice Award in Transactions on Emerging Telecommunications Technology (2012) Dr. Anpalagan is a Co-Author of a paper that received the IEEE SPS Young Author Best Paper Award (2015).