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Users First: Service-Oriented Spectrum Auction with a Two-Tier Framework Support

Xuanheng Li, *Student Member, IEEE*, Haichuan Ding, Miao Pan, *Member, IEEE*, Yi Sun, *Member, IEEE* and Yuguang Fang, *Fellow, IEEE*

***Abstract*—Auction-based secondary spectrum market provides a platform for spectrum holders to share out their under-utilized licensed bands with secondary users (SUs) for economic benefits. However, it is challenging for SUs to directly participate due to their limited battery power and capability in computation and communications. To shift complexity away from users, in this paper, we propose a novel multi-round service-oriented combinatorial (MRSC) spectrum auction with two-tier framework support. In Tier I, we introduce several secondary service providers (SSPs) to provide end-users with services by using purchased licensed bands even if the end-users do not have cognitive radio (CR) capability. When an SU submits its service request with certain bidding allowance to its SSP, the SSP will help find out which bands within its area are available and bid for the desired ones from the market in Tier II. Specifically, we formulate the bidding process at the SSP as an optimization problem by considering interference management, spectrum uncertainty, flow routing, and budget allowance. In Tier II, considering two possible manners of the seller, we propose two social welfare maximizing auction mechanisms accordingly, including the winner determination based on weighted conflict graph and the Vickrey-Clarke-Groves (VCG)-styled price charging mechanism. Extensive simulations have been conducted and the results have demonstrated the higher revenue of the proposed scheme compared with the traditional commodity-oriented single-round truthful schemes.**

***Index Terms*—Cognitive radio networks, service-oriented spectrum auction, spectrum sharing, social welfare maximization.**

I. Introduction

Recent years have witnessed flourish of various kinds of wireless services due to the popularity of smart devices. The consequent substantial growth in mobile traffic leads to a dramatically increasing demand for radio spectrum, which makes it an extremely precious resource. Nevertheless, the static spectrum allocation policy employed by Federal Communications Commission (FCC) in the past resulted in significant spectrum waste because the licensed spectrum bands are under-utilized in either temporal or spatial domain. Cognitive radio (CR) technology emerges as one promising solution to enhancing spectrum utilization [1], [2]. It can realize dynamic spectrum sharing through enabling unlicensed users, i.e., the so-called secondary users (SUs), to be aware of their operating environments and opportunistically access vacant licensed bands without imposing significant impacts on services of licensed users, i.e., the so-called primary users (PUs). Although CR can achieve efficient spectrum sharing, incentives are needed for spectrum holders to open up their spectrum bands. Along with this direction, spectrum trading market arises, leveraging economic profit to encourage spectrum holders to share their spectrum bands [3]. In such a market, one win-win situation can be achieved if spectrum holders could sell/lease/auction their idle bands for monetary gains while SUs could buy/rent/bid them according to their needs for opportunistic access by following the ground rules for CR technologies. In fact, such a spectrum market, e.g., Spectrum Bridge, has already been in existence [4].

Remarkable potential economic benefits and significant spectrum utilization have made spectrum trading market very attractive, especially for the spectrum auction design [5]–[18]. However, from a practical perspective, some crucial problems are still ambiguous in most of the existing spectrum auction mechanisms. First of all, similar to general auctions in economics, most existing spectrum auctions are commodity-oriented, i.e., each end-user has specific desired commodities (bands) with certain valuations and bids for them in the market. Nevertheless, for end-users, they usually lack the global knowledge of the network, such as network topology and transmission related information. Therefore, they will confront with many problems in such spectrum auctions, e.g., how many spectrum bands are needed for certain level of quality of service (QoS), which set of bands is the best choice, how to valuate different bands, etc. In fact, for most end-users, they even may not know what the ‘spectrum bands’ are around them. Thus, unlike traditional auctions where buyers are familiar with the commodities, in spectrum market, what the end-users exactly know is just the service they want to acquire, such as downloading a HQ-video with 1.5Gbits from Dropbox within 10 minuets, which makes the traditional commodity-oriented auctions not suitable for spectrum auction.

Besides the end-user side, some problems also appear on the auctioneer side in the spectrum market. First, how to support the information exchange between bidders and auctioneer in such a market is important but widely neglected. For the auctioneer, some research works let the spectrum holder be the auctioneer. Since SUs do not subscribe services from the primary network, how could they get the information on the auctioned bands and submit their bids to the spectrum holder?

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X. Li and Y. Sun are with the School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China. Email: lixuanheng@mail.dlut.edu.cn, lslwf@dlut.edu.cn.

H. Ding and Y. Fang are with the Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611. Email: dhcbit@gmail.com, fang@ece.ufl.edu.

M. Pan is with the Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77004. Email: mpan2@uh.edu.

In parallel with that, some studies advocate employing a third-party as the auctioneer. Then, some exclusive bands/channels must be reserved for the information exchange, but where do they come from? Second, since the number of end-users is usually extremely large, considerable computational complexity may be imposed on the auctioneer, which may become the bottleneck, even for some heuristic algorithms to achieve an approximate maximum of social welfare. Moreover, due to the salient feature of spectrum auctions, i.e., one band can be shared by many non-conflicting users, the auctioneer needs to figure out the conflict relationship among different users' transmissions, which is difficult, and even not a duty for the auctioneer.

In addition to the aforementioned issues, spectrum uncertainty is also an important factor for spectrum auction, which is, unfortunately, rarely considered. As we all know, one of the most important issues for CRNs is to protect PUs from being interfered by SUs. In other words, although SUs have made payments, what they get is actually the authorization to access certain licensed bands, rather than using them arbitrarily as PUs. An SU still needs to obey the FCC ruling and immediately evacuate from the licensed band if a PU returns to use it. Therefore, unpredictable risk of using a licensed band exists when an SU bids for it due to the unexpected return of PUs. Furthermore, to monitor PUs' activity, SUs have to execute spectrum sensing when they access licensed bands [19]–[21]. Those sensing activities may impose unbearable burdens on SUs' light-weighted mobile devices, such as dedicated antennas and considerable energy consumptions, etc.

Even if all above concerns could be handled well and SUs could get what they need from the spectrum market, SUs may still not be able to utilize them efficiently. On the one hand, there may exist stringent requirements on SUs' devices if they want to use the purchased non-contiguous licensed bands, such as reconfigurable antennas, multiple transceivers/RF chains, high power battery to support frequent band switching, etc. Note that it is extremely hard, if not impossible, to integrate all of those on a portable terminal device with limited capability. On the other hand, as for multi-hop transmissions, an SU, as an end-user, may not have enough information to design an optimal scheduling, and even may not be able to meet its QoS requirement.

Whether or not all above problems could be addressed well is extremely important, which motivates us to develop a solid and feasible architecture for spectrum auction with a comprehensive consideration of multiple specific issues. In this paper, we propose a novel <u>m</u>ulti-<u>r</u>ound <u>s</u>ervice-oriented <u>c</u>ombinatorial (MRSC) spectrum auction with a two-tier framework. In tier I, a secondary service provider (SSP) is introduced to coordinate a mesh network of CR facilities, also called CR routers [13]. On the one hand, it aggregates the service's requests[1] from its own end-users and purchases needed spectrum bands accordingly from the spectrum market (via spectrum auction). On the other hand, it can also facilitate the access of end-users without CR capability. In tier II, SSPs participate in the spectrum auction and bid for their desired needed bands within desired regions. Winning SSPs are determined and charged with certain price by a trusted third-party auctioneer based on a multi-round auction (described later). Note that different from the commodity-oriented spectrum auction, in the proposed MRSC spectrum auction, SUs only need to claim their desired services and expected prices. Under this two-tier framework, since the bidders are SSPs, information exchange is no longer a problem and the number of participants is reduced dramatically, which makes spectrum auction much more practical.

In this paper, we have made the following major contributions.

- Unlike most existing works, we consider the spectrum auction design from a more practical perspective and have developed an innovative service-oriented spectrum auction scheme with a solid two-tier architecture. In the proposed market, each end-user only needs to submit its service request and bidding allowance to its SSP, and the SSP will act as an agent to bid for bands that can support the requested services. This shifts the complexity from SUs' side to the operator which has more capability to accomplish the bidding goal.
- Different from most existing spectrum auctions, where each band is represented simply by using an index, we have comprehensively considered both spectrum heterogeneity and spectrum uncertainty. Specifically, we have introduced a fine-grained available spectrum map (ASM) and an information table (IT) to represent a multi-dimensional information of each band, including its available regions, reserve price (the lowest price allowed by the seller), historical data about available bandwidth, etc, which can offer bidders, i.e., SSPs, more information to decide which bands to bid to meet its users' QoS requirements, and also make the auctioneer easier to determine the conflict relationship among the bidders.
- Under this two-tier framework, we consider specific transmission features of each bidder and design a 3-dimensional desired bundle (3D^2-bundle) representation to characterize the aggregated user demand for an SSP, i.e., which bands within which regions it needs to support its services to its users. We build this representation by formulating an optimization problem considering many important factors, e.g., interference management, spectrum uncertainty, flow routing, budget allowance, etc. In particular, to characterize the spectrum uncertainty, we have introduced a probabilistic link capacity with α-confidence level. Instead of common statistic-based methods [13], [22], we have proposed a novel data-based approach to achieve an approximation of this α-link capacity, which is more practical.
- We have proposed a multi-round spectrum auction scheme to achieve more transactions at each auction period, where losing SSPs at each round can continue to join the following rounds until there are no bundled bands available in the market to support requested services for any SSP. More specifically, inspired by the well-

[1] Since the purchased licensed bands have uncertainty, the services requested by SUs should be delay-tolerant ones.

known Vickrey-Clarke-Groves (VCG) auction [23]–[25], we have proposed two social welfare maximizing auction mechanisms in two possible manners to leverage the use of winner determination based on weighted conflict graph and VCG-styled price charging mechanism. It is expected that the proposed method could find the best match between the random service demands and random spectrum resource availability.

The rest of the paper is organized as follows. In Section II, we review the related works in spectrum auction. In Section III, we introduce the network model for the two-tier framework and some preliminaries of the spectrum auction. In Section IV, we mathematically describe the construction of an SSP's 3D^2-bundle. In Section V, we develop two social welfare maximizing auction mechanisms for our MRSC spectrum auction. Finally, we present the simulation results in Section VI and draw conclusion remarks and future works in Section VII.

II. Related Work

Auction theory as a branch of economics has been introduced to spectrum sharing between PUs and SUs, which can date back to a decade ago [26]. Numerous studies have raised on economic properties, e.g., truthfulness, in spectrum auctions. Zhou *et al.* proposed VERITAS in [5] as one of the first truthful spectrum auctions, and then further proposed a truthful double auction named TRUST in [6] by considering multiple sellers as well. In [7], Gopinathan *et al.* studied periodic truthful auctions for balancing social welfare and user fairness. As an online truthful double auction, LOTUS was designed by Chen *et al.* in [8], which has taken buyers' location information into account. Although these promising studies have promoted the progress on truthful spectrum auction design, three other important factors seem to be widely neglected, namely, spectrum heterogeneity, spectrum uncertainty, and transmission features. In view of spectrum heterogeneity, Chen *et al.* proposed TAMES in [9] by considering both spatial heterogeneity and frequency heterogeneity, and Dong *et al.* [11] tackled the spectrum allocation in CR networks with time-frequency flexibility. In view of transmission features, Li *et al.* [11] designed a truthful randomized auction framework for multi-hop secondary networks, and Li *et al.* [12] proposed an economic-robust transmission opportunity auction scheme for multi-hop data traffic. In view of spectrum uncertainty, Pan *et al.* [13] proposed a session based spectrum auction system called spectrum cloud in multi-hop CR networks. Unfortunately, none of these has taken all the above four factors into consideration simultaneously.

Besides these four factors, several practical issues are not clear enough in most existing studies, such as how end-users figure out their desired bands to bid, how they communicate with the auctioneer, how they use the purchased bands efficiently on their light-weighted devices with limited capability, etc. Thus, from a practical perspective, the limitation of end-users must be taken into consideration and all participating parties and their interactive functionalities must be clarified. In this paper, with all these considerations, we develop a novel service-oriented spectrum auction scheme based on a solid two-tier framework to facilitate the limited end-users and make the spectrum auction more practical. In fact, some research works have devoted to the design of similar multi-tiered architectures. In [14], Tang and Jain presented a hierarchical auction model where multiple auction markets are cascaded as multiple tiers to iteratively trade the spectrum resource. Similarly, in [15], Xu *et al.* designed a two-tier market for decentralized dynamic spectrum access, in which SUs buy spectrum in Tier-1 market in a large time scale and trade with other SUs in Tier-2 market in a small time scale. In [16], Lin *et al.* developed a three-stage auction framework, including an outer auction between secondary access point (SAP) and SUs and an inner auction between spectrum holder and SAPs. However, although these works have similar architectures to ours, they actually design schemes in different tiers separately based on the traditional commodity-oriented auction, rather than the service-oriented auction with a cross-tier design as ours. In [17], Berry *et. al.* focused on the distinction between owned and leased spectrum assets and proposed a two-tier market, in which spectrum access rights are traded among different spectrum owners and spectrum owners rent/lease their spectrum to service providers (SPs). Such a two-tier market can be regarded as an upper level for our proposed market and the user side is not considered. In [18], Sengupta *et. al.* investigated a two-tier trading system including two main components, namely, the spectrum allocation to SPs and the interaction between users and SPs. In this market, the bidders, SPs, participate in the auction based on the estimation on the demand for bandwidth. However, actual message transmissions for end users are not really elaborated, which is critically important in practice. Different from these works, in our proposed two-tier MRSC spectrum auction, our SSP is to deploy the needed communication infrastructure together with corresponding network protocols to handle all control messages needed to support the auction. Users submit their services in Tier I and SSPs bid for needed bands accordingly in Tier II.

III. Network Model

A. Two-Tier System Architecture for Service-Oriented Spectrum Auction

In this study, we consider a secondary spectrum market with one primary service provider (PSP) and N infrastructure-based secondary service providers (SSPs). The PSP can share its seldomly-used licensed bands for economic profits, and SSPs can bid for them to support their wireless services. To be specific, a multi-round auction is held periodically in the market. At each period, the PSP constructs a fine-grained available spectrum map (ASM) and an information table (IT) to show which bands are opened within which regions in the next time period, and each SSP bids for needed bands within certain regions in an all-or-none manner, i.e., either fully obtained or rejected, according to users' service requests. Different from the traditional spectrum market, where end-users directly bid for specific bands, in this market, although the initiators are still the end-users, they only need to submit

TABLE I
THE LIST OF NOTATIONS

Symbol	Definition
$\mathcal{N}$	The set of SSPs
$\mathcal{M}$	The set of unoccupied bands auctioned in the market
s_l^i,d_l^i,z_l^i,p_l^i	The source, destination, data size, and bidding allowance of end-user l of SSP i
$\mathcal{Z}_m$, $\mathcal{Q}_m$	The set of available zones and further divided blocks of band m
$\mathcal{B}_m^i$	The set of all needed blocks of band m by SSP i
$\bar{p}_{m_q}$	The PSP's reserve price of band m within block q
$\bar{W}_{m^z}$	A random variable representing the available bandwidth of band m within zone z
$\left\{\hat{W}_{m^z}^1, \cdots, \hat{W}_{m^z}^D\right\}$	D historical data for the average bandwidth of band m within zone z
$\bar{\mathcal{Q}}_{m,k}^i$	The bundled blocks of band m for CR router k of SSP i
$\mathcal{M}_k^i$	The set of available bands of CR router k of SSP i
$\mathcal{T}_{k,m}^i$, $\mathcal{I}_{k,m}^i$	The transmission/interfered neighbors of SSP i's CR router k on band m
$c_{kg,m}^i$	The capacity of SSP i's link k to g on band m
$\bar{c}_{kg,m^z,\alpha}^i$	The α-link capacity of SSP i's link k to g on band m within zone z
$\hat{c}_{kg,m^z,\alpha,D}^i$	The DA-α-link capacity of link k to g on band m within zone z based on D historical data
b_t^i, v_t^i	The bidding value and true value of SSP i in the t-th auction round
$\hat{p}_t^i$	The clearing price for winning SSP i
$u_t^{\text{ma-p}}$, $u_t^{\text{mi-p}}$	The utility of the PSP with macro-manner and micro-manner
$u_t^{\text{s},i}$	The utility of SSP i

their service requests and the buyers who truly participate in the auction are the SSPs, which is thus called multi-round service-oriented combinatorial (MRSC) spectrum auction. It has a two-tier framework as shown in Fig. 1.

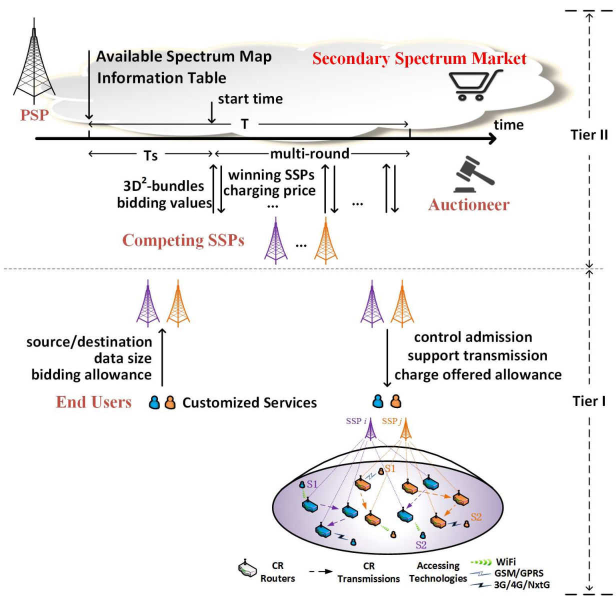

Fig. 1. Two-Tier framework for multi-round service-oriented combinatorial spectrum auction.

1) Mesh Network of an SSP in Tier I: Tier I is between SSPs and their end-users. For end-users, generally speaking, they do not know what the spectrum market is, which spectrum bands are needed, how to complete their data transmissions, but only know their expected services and affordable monetary costs. To facilitate these end-users with better service provisioning, each SSP acts as an admission controller, a bidding agent, and a service provider for its own users. Specifically, as shown in Fig. 1, each SSP$_i$, $i \in \mathcal{N} = \{1, 2, \cdots, N\}$, consists of base stations (BSs) and other network facilities to form the backbone network in the coverage area, and under each BS, a mesh network of CR routers forms a backhaul network. Each BS serves as a central controller in its coverage area with some basic bands to provide reliable common control signaling to manage the network resources (both basic bands and harvested bands). The BS also manages the mesh network of CR routers deployed in its coverage area, which have CR capability to operate over the purchased PSP's bands. End-users can access CR routers through the basic bands of SSP using any accessing approaches, e.g.,Wi-Fi, GSM/GPRS, 3G/4G/NxtG, etc., without making any changes on their devices.

Two main functions are provided by the CR mesh network. One is aggregating information from its end-users. For the i-th SSP, suppose that there are $\mathcal{K}_i = \{1, \cdots, K_i\}$ CR routers deployed in the network serving $\mathcal{L}_i = \{1, \cdots, L_i\}$ end-users. Each end-user requests one service, corresponding to L_i different services totally[2]. The information of service $\forall l \in \mathcal{L}_i$ includes its source/destination, data size, and bidding allowance denoted as s_l^i/d_l^i, z_l^i, and p_l^i, respectively, and each SSP aggregates its end-users' service information through their nearby CR routers on certain basic bands. The other function is admission control and transmission support for end-users. According to the aggregated information from the end-users and available bands in the market, each SSP bids for needed bands during the auction. Then, based on the auction outcome, following the schedule algorithm, each SSP broadcasts its admission decision using a basic band, charges each admitted end-user its bidding allowance, and provides its requested service in a multi-hop manner through its CR routers using

[2]In this paper, we do not consider the payoff caused by the choice of certain service of each end-user, and have made a simplified assumption that each end-user has a specific service request, including certain rate requirement and an affordable price, and submits to the SSP through the closest CR router. The strategy design on user side is beyond to the scope of this paper, and we leave it as one of our future works.

the purchased PSP's bands.

2) Auction-based Spectrum Market in Tier II: In Tier II, a series of multi-round auctions are held by a third-party auctioneer every time period T for access rights to the unoccupied bands in the next time period. As shown in Fig. 1, for the seller PSP, at the starting time of each auction period, it provides a fine-grained ASM and an IT to reveal the information of the available bands and regions in the next period T. An example of the fine-grained ASM is shown as Fig. 2. It has several overlapped zones, and each one represents an available region for certain unoccupied band, which is further divided into many blocks with corresponding specific location coordinates. The bands in separated zones can be either different or the same. Suppose that there are M bands available and each band m has Z_m available zones which cover Q_m available blocks. We denote band $\forall m \in \mathcal{M}$ within zone $\forall z \in \mathcal{Z}_m$ as m^z, and that within block $\forall q \in \mathcal{Q}_m$ as m_q. For ease of presentation, we use m, m_q, and m^z interchangeably to represent a band in the subsequent development. In this secondary spectrum market, for certain band $m \in \mathcal{M}$, if SSP$_i$, $\forall i \in \mathcal{N}$, wants to bid for it, it has to specify which blocks it wants to get, i.e., it has to bid for a bundle of m_q corresponding to all needed blocks, denoted as $\mathcal{B}^i_m$, and each element in this bundle, actually, is also a bundle including the band's index and the block's coordinates, denoted as $\{m,(x,y)\}$. Then, considering all desired bands, each SSP, actually, has to claim a 3-dimensional desired bundle (3D^2-bundle). Note that the 3D^2-bundle is purchased in an all-or-none manner, i.e., only part of this is unacceptable.

IT is provided as the supplement to the ASM including multi-dimensional information of band $\forall m \in \mathcal{M}$. First, it contains the specific spectrum range with bandwidth W_m and the available blocks' coordinates. Second, for each available block q, $q \in \mathcal{Q}_m$, a reserve price $\bar{p}_{m_q}$ required by the PSP is also included in the IT. Furthermore, as reported in [27], PUs' activities are diverse in different areas during different time periods. Therefore, to capture spatial variation in spectrum availability, we assume that the actual available bandwidth of band m within zone $\forall z \in \mathcal{Z}_m$ is a random variable, expressed as $\bar{W}_{m^z} \le W_m$. In order to help SSPs to take such an uncertainty into consideration, in the IT, D historical data for each m^z is also provided, respectively, representing the average available bandwidth of band m within zone z during the same time period everyday in previous D days [3], which are denoted as $\left\{\hat{W}^1_{m^z},\cdots,\hat{W}^D_{m^z}\right\}$.

For competing SSPs, they should submit their 3D^2-bundles to the auctioneer before the auction starts, i.e., within the first T_s, in each period. Considering CR router k of SSP$_i$ located within block $q \in \mathcal{Q}_m$, if SSP$_i$ wants to obtain band m for its data transmissions, it has to claim an exclusive area, i.e., specify certain needed blocks denoted as $\bar{\mathcal{Q}}^i_{m,k}$. On the one hand, no other SSPs can use band m in this area if it has been claimed already. On the other hand, the CR router k can transmit data using band m only within this area, i.e., no interference caused to other areas. For certain transmission power, the exclusive area can be described as a circle, with the CR router k as the center and the interference range as the radius, and the desired bundle of blocks, $\bar{\mathcal{Q}}^i_{m,k}$, corresponds to the minimal set of blocks covering this circle. For a band, we call it an available band to CR router k only when SSP$_i$ can find available blocks to cover the corresponding exclusive area, and we denote the available band set for SSP$_i$'s router k as $\mathcal{M}^i_k$.

3) Summary: After aggregating the information of services from users, according to the available bands of each router, each SSP optimally schedules its network transmissions to create its needed 3D^2-bundle, and submits to the auctioneer with certain bidding value. When the auction begins, the auctioneer determines winners and their charging prices[4]. After that, the sold blocks of bands will be deleted from the ASM, and each losing SSP can re-schedule its network transmissions according to the remaining ones and bids for them as the next auction round. The auction continues multiple rounds until no available bands on ASM or no participating SSPs is left, or this auction period is over[5]. Note that such an aggregation of service requests might make some 'rich' user fail to get his service although he has a high affordable price because his SSP, acting as his agent, might have a low traffic demand in the network. Furthermore, the aggregation needs to take some basic bands as control channels to support the reliable submission transmissions, which might introduce certain overhead for the network. However, due to the service-oriented approach, end-users could be relieved from the complex auction process and the overhead imposed on the network will not be too much. In addition, based on the aggregated information, each SSP could address the conflicting interests of his own users well, and the allocated spectrum can be used efficiently by each SSP.

B. Related Models for a Mesh Network of an SSP

1) Transmission Range and Interference Range: In our mesh network of SSP$_i$, $\forall i \in \mathcal{N}$, the data transmission from CR router k to g, $\forall k \neq g \in \mathcal{K}_i$, is considered as successful only if the received signal power exceeds a threshold denoted as P^T_{th}. We adopt a widely used model [29] to represent the power propagation gain from CR router k to g, described as $g^i_{kg} = \lambda \cdot \left(d^i_{kg}\right)^{-\beta}$, in which λ is an antenna related parameter, β is the path loss factor, and d^i_{kg} is the distance between the two routers. Denote the transmission power at the router k on

[3]Some methods can be used to obtain such data. For example, in [28], Yin et al. carried out a set of spectrum measurements in the 20MHz to 3GHz spectrum bands in Guangdong province of China, and conducted a set of analysis. Such spectrum measurement should be implemented in a large scale. Thus, we consider the spectrum uncertainty based on zones, rather than blocks, for the auctioned bands.

[4]It is noteworthy that although the auctioneer works as an centralized controller who determines the socially optimal resource allocation, the social welfare maximization cannot be achieved simply by solving an optimization problem because the true valuation of each buyer is unavailable to the auctioneer. Therefore, how to enforce buyers to bid truthfully is important for an auction mechanism, which makes the auction based approach distinctive.

[5]Such a multi-round auction mechanism can achieve more transactions in this market and thus generate higher revenue for both PSP and SSPs. Actually, many other mechanisms can also be adopted in the architecture to fulfill different design goals, such as the one introducing fairness among different SSPs as what have been developed in [7], the double auction dealing with several coexisting PSPs as TRUST in [6], the one using a greedy algorithm to determine winners as the computationally-efficient VERITAS in [5], etc.

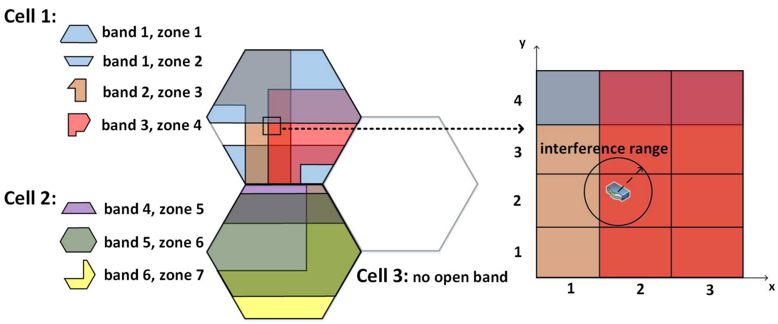

Fig. 2. An example of the fine-grained available spectrum map.

band m as $P^i_{k,m}$. Then, we can obtain its transmission range as $T^i_{k,m} = \left(P^i_{k,m} \cdot \lambda \big/ P^T_{th}\right)^{1/\beta}$. Accordingly, we define the transmission neighbors as

$$\mathcal{T}^i_{k,m} = \left\{g \in \mathcal{K}_i | d^i_{kg} \leq T^i_{k,m}, g \neq k, m \in \mathcal{M}^i_k\right\}. \quad (1)$$

Considering all available bands, then all transmission neighbors are $\mathcal{T}^i_k = \cup_{m\in\mathcal{M}^i_k} \mathcal{T}^i_{k,m}$.

Similarly, for each CR router, the received interference power from unexpected transmitters can be ignored only if it is less than a threshold P^I_{th} ($P^I_{th} < P^T_{th}$). Hence, there exists an interference range for CR router k as well when it transmits data on band m, which is just the radius of the aforementioned exclusive area and can be calculated as $I^i_{k,m} = \left(P^i_{k,m} \cdot \lambda \big/ P^I_{th}\right)^{1/\beta}$. Accordingly, we also define the interfered neighbors as

$$\mathcal{I}^i_{k,m} = \left\{g \in \mathcal{K}_i | d^i_{kg} \leq I^i_{k,m}, g \neq k, m \in \mathcal{M}^i_k\right\}, \quad (2)$$

and all interfered neighbors are $\mathcal{I}^i_k = \cup_{m\in\mathcal{M}^i_k} \mathcal{I}^i_{k,m}$.

2) Probabilistic Link Capacity with α-Confidence Level: Considering a link from CR router k to g on band $\forall m \in \mathcal{M}^i_k$, $\forall k \in \mathcal{K}_i$, $\forall g \neq k \in \mathcal{T}^i_{k,m}$, $\forall i \in \mathcal{N}$, according to Shannon-Hartley theorem, the link capacity can be expressed as

$$c^i_{kg,m} = W_m \cdot \log_2\left(1 + \frac{P^i_{k,m} \cdot g^i_{kg}}{\eta_g \cdot W_m}\right), \quad (3)$$

where η_g is the ambient Gaussian noise density at CR router g[6].

Nevertheless, as aforementioned, although the bandwidth of band $\forall m \in \mathcal{M}$ published by PSP is W_m, due to the uncontrollable PUs' activities, the actual available bandwidth is a random variable less than that, which causes that the actual link capacity is also random and less than that calculated by Eqn. (3). Therefore, to represent the uncertain capacity of a link, we introduce a probabilistic link capacity with α-confidence level called α-link capacity. To be specific, for the link k to g on band m^z, its α-link capacity, $\bar{c}^i_{kg,m^z,\alpha}$, is defined as

$$\bar{c}^i_{kg,m^z,\alpha} = \sup\left\{\bar{c} : \Pr\left\{\bar{W}_{m^z} \cdot \log_2\left(1 + \frac{P^i_{k,m^z} \cdot g^i_{kg}}{\eta_g \cdot \bar{W}_{m^z}}\right) \geq \bar{c}\right\} \geq \alpha\right\}, \quad (4)$$

[6]No interference is considered here owing to the interference constraints as shown in the following section.

in which $0 < \alpha < 1$. For example, let $\alpha = 0.9$, and the 0.9-link capacity obtained based on Eqn. (4) means that this link capacity can be 90 percent surely achieved.

C. Preliminaries for Spectrum Auctions

In this part, we clarify some concepts used in spectrum auctions [5], [26].

True Value: in an auction, for certain commodity, each buyer has a true value in his mind, i.e., the true price he is willing to pay. In the proposed MRSC spectrum auction, at round t, assume that SSP$_i$ wants to admit a set of end-users, denoted as $\hat{\mathcal{L}}^i_t \subseteq \mathcal{L}_i$. Then, its true value is equal to the sum of bidding allowances from all these end-users, i.e., $v^i_t = \sum_{l\in\hat{\mathcal{L}}^i_t} p^i_l$.

Bidding Value: at round t, SSP$_i$ has a bidding value denoted as b^i_t. Note that b^i_t may not be equal to v^i_t unless the auction mechanism can satisfy the truthfulness property.

Clearing Price: according to 3D^2-bundles and the corresponding bidding values from all competing SSPs, the auctioneer will determine a winner set at round t, denoted as $\mathcal{N}^*_t$, and charge winning SSP$_i$, $\forall i \in \mathcal{N}^*_t$, with certain price, which is called clearing price and denoted as $\hat{p}^i_t$, based on the auction mechanism.

Utility Function: for the seller PSP, we consider two types of utility. One is from a macro-perspective, and the utility at round t is the sum of clearing prices from all winning SSPs, denoted as $u^{\text{ma-p}}_t = \sum_{i\in\mathcal{N}^*_t} \hat{p}^i_t$. Such a macro-manner mainly focuses on the overall revenue at each auction round. The other one is from a micro-perspective, and the utility at round t is the gap between total income and the total reserve price of the sold items (band-block pairs). Different from the macro-manner aiming to sell items as many as possible, such a micro-manner pursues a higher individual revenue because the unsold items can be re-auctioned in the next round. Denote the sold bands at round t as $\hat{\mathcal{M}}_t \subseteq \mathcal{M}$ and the sold blocks of band $m \in \hat{\mathcal{M}}_t$ as $\hat{\mathcal{Q}}_{t,m} \subseteq \mathcal{Q}_m$. Then, the utility of PSP in micro-manner can be expressed as $u^{\text{mi-p}}_t = \sum_{i\in\mathcal{N}^*_t} \hat{p}^i_t - \sum_{m\in\hat{\mathcal{M}}_t} \sum_{q\in\hat{\mathcal{Q}}_{t,m}} \bar{p}_{m_q}$.

For buyer SSP$_i$, $\forall i \in \mathcal{N}$, its utility function at the t-th auction round is defined as

$$u^{\text{s},i}_t = \begin{cases} v^i_t - \hat{p}^i_t = \sum_{l\in\hat{\mathcal{L}}^i_t} p^i_l - \hat{p}^i_t, & \text{if SSP } i \text{ wins at round } t, \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

Social Welfare: the social welfare of an auction is the aggregate of utilities of all players, i.e., buyers and sellers. Hence, in the proposed MRSC spectrum auction, at round t, if the PSP is in the macro-manner, the social welfare of the market is

$$S_t^{\text{ma}} = u_t^{\text{ma-p}} + \sum_{i \in \mathcal{N}_t^*} u_t^{\text{s},i} = \sum_{i \in \mathcal{N}_t^*} v_t^i, \tag{6}$$

and if the PSP is in the micro-manner, that is

$$S_t^{\text{mi}} = u_t^{\text{mi-p}} + \sum_{i \in \mathcal{N}_t^*} u_t^{\text{s},i} = \sum_{i \in \mathcal{N}_t^*} v_t^i - \sum_{m \in \hat{\mathcal{M}}_t} \sum_{q \in \hat{\mathcal{Q}}_{t,m}} \bar{p}_{m_q}. \tag{7}$$

IV. Optimal Schedule with 3D^2-Bundle

In this section, we first present the constraints considered in the optimal scheduling when the SSP determines its 3D^2-bundle. Then we present the formulation of the optimization problem.

A. Interference Management

We exploit a binary value to describe the condition of the link from CR router k to g, $\forall k \in \mathcal{K}_i$, $\forall g \in \mathcal{T}_{k,m}^i$, $\forall i \in \mathcal{N}$, on band $\forall m \in \mathcal{M}_k^i$ as

$$x_{kg,m}^i = \begin{cases} 1, & \text{if band } m \text{ is allocated on link from } k \text{ to } g, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

For CR router k, first, it cannot transmit to or receive from multiple CR routers using the same band, which can be described as

$$\begin{aligned} &\sum_{g \in \mathcal{T}_{k,m}^i} x_{kg,m}^i \le 1, \forall m \in \mathcal{M}_k^i, \\ &\sum_{\{h | k \in \mathcal{T}_{h,m}^i\}} x_{hk,m}^i \le 1, \forall m \in \mathcal{M}_h^i. \end{aligned} \tag{9}$$

Furthermore, it cannot use the band m for transmitting and receiving simultaneously, due to the "self-interference" at physical layer. Thus, we have

$$\begin{aligned} &x_{hk,m}^i + \sum_{g \in \mathcal{T}_{k,m}^i} x_{kg,m}^i \le 1, \\ &\left\{ \forall h,\ \forall m : m \in \mathcal{M}_h^i \cap \mathcal{M}_k^i, k \in \mathcal{T}_{h,m}^i \right\}. \end{aligned} \tag{10}$$

Moreover, considering interference among different CR routers, if the CR router k is transmitting data on its available band $m \in \mathcal{M}_k^i$, all interfered neighbors cannot receive data on the same band m simultaneously. Hence we obtain

$$\begin{aligned} &x_{hj,m}^i + \sum_{g \in \mathcal{T}_{k,m}^i} x_{kg,m}^i \le 1, \\ &\left\{ \forall h, \forall m, \forall j : m \in \mathcal{M}_h^i \cap \mathcal{M}_k^i, j \in \mathcal{I}_{k,m}^i \cap \mathcal{T}_{h,m}^i \right\}. \end{aligned} \tag{11}$$

B. Flow Routing

For SSP$_i$, $\forall i \in \mathcal{N}$, we employ a binary variable to denote whether end-user l, $\forall l \in \mathcal{L}_i$, is admitted or not, which is expressed as

$$y_l^i = \begin{cases} 1, & \text{if end-user } l \text{ is admitted,} \\ 0, & \text{otherwise,} \end{cases} \tag{12}$$

and let $f_{kg}^i(l)$ represent the flow attributed to end-user l on link from CR router k to g, $\forall k \in \mathcal{K}_i$, $\forall g \in \mathcal{T}_k^i$. The flow balance equations are presented as follows.

Considering the service request submitted by the end-user l of SSP$_i$, since the data size requested to transmit in next time period T is z_l^i, the outgoing flow rate at the source CR router s_l^i should satisfy the rate requirement $r_l^i = z_l^i / T$. Meanwhile, the total incoming flow should be zero. Thus, we have

$$\begin{aligned} &\sum_{g \in \mathcal{T}_k^i} f_{kg}^i(l) \cdot y_l^i = r_l^i, \\ &\sum_{\{h | k \in \mathcal{T}_t^i\}} f_{hk}^i(l) \cdot y_l^i = 0, \forall l \in \mathcal{L}_i, \text{where } k = s_l^i. \end{aligned} \tag{13}$$

On the other hand, for the destination CR router d_l^i, there is no outgoing flow and the incoming flow rate should meet r_l^i, which can be written as

$$\begin{aligned} &\sum_{g \in \mathcal{T}_k^i} f_{kg}^i(l) \cdot y_l^i = 0, \\ &\sum_{\{h | k \in \mathcal{T}_t^i\}} f_{hk}^i(l) \cdot y_l^i = r_l^i, \forall l \in \mathcal{L}_i, \text{where } k = d_l^i. \end{aligned} \tag{14}$$

Then, consider an intermediate CR router $k \in \mathcal{K}_i$, i.e., $k \neq s_l^i$ and $k \neq d_l^i$. The incoming flow rate should be equal to outgoing flow rate, and thus we obtain the third constraint as

$$\sum_{\{h | k \in \mathcal{T}_h^i\}}^{h \neq d_l^i} f_{hk}^i(l) \cdot y_l^i = \sum_{g \in \mathcal{T}_k^i}^{g \neq s_l^i} f_{kg}^i(l) \cdot y_l^i, \forall l \in \mathcal{L}_i. \tag{15}$$

Furthermore, for link from CR router k to g, $\forall k \in \mathcal{K}_i$, $\forall g \in \mathcal{T}_k^i$, if it is feasible under the interference management, i.e., $\exists x_{kg,m}^i = 1$, $m \in \mathcal{M}_k^i$, the total flow arranged on it cannot exceed its capacity. Taking the uncertainty into consideration, we leverage the proposed α-link capacity and formulate the constraint as

$$\sum_{l \in \mathcal{L}_i}^{k \neq d_l^i, g \neq s_l^i} f_{kg}^i(l) \cdot y_l^i \le \sum_{\{m^z \in \mathcal{M}_k^i | g \in \mathcal{T}_{k,m^z}^i\}} \bar{c}_{kg,m^z,\alpha}^i \cdot x_{kg,m^z}^i, \forall l \in \mathcal{L}_i, \tag{16}$$

where $\bar{c}_{kg,m^z,\alpha}^i$ is the α-link capacity defined as in Eqn. (4).

C. Data-based Approximation for α-Link Capacity

To derive the α-link capacity, we need to obtain the probability density function (p.d.f.) of $\bar{W}_{m^z}$, $\forall m^z \in \mathcal{M}$, which is extremely difficult. Even though it might be available through certain spectrum measurements and analysis as mentioned in [22], [28], it would impose high overhead on the PSP and be still hard for SSPs to get the α-link capacity due to the complexity.

Generally, historical data of spectrum usage is relatively easy to record and open to the market. Therefore, in this subsection, we propose a data-based method to get an approximation for α-link capacity (DA-α-link capacity) according to the historical data of bandwidth. Recall the α-link capacity for link k to g on band m^z as in Eqn. (4). We rewrite it as

$$\bar{c}^i_{kg,m^z,\alpha}=\{\bar{c}:F(\bar{c})=\alpha\}\,,F(\bar{c})=\int_{h(\bar{W}_{m^z})\geq\bar{c}} f\left(\bar{W}_{m^z}\right)d\bar{W}_{m^z}, \tag{17}$$

where $f\left(\bar{W}_{m^z}\right)$ is the p.d.f. of $\bar{W}_{m^z}$ and

$$h\left(\bar{W}_{m^z}\right)=\bar{W}_{m^z}\cdot\log_2\left(1+\frac{P^i_{k,m^z}\cdot g^i_{kg}}{\eta_g\cdot\bar{W}_{m^z}}\right). \tag{18}$$

Inspired by Theorem 1 in [22], we construct a function and obtain the following theorem to achieve the DA-α-link capacity[7].

Theorem 1: For link from CR router k to g on band $\forall m^z\in\mathcal{M}^i_k$, $\forall k\in\mathcal{K}_i$, $\forall g\in\mathcal{T}^i_{k,m^z}$, $\forall i\in\mathcal{N}$, its α-link capacity is

$$\bar{c}^i_{kg,m^z,\alpha}=\arg\min_{\bar{c}}\xi(\bar{c})\,, \tag{19}$$

where

$$\xi(\bar{c})=\alpha\cdot\bar{c}+\int_{\bar{W}_{m^z}\in\mathcal{R}^+}\left[h\left(\bar{W}_{m^z}\right)-\bar{c}\right]^+\cdot f\left(\bar{W}_{m^z}\right)d\bar{W}_{m^z}, \tag{20}$$

where $[x]^+=\max\{0,x\}$.

Proof: Observing Eqn. (20), we can find that $\psi(\bar{c})=\left[h\left(\bar{W}_{m^z}\right)-\bar{c}\right]^+$ is convex, continuous, and subdifferentiable. Then, according to Proposition 2.1 in [30], we can obtain that its expected value function in terms of $\bar{W}_{m^z}$, denoted as $\mathbb{E}[\psi(\bar{c})]$, is also a convex and continuously subdifferentiable function, and

$$\frac{d}{d\bar{c}}\mathbb{E}[\psi(\bar{c})]=\mathbb{E}\left[\frac{d}{d\bar{c}}\psi(\bar{c})\right], \tag{21}$$

i.e.,

$$\begin{aligned}&\frac{d}{d\bar{c}}\int_{\bar{W}_{m^z}\in\mathcal{R}^+}\psi(\bar{c})\cdot f\left(\bar{W}_{m^z}\right)d\bar{W}_{m^z}\\&=\int_{\bar{W}_{m^z}\in\mathcal{R}^+}\frac{d}{d\bar{c}}\psi(\bar{c})\cdot f\left(\bar{W}_{m^z}\right)d\bar{W}_{m^z}.\end{aligned} \tag{22}$$

Therefore, we can conclude that $\xi(\bar{c})$ is convex and continuously subdifferentiable as well and

$$\begin{aligned}&\frac{d}{d\bar{c}}\xi(\bar{c})=\alpha+\int_{\bar{W}_{m^z}\in\mathcal{R}^+}\frac{d}{d\bar{c}}\psi(\bar{c})\cdot f\left(\bar{W}_{m^z}\right)d\bar{W}_{m^z}\\&=\alpha+\int_{h(\bar{W}_{m^z})\geq\bar{c}}\frac{d}{d\bar{c}}\left[h\left(\bar{W}_{m^z}\right)-\bar{c}\right]\cdot f\left(\bar{W}_{m^z}\right)d\bar{W}_{m^z}\\&=\alpha-F(\bar{c})\,.\end{aligned} \tag{23}$$

As a consequence, we note that for the stationary point $\bar{c}$ of $\xi(\bar{c})$, we also have $F(\bar{c})=\alpha$. Thus, based on the rewritten format as in (17), we can claim that finding the α-link capacity $\bar{c}^i_{kg,m^z,\alpha}$ is equivalent to finding the minimum value $\bar{c}$ of $\xi(\bar{c})$. ■

[7]It is noteworthy that the α-link capacity proposed in this paper is totally different from the X-loss addressed in [22]. Although we construct a similar function here, we aim to achieve the data-based approximation of the α-link capacity, which is a novel method proposed in this paper by considering the unavailability of the specific distribution of available spectrum bands.

According to Theorem 1, we next focus on the problem (19) and present the data-based approximation for $\bar{c}^i_{kg,m^z,\alpha}$, expressed as $\hat{c}^i_{kg,m^z,\alpha,D}$. Since the integral term in $\xi(\bar{c})$ is actually the expectation of $\psi(\bar{c})$, $\xi(\bar{c})$ can be approximated by using $\hat{W}^d_{m^z}$, $d=1,\cdots,D$, as the sample average of samples offered in the IT as

$$\tilde{\xi}(\bar{c})=\alpha\cdot\bar{c}+\frac{1}{D}\sum_{d=1}^{D}\left[h\left(\hat{W}^d_{m^z}\right)-\bar{c}\right]^+. \tag{24}$$

After that, by replacing $\xi(\bar{c})$ with its approximation $\tilde{\xi}(\bar{c})$ in problem (19), we can get the DA-α-link capacity through solving the following linear-programming (LP) problem.

$$\begin{aligned}&\hat{c}^i_{kg,m^z,\alpha,D}=\underset{\bar{c}}{\text{argmin}}\left\{\alpha\cdot\bar{c}+\frac{1}{D}\sum_{d=1}^{D}\theta_{m^z,d}\right\}\\&\text{s.t.}\quad\theta_{m^z,d}\geq h\left(\hat{W}^d_{m^z}\right)-\bar{c},\ \theta_{m^z,d}\geq0,\ d=1,\cdots,D.\end{aligned} \tag{25}$$

Therefore, the flow routing constraint (16) can be rewritten as

$$\sum_{l\in\mathcal{L}_i}^{k\neq d^i_l,g\neq s^i_l} f^i_{kg}(l)\cdot y^i_l\leq\sum_{\left\{m^z\in\mathcal{M}^i_k|g\in\mathcal{T}^i_{k,m^z}\right\}}\hat{c}^i_{kg,m^z,\alpha,D}\cdot x^i_{kg,m^z},\forall l\in\mathcal{L}_i. \tag{26}$$

D. Budget Balance

When the SSP schedules its network transmissions to develop certain 3D[2]-bundle, it should guarantee that the total bidding allowance from all admitted end-users can be higher than the total reserve price. We employ a binary variable to represent whether SSP$_i$ bids for $\bar{\mathcal{Q}}^i_{m,k}$ or not, which is described as

$$e^i_{m,k}=\begin{cases}1, & \text{if SSP}_i\text{ bids for }\bar{\mathcal{Q}}^i_{m,k}\text{ in the market,}\\0, & \text{otherwise.}\end{cases} \tag{27}$$

Accordingly, we have the following budget balance constraint as

$$\sum_{l\in\mathcal{L}_i}p^i_l\cdot y^i_l\geq\sum_{k\in\mathcal{K}_i}\sum_{m\in\mathcal{M}^i_k}\sum_{q\in\bar{\mathcal{Q}}^i_{m,k}}\bar{p}_{m_q}\cdot e^i_{m,k}. \tag{28}$$

Furthermore, note that for CR router k, $\forall k\in\mathcal{K}_i$, if band m, $m\in\mathcal{M}^i_k$, is abandoned by SSP$_i$, i.e., $e^i_{m,k}=0$, this CR router cannot transmit data on this band, i.e., $x^i_{kg,m}=0$, $\forall g\in\mathcal{T}^i_{k,m}$. Thus, we achieve an additional constraint as

$$\sum_{g\in\mathcal{T}^i_{k,m}}x^i_{kg,m}\leq e^i_{m,k},\forall k\in\mathcal{K}_i,\forall m\in\mathcal{M}^i_k. \tag{29}$$

E. Objective Function

For SSP$_i$, $\forall i\in\mathcal{N}$, the objective function is to maximize its own potential profit, calculated by $\sum_{l\in\mathcal{L}_i}p^i_l\cdot y^i_l-\sum_{k\in\mathcal{K}_i}\sum_{m\in\mathcal{M}^i_k}\sum_{q\in\bar{\mathcal{Q}}^i_{m,k}}\bar{p}_{m_q}\cdot e^i_{m,k}$. We call it potential profit because the final clearing price charged by the auctioneer may be higher than the reserve price. Although it is a potential profit, it can act as a token for SSPs, and prevent SSPs from

$$\text{OP:}\ \ \text{Max} \ \sum_{l\in\mathcal{L}_i} p_l^i \cdot y_l^i - \sum_{k\in\mathcal{K}_i}\sum_{m\in\mathcal{M}_k^i}\sum_{q\in\bar{\mathcal{Q}}_{m,k}^i} \bar{p}_{m_q}\cdot e_{m,k}^i$$
$$\text{s.t.}\quad (9),\ (10),\ (11)\ (13),\ (14),\ (15),\ (26)\ ,(28),\ (29)$$
$$x_{kg,m}^i \in \{0,1\} \quad (k\in\mathcal{K}_i, m\in\mathcal{M}_k^i, g\in\mathcal{T}_{k,m}^i),\ f_{kg}^i(l)\geq 0 \quad (k\neq d_l^i\in\mathcal{K}_i, g\neq s_l^i\in\mathcal{T}_k^i, l\in\mathcal{L}_i),$$
$$e_{m,k}^i\in\{0,1\} \quad (k\in\mathcal{K}_i, m\in\mathcal{M}_k^i),\ \ y_l^i\in\{0,1\} \quad (l\in\mathcal{L}_i),$$

purchasing more bands than what they need, i.e., SSP$_i$ bids for $\bar{\mathcal{Q}}_{m,k}^i$ only when it wants to use it on CR router k, otherwise, it will make $e_{m,k}^i = 0$ to maximize its potential profit. Thus, we obtain the optimization problem formulation as shown in the next page, in which r_l^i, $\hat{c}_{kg,m^z,\alpha,D}^i$, p_l^i, and $\bar{p}_{m_q}$ are given constants, and $x_{kg,m}^i$, $f_{kg}^i(l)$, $e_{m,k}^i$, and y_l^i are optimization variables. Note that the formulated problem is a mixed-integer non-linear programming (MINLP) problem. Since the non-linear part is only introduced by the multiplication in flow routing constraints that $f_{kg}^i(l)\cdot y_l^i$, we substitute it by one variable $F_{kg}^i(l)$ and the problem will turn to be a MILP. Although it is still generally NP-hard to solve [31], several promising solutions have been proposed such as branch and bound algorithm in [32], two-step algorithm in [33], heuristic algorithms in [34], etc., which can make SSPs capable of handling the computational complexity[8].

V. Social Welfare Maximizing Auction Mechanism

Social welfare, representing the total profit raised in the market, is a widely used metric for an auction. It comprehensively considers the benefit on both seller side and bidder side, and could lead to an efficient spectrum allocation. Thus, we take the social welfare maximization as the objective, which could make both sellers and bidders satisfied and motivate them to join the auction. Inspired by the well-known VCG auction, which can achieve the maximal social welfare by encouraging each bidder to bid truthfully [23]–[25], at each auction round, for each manner, we propose a social welfare maximizing auction mechanism, including the weighted conflict graph based socially optimal winner determination and the VCG-styled pricing mechanism[9]. Actually, the VCG auction has a serious deficiency, i.e., the high computation complexity, which makes it difficult to use in practice. To achieve the maximal social welfare, the auctioneer has to determine winners in an optimal fashion and calculate each winner's critical value as his clearing price based on the VCG pricing mechanism. The computation process is of high complexity and quickly becomes impractical as the number of buyers increases. Fortunately, in the proposed service-oriented two-tier spectrum market, the buyers are the SSPs, rather than the end-users. Therefore, the number of buyers can be reduced significantly and the corresponding calculations could be easily handled by the auctioneer.

A. Weighted Conflict Graph based Socially Optimal Winner Determination

Regarding the 3D^2-bundles and bidding values from all participating SSPs, we introduce a *weighted conflict graph* to characterize the conflict relationship among different SSPs and help the auctioneer make the socially optimal decision. At auction round t, for SSP$_i$, $\forall i\in\mathcal{N}$, we interpret it as a 3-dimensional-vertex (3D-vertex), including a 3D^2-bundle as $\hat{\mathcal{B}}_t^i$, a bidding value as b_t^i, and a weight as w_t^i which is equal to the social welfare it brings. Recall the social welfare for the two manners of the PSP, i.e., macro-manner and micro-manner, calculated by Eqn. (6) and Eqn. (7), respectively. Owing to the proposed VCG-styled price charging mechanism, each SSP is willing to take its true value as the bidding value (proved later), and thus we obtain that the weight for vertex i (SSP$_i$) under the macro-manner and the micro-manner is $w_t^{\text{ma},i} = b_t^i$ and $w_t^{\text{mi},i} = b_t^i - \sum_{m_q\in\hat{\mathcal{B}}_t^i} \bar{p}_{m_q}$, respectively. Considering arbitrary two vertices $i\neq j\in\mathcal{N}$, i.e., two different SSPs, towards each band that both of them want, if they have common desired blocks, i.e., $\mathcal{B}_m^i\cap\mathcal{B}_m^j\neq\emptyset$, then they conflict with each other and there is an edge between the two vertices. Therefore, based on the defined vertices and edges, a weighted conflict graph $\mathcal{G}_t = (\mathcal{V}_t,\mathcal{E}_t)$ can be constructed by the auctioneer at the round t. In the conflict graph, for a set of vertices $\hat{\mathcal{V}}\subseteq\mathcal{V}_t$, if any two of them have no conflict with each other, i.e., no edge exists between them, we call it an independent set (IS). Furthermore, if adding any other vertex into $\hat{\mathcal{V}}$ can cause it to be a non-independent set, then we call it a maximal independent set (MIS). For the auctioneer, the socially optimal winner determination is equivalent to searching for all MISs and finding the one with the maximal sum weight. Generally speaking, finding the socially optimal allocation is a NP-complete problem [31], and that is why most existing studies on spectrum auction endeavor to propose some computationally-efficient heuristic algorithms to achieve an approximate maximum social welfare. In this paper, since the bidders are SSPs, rather than end-users, the number of participants in the market is reduced dramatically, and thus the computational complexity is no longer an issue and can be easily handled by the auctioneer.

[8]Note that due to the optimal scheduling, the requirements of the PSP and the admitted end-users can be satisfied, which have been considered as some constraints when SSPs design their bidding strategies. Furthermore, the spectrum allocated to each winning SSP could be used efficiently and thus there is no wasted allocation in the market.

[9]In this paper, we treat the service based on the purchased bands from the market as a kind of value-added service aside from the basic service. Thus, we do not consider the fairness among different SSPs and only focus on the social welfare maximization. In fact, instead of the proposed VCG-styled mechanism, many other types of mechanisms can also be used here, such as the first-price auction and generalized second-price (GSP) auction with simpler auction process but without the guarantee on truthfulness, or English auction in the 'open outcry' manner but needs SSPs to increase their bids iteratively which makes the auction time-consuming.

B. VCG-styled Price Charging

Inspired by the VCG auction, we propose two pricing mechanisms for the two manners.

1) Macro-Manner: Assume that N_t SSPs participate in the auction round t. As aforementioned, for the macro-manner, the weight for vertex (SSP) $\forall i \in \mathcal{N}_t$ is equal to its own bidding value, i.e., $w_t^{\text{ma},i} = b_t^i$. Based on this, we denote the optimal winner determination, i.e., finding the maximal weighted MIS according to all participating SSPs' weights, $\mathbf{w}_t^{ma} = \mathbf{b}_t = \{b_t^i\}$, $i \in \mathcal{N}_t$, as a vector $\mathbf{a}(\mathbf{b}_t) = \{a_i(\mathbf{b}_t)\}$, $i \in \mathcal{N}_t$, where $a_i(\mathbf{b}_t) \in \{0,1\}$ represents whether SSP$_i$ wins or not. Then, by referring to the idea of VCG auction, the VCG-styled clearing price to winning SSP$_i$, $\forall i \in \mathcal{N}_t^*$, can be expressed as

$$p_{\text{VCG},t}^{\text{ma},i} = \sum_{j \neq i \in \mathcal{N}_t} b_t^j \cdot a_j\left(\mathbf{b}_t^{-i}\right) - \sum_{j \neq i \in \mathcal{N}_t^*} b_t^j, \tag{30}$$

where $\mathbf{b}_t^{-i} = \mathbf{b}_t \backslash \{b_t^i\}$ represent the situation that SSP$_i$ quits the auction. However, it is noteworthy that $p_{\text{VCG},t}^{\text{ma},i}$ cannot be adopted directly as the clearing price to SSP$_i$, $i \in \mathcal{N}_t^*$, because it cannot guarantee the reserve price of PSP, and even can be zero if it has no conflict with all others. Considering the 3D^2-bundle of the winning SSP$_i$, $\hat{\mathcal{B}}_t^i$, the clearing price should be able to cover the total reserve price, i.e., $\hat{p}_t^i \geq \sum_{m_q \in \hat{\mathcal{B}}_t^i} \bar{p}_{m_q}$. Therefore, we make an adjustment on the VCG-styled price and the final clearing price can be described as

$$\hat{p}_t^{\text{ma},i} = \max\left[p_{\text{VCG},t}^{\text{ma},i}, \sum_{m_q \in \hat{\mathcal{B}}_t^i} \bar{p}_{m_q}\right]. \tag{31}$$

2) Micro-Manner: For this manner, at auction round t, the weight of SSP$_i$, $\forall i \in \mathcal{N}_t$, is defined as how much higher it bids than the reserve price asked by the PSP, denoted as $w_t^{\text{mi},i} = b_t^i - \sum_{m_q \in \hat{\mathcal{B}}_t^i} \bar{p}_{m_q}$. According to the similar idea of the VCG-styled clearing price as Eqn. (30), the clearing price to winning SSP$_i$, $\forall i \in \mathcal{N}_t^*$, for the micro-manner is defined as

$$\hat{p}_t^{\text{mi},i} = \sum_{m_q \in \hat{\mathcal{B}}_t^i} \bar{p}_{m_q} + \left(\sum_{j \neq i \in \mathcal{N}_t} w_t^{\text{mi},j} \cdot a_j\left(\mathbf{w}_t^{\text{mi}-i}\right) - \sum_{j \neq i \in \mathcal{N}_t^*} w_t^{\text{mi},j}\right), \tag{32}$$

where $\mathbf{w}_t^{\text{mi}-i} = \mathbf{w}_t^{\text{mi}} \backslash w_t^{\text{mi},i}$.

3) Truthfulness: Truthfulness is an important property for the VCG auction that when other buyers' bids are fixed, no buyer can get a higher utility by biding untruthfully, and each buyer is willing to bid just as its own true value. In our auction mechanisms, similarly, the social welfare maximization can be achieved via the truthfulness property as well. In this subsection, we present the proof of the truthfulness of our auction mechanisms.

We first present two lemmas as follows.

Lemma 1: For each manner, at each round of the proposed MRSC spectrum auction, the socially optimal allocation is a monotonic allocation. In other words, for each manner, considering certain SSP$_i$, if it wins at this round, it can also win by bidding higher. On the contrary, if it loses at this round, it will also lose with a lower bidding value.

Lemma 2: For each manner, at each round of the proposed MRSC spectrum auction, the clearing price to each winning SSP is a critical value independent of its own bid. The critical value is a boundary value and each participating SSP has such a value that if this SSP can bid higher than it, it can win, otherwise, it will lose.

These two claims are not difficult to prove and thus we omit the proof here due to limited space. Then, according to these two lemmas, we give the following proposition.

Proposition 1: For each manner, at each round of the proposed MRSC spectrum auction, each participating SSP is willing to take the true valuation of its 3D^2-bundle as the bidding value.

Proof: Considering certain SSP i, assume that the bidding value is unequal to its true valuation, i.e., $b_t^i \neq v_t^i$. Then, four possible results exist when i bids truthfully and untruthfully, i.e., win and win, win and lose, lose and win, lose and lose. By the definition of truthfulness, we will show that in all four cases, SSP i's utility under the truthful bid is always better than that under the untruthful one, i.e., $u_t^{s,i}\left(v_t^i\right) \geq u_t^{s,i}\left(b_t^i\right)$.

We start with $b_t^i > v_t^i$. a) Case 1: i wins under both situations. According to Lemma 2, we can see that in both cases, SSP i will be charged the same price which is a critical value independent of its bid. Thus, $u_t^{s,i}\left(v_t^i\right) = u_t^{s,i}\left(b_t^i\right)$. b) Case 2: i wins with v_t^i but loses with a higher bid b_t^i. By Lemma 1, this situation cannot happen. c) Case 3: i loses with v_t^i but wins with b_t^i. Since the charging price is the critical value (Lemma 2), we have $b_t^i > \hat{p}_t^i > v_t^i$. Then we observe that although the untruthfully bidding manner makes i win the auction, its utility is negative ($v_t^i - \hat{p}_t^i < 0$). Hence, $u_t^{s,i}\left(v_t^i\right) = 0 > u_t^{s,i}\left(b_t^i\right)$. d) Case 4: i loses under both situations. The claim still holds that $u_t^{s,i}\left(v_t^i\right) = u_t^{s,i}\left(b_t^i\right) = 0$.

Next we consider the scenario that $b_t^i < v_t^i$. a) Case 1: This case is the same as the Case 1 above. b) Case 2: From Lemma 2, we have $b_t^i < \hat{p}_t^i < v_t^i$. Then truthfully bidding manner can win the auction and achieve a positive utility, i.e., $u_t^{s,i}\left(v_t^i\right) > u_t^{s,i}\left(b_t^i\right) = 0$. c) Case 3: Based on Lemma 1, this case cannot happen. d) Case 4: This case is the same as the Case 4 above.

In summary, we have proved that in all possible cases, bidding truthfully can always make its utility no less than bidding untruthfully. Thus, there is no reason for each participating SSP to bid unequal to its true valuation. ■

VI. Performance Evaluation

A. One-Shot Experiment

First, we present an one-shot experiment to illustrate the operation of the proposed MRSC spectrum auction. We consider a 1000×600 m^2 grid network with 3 SSPs owning 9 CR routers respectively as Fig. 3. SSP$_1$ has two requests as ($7 \rightarrow 5$, $r_1^1 = 6$Mbps, $p_1^1 = 20$) and ($1 \rightarrow 3$, $r_2^1 = 1.3$Mbps, $p_2^1 = 10$), respectively. SSP$_2$ has three requests as ($5 \rightarrow 1$, $r_1^2 = 6$Mbps, $p_1^2 = 19$), ($5 \rightarrow 1$, $r_2^2 = 4$Mbps, $p_2^2 = 7$) and ($5 \rightarrow 7$, $r_3^2 = 5$Mbps, $p_3^2 = 17$), respectively. SSP$_3$ has one request as ($6 \rightarrow 4$, $r_1^3 = 7$Mbps, $p_1^3 = 25$). Assume that 4 bands are opened by the PSP and each one is available to all CR routers in all 15 blocks. The 4 numbers in each block in

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TABLE II
INFORMATION OF THE 4 UNOCCUPIED BANDS

band	bandwidth	historical data (MHz)												
1	0.4MHz	0.34	0.37	0.13	0.37	0.28	0.12	0.18	0.26	0.38	0.38	0.14	0.39	0.38
2	1.8MHz	1.54	1.19	1.45	0.97	1.50	0.83	1.07	0.84	0.89	1.62	1.49	1.11	1.75
3	4.0MHz	2.06	2.87	2.76	3.53	3.59	2.37	2.97	2.89	3.29	3.41	3.50	2.55	3.35
4	5.5MHz	4.21	5.00	3.35	4.05	5.28	4.98	5.39	4.63	3.08	5.12	5.33	4.69	4.89

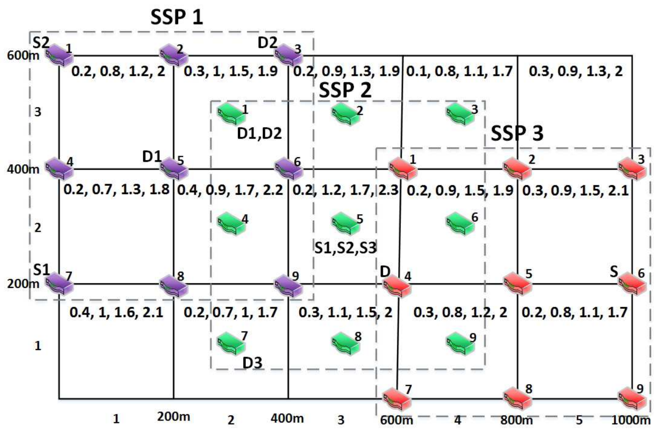


Fig. 3. Topology of the grid network for one-shot experiment.

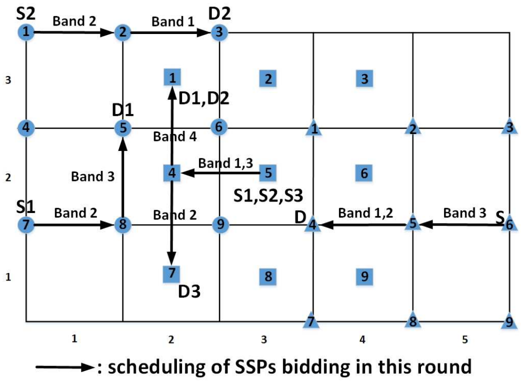


Fig. 4. Round 1 of MRSC spectrum auction for both manners.

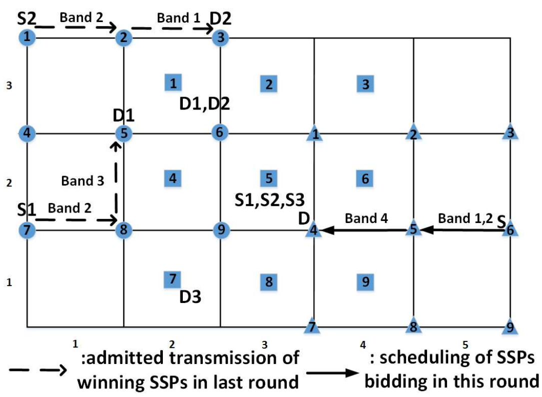


Fig. 5. Round 2 of MRSC spectrum auction for micro-manner.

Fig. 3 represent the reserve price of the 4 bands within this block and some other information including the bandwidth and 13 sets of historical data is shown in Table II. For the 3 SSPs, suppose that they have the same parameter $\beta = 4$ and $\lambda = 4$, the same noise density power at each CR router $\eta = 10^{-16}$W/Hz , and the same transmission power at each CR router on each band as 5W with a transmission/interference range as 210m and 350m, respectively.

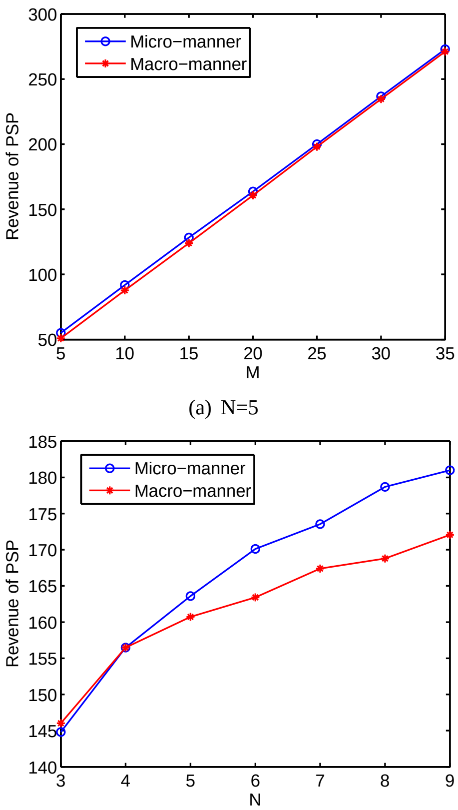
As two levels of QoS promised by SSPs, we consider two confidence levels for probabilistic link capacity adopted by each SSP. We regard α as a constant during this one-shot experiment representing certain specific QoS. First, let $\alpha = 0.8$. According to the network topology shown as Fig. 3, the assumption about the same noise density power at each node, and the historical data presented in Table II, we can derive that the DA-α-link capacity for each link is the same as 1.37Mbps, 6.36Mbps, 14.39Mbps, and 20.23Mbps, corresponding to the four bands. The optimal scheduling of each SSP is shown as in Fig. 4. Accordingly, the bidding values of the 3 SSPs are 30, 43, and 25, respectively, and the total reserve prices of their desired blocks are 18.4, 40.9, and 18.2, respectively. Obviously, 3 SSPs conflict with each other. Firstly, considering the macro-manner, since the bid of SSP_2 is the maximum, it becomes the winner and the corresponding clearing price is $\max(40.9, 30) = 40.9$ according to Eqn. (31). The auction only has one round for this manner because all bands within the middle region have been sold to SSP_2, and SSP_1 and SSP_3 cannot find any bundled remaining bands to support any service. Next, consider the micro-manner. For this manner, SSP_1 will turn to be the winner because it can bring the maximal social welfare as $(30 - 18.4) = 11.6$, and the corresponding clearing price is $18.4 + 6.8 = 25.2$ based on Eqn. (32). Note that different from the macro-manner, for this manner, the auction has the second round as shown in Fig. 5. According to the remaining available blocks of bands, SSP_2 quits the auction, but SSP_3 has an updated 3D^2-bundle by re-scheduling its own network.

Next, we consider $\alpha = 0.95$, representing a higher quality assurance compared with $\alpha = 0.8$. Accordingly, a smaller DA-α-link capacity will be adopted for each link, which can be calculated as 1.20Mbps, 6.01Mbps, 12.25Mbps, and 16.56Mbps, on the four bands. Such a stricter constraint can make each admitted end-user satisfy with the rate requirement with a high probability. Nevertheless, some scheduling by each SSP under $\alpha = 0.8$ might be not available any more due to the increase of the confidence level, such as the scheduling for SSP_1's user from node 1 to 3 by using band 1 and 2 as shown in Fig. 4. Furthermore, it is noteworthy that compared with the traditional commodity-oriented manner, in which users bid for specific bands by themselves, the proposed service-oriented manner could make more users get what they want. To be specific, users usually do not know others' bidding targets and thus serious conflicting interests may occur among different users. By introducing SSPs as centralized controllers, such a conflict among different users belonging to the same SSP could be addressed well due to the optimal scheduling. For example, considering the three users of SSP_2, all of them request the service from node 5. Thus, it is hardly to make all of them get their services if they participate in the auction by themselves.

B. Multi-Shot Experiments

In this subsection, we present several multi-shot experiments to capture the characteristics of the two manners, i.e., macro-manner and micro-manner, and demonstrate the effectiveness of the proposed MRSC auction. Since the objective here is to evaluate the performance of the proposed auction mechanisms, we make some simplified assumptions without the consideration of the specific transmission in Tier I. In particular, we simply assume that M bands are available within all regions, and N SSPs bid for them. Each SSP wants certain combination of some of these bands within all regions, and each band has a random reserve price within $[5, 10]$.

First, we discuss the different characteristics and suitable scenarios for the two manners through Fig. 6 and Fig. 7 by observing the revenue of the PSP. Generally speaking, as for the two manners, the macro-manner standing on the view of the whole revenue should be more suitable for single-round auctions, but for multi-round auctions, micro-manner focusing on the individual revenue should be better which can generate more profit for the PSP. To be specific, the PSP's revenue generated in the first round of MRSC auction based on the two manners are presented in Fig. 6 in terms of different numbers of bands, in which $N = 4$ and the desired bands of each SSP are selected randomly from all M bands. The bidding value of each SSP is a random value within the range from the total reserve price to that added 20. From Fig. 6, we can see that in a single round, in general, macro-manner can generate much more profit for the seller PSP, especially when the number of bands is large. That is because if the auction only has one round, all bands only have one chance to be sold and thus taking the whole revenue as the objective should be better. Nevertheless, when the auction is held multiple rounds as the proposed MRSC auction, the micro-manner will present its advantage as shown in Fig. 7. Specifically, Fig. 7 shows the average revenue of PSP gained from the multi-round auction based on 1000 times of simulation. For the multi-round auction, the setting in the first round is the same as that in Fig. 6, and in the next round, all sold bands are removed from the market and each remaining SSP bids for a random combination from remaining bands with a random bidding value, which is higher than the total reserve price but with a smaller gap than that in the last round corresponding to a suboptimal scheduling. From Fig. 7, we can observe the superiority of the micro-manner even when the number of bands is large. The reason is that when multiple rounds exist, the unsold bands in each round can be re-auctioned in the next round. Therefore, pursuing a higher individual revenue as the micro-manner can achieve a better revenue.



(a) N=5

(b) M=20

Fig. 7. Average revenue of PSP in MRSC spectrum auction for macro-manner and micro-manner.

Next, we show the social welfare generated by the MRSC auction mechanism in Fig. 8 with $M = 20$ and $N = 5$. Compared with commodity-oriented single-round truthful auctions, the MRSC auction mechanism has two characteristics. The first one is the optimal winner determination. Since the bidders in the market are the SSPs, the number of bidders has been reduced significantly and thus the optimal winner determination can be easily achieved with a relatively low computation complexity. The other one is the multi-round auction manner. It enables the losing SSPs at each round to re-schedule its network transmissions and join the following auction rounds. To reflect these two characteristics, we take a well-known single-round truthful auction, i.e., VERITAS in [5], as an example to make a comparison. From Fig. 8, we can find that the social welfare of the MRSC auction is much better for both manners. On the one hand, multiple rounds are held in MRSC auction, which makes the auction more flexible and facilitates more transactions in the market. On the other hand, at each round, MRSC auction mechanism selects an optimal winner set to achieve a maximal social welfare but VERITAS may only achieve a suboptimal one by a greedy algorithm.

Finally, we illustrate the utility of an arbitrary SSP in a single round with truthful bid and untruthful bid in Fig. 9. As a rational bidder, we consider two possible situations that he might bid untruthfully to gain more profit, i.e., if he could win, we set a lower bid for him which could keep him winning,

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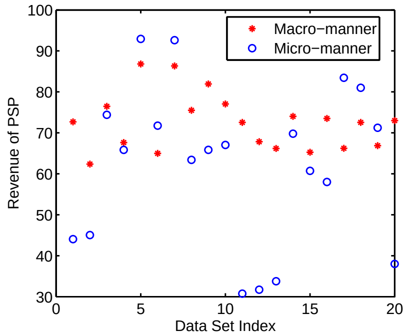
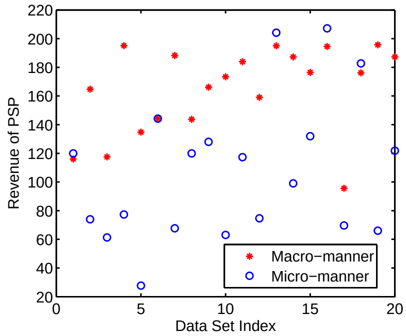
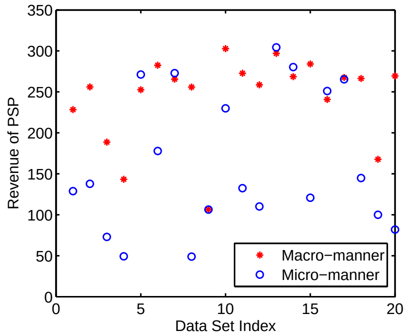


(a) M=10

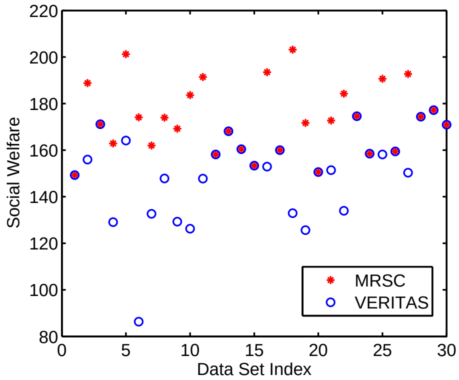


(b) M=25

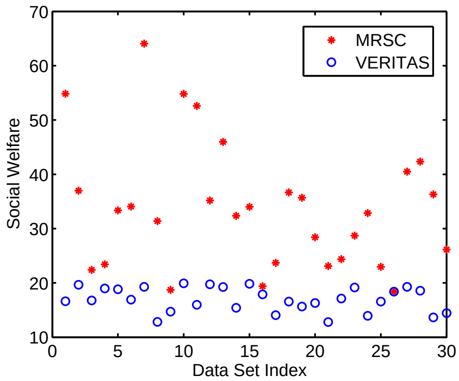


(c) M=40

Fig. 6. The revenue of PSP in one auction round for macro-manner and micro-manner.

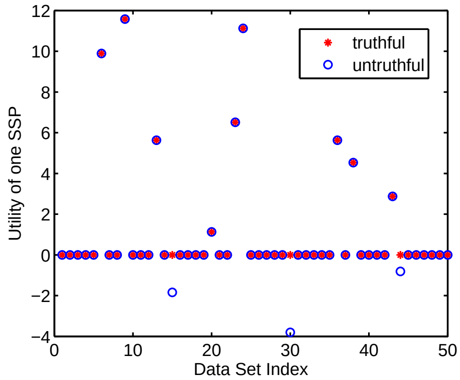


(a) Social welfare for macro-manner.

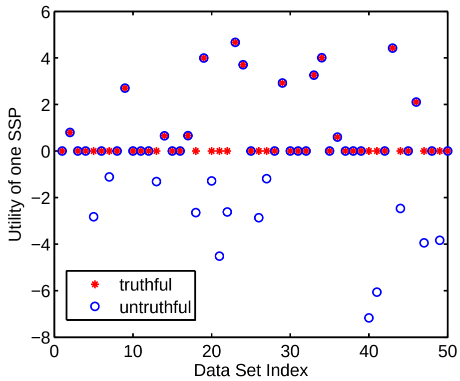


(b) Social welfare for micro-manner.

Fig. 8. Social welfare of MRSC and VERITAS auction mechanisms.



(a) macro-manner.



(b) micro-manner.

Fig. 9. Utility of an arbitrary SSP with truthful bid and untruthful bid

otherwise, we add a random value within $[0, 10]$ on his truthful bid as the untruthful one. In Fig. 9, 50 data sets represent 50 independent experiments, and at each time, we consider $M = 30$ and $N = 5$, and other settings are the same with those in Fig. 6. Comparing the two bidding strategies in Fig. 9, we can see that in both manners, the SSP cannot gain higher revenue by bidding untruthfully. Specifically, if it lowers the bid and keeps winning, the utility cannot be increased because the charging price keeps constant as the critical value independent with its own bid. If it raises the bid to avoid being a loser, although it might win the auction, it will achieve a negative utility because the charging price will be higher than its true valuation. In summary, the utility of the SSP with untruthful bid is always no more than that with truthful bid and thus each SSP is willing to bid truthfully.

VII. Conclusion

In order to benefit end-users from the spectrum market without joining the auction by themselves, in this paper, we have proposed a service-oriented spectrum auction scheme with a two-tier architecture. By leveraging SSPs as admission controllers, bidding agents, and service providers, the original stringent requirements on users' side are relieved and shifted to the SSPs' side, which makes the auction-based spectrum sharing in CR networks much more practical. In the proposed MRSC auction, we consider the detailed information of each band and propose a new metric called α-link capacity to handle the spectrum uncertainty. Furthermore, with two possible operational manners of the seller PSP, we have developed two social welfare maximizing auction mechanisms accordingly and analyzed the performance through extensive simulations. We expect that the proposed approach opens a new research direction in spectrum auction for CR networks. As our future works, we will further consider the specific payoff of each end-user and introduce the fairness in the market.

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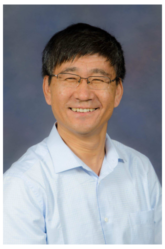
Xuanheng Li (S'13) is currently pursuing the Ph.D. degree in Communication and Information System at Dalian University of Technology. He received the B.S. degree in Electronic and Information Engineering from Dalian University of Technology, Dalian, China, in 2012. From Oct. 2015 to now, he is with the Wireless Networks Laboratory (WINET) at the University of Florida as a visiting student. He received the Best Paper Award at IEEE Globecom 2016. He serves as a reviewer for IEEE Transactions on Vehicular Technology, IEEE Communications Letters, IEEE Internet of Things Journal, Infocom, etc. His research interests include Interference Alignment, Cognitive Radio Networks, Green Communications, and Underwater Communications.

Haichuan Ding is currently a Ph.D. student at the University of Florida. He received the B.Eng. and M.S. degrees in electrical engineering from Beijing Institute of Technology (BIT), Beijing, China, in 2011 and 2014, respectively. From 2012 to 2014, he was with the Department of Electrical and Computer Engineering, the University of Macau, as a visiting student. During his M.S. studies, he mainly worked on the analysis of HARQ techniques using the tools of stochastic geometry. His current research is focused on cognitive radio networks, vehicle networks and security and privacy in distributed systems.

Miao Pan (S07-M12) received his BSc degree in Electrical Engineering from Dalian University of Technology, China, in 2004, MASc degree in electrical and computer engineering from Beijing University of Posts and Telecommunications, China, in 2007 and Ph.D. degree in Electrical and Computer Engineering from the University of Florida in 2012, respectively. He is now an Assistant Professor in the Department of Electrical and Computer Engineering at University of Houston. He was an Assistant Professor in the Computer Science at Texas Southern University from 2012 to 2015. His research interests include cognitive radio networks, cyber-physical systems, and cybersecurity. His work on cognitive radio network won Best Paper Award in Globecom 2015. Dr. Pan is currently Associate Editor for IEEE Internet of Things (IoT) Journal. He is a member of IEEE.

Yi Sun (M'06) is currently a professor of the School of Information and Communication Engineering at Dalian University of Technology. She received her Ph.D. degree in Optical Engineering at Dalian University of Technology, Dalian, China, in 2002. From Sep. 2006 to Mar. 2007, she visited Stanford University as a senior visiting scholar. Her research interests include Interference Alignment, Cognitive Radio Networks, Green Communications, and Underwater Communications.



Yuguang Fang (F'08) received an MS degree from Qufu Normal University, Shandong, China in 1987, a Ph.D degree from Case Western Reserve University in 1994, and a Ph.D. degree from Boston University in 1997. He joined the Department of Electrical and Computer Engineering at University of Florida in 2000 and has been a full professor since 2005. He held a University of Florida Research Foundation (UFRF) Professorship (2006-2009), a Changjiang Scholar Chair Professorship with Xidian University, China (2008-2011) and with Dalian Maritime University, China (2015-present), and a Guest Chair Professorship with Tsinghua University, China (2009-2012).

Dr. Fang received the US National Science Foundation Career Award in 2001 and the Office of Naval Research Young Investigator Award in 2002, 2015 IEEE Communications Society CISTC Technical Recognition Award, 2014 IEEE Communications Society WTC Recognition Award, and the Best Paper Award from IEEE ICNP (2006). He has also received a 2010-2011 UF Doctoral Dissertation Advisor/Mentoring Award, 2011 Florida Blue Key/UF Homecoming Distinguished Faculty Award, and the 2009 UF College of Engineering Faculty Mentoring Award. He is the Editor-in-Chief of IEEE Transactions on Vehicular Technology, was the Editor-in-Chief of IEEE Wireless Communications (2009-2012), and serves/served on several editorial boards of journals including IEEE Transactions on Mobile Computing (2003-2008, 2011-present), IEEE Transactions on Communications (2000-2011), and IEEE Transactions on Wireless Communications (2002-2009). He has been actively participating in conference organizations such as serving as the Technical Program Co-Chair for IEEE INOFOCOM2014 and the Technical Program Vice-Chair for IEEE INFOCOM'2005. He is a fellow of the IEEE and a fellow of the American Association for the Advancement of Science (AAAS).