Collaborative Spectrum Trading and Sharing for Cognitive Radio Networks

Xuanheng Li, Haichuan Ding, Yuguang Fang, Miao Pan, Pan Li,
Xiaoxia Huang, and Savo Glisic

Abstract

Spectrum trading is one of the most promising approaches to enabling dynamic spectrum access (DSA) in cognitive radio networks (CRNs). With this approach, unlicensed users (a.k.a. secondary users) offer licensed users (a.k.a. primary users) with monetary rewards or improved quality of services (QoSs) in exchange for spectrum access rights. In this chapter, we present a comprehensive introduction to spectrum trading. First, we provide a brief introduction to DSA and CRNs as the background and motivation for the spectrum trading. Then,

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X. Li (✉)
School of Information and Communication Engineering, Dalian University of Technology, Dalian, Liaoning, China
e-mail: lixuanheng@mail.dlut.edu.cn

H. Ding • Y. Fang
Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL, USA
e-mail: dhcbit@gmail.com; fang@ece.ufl.edu

M. Pan
Department of Electrical and Computer Engineering, University of Houston, Houston, TX, USA
e-mail: mpan2@uh.edu

P. Li
Department of Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, OH, USA
e-mail: lipan@case.edu

X. Huang
Shenzhen Institutes of Advanced Technology, China Academy of Sciences, Shenzhen, Guangdong, China
e-mail: xx.huang@siat.ac.cn

S. Glisic
Department of Communication Engineering, University of Oulu, Oulu, Finland
e-mail: savo.glisic@ee.oulu.fi

W. Zhang (ed.), *Handbook of Cognitive Radio*,
DOI 10.1007/978-981-10-1389-8_27-1

we present various state-of-the-art spectrum trading mechanisms for spectrum sharing. Finally, by analyzing various design issues in these mechanisms, we introduce the concept of service-oriented spectrum trading and offer a novel collaborative network architecture, called a cognitive mesh assisted network, to effectively utilize unused licensed/unlicensed spectrums with high spectral efficiency. We expect that this chapter provides readers with basic understanding on spectrum trading technology and foster future research initiatives.

Keywords
Dynamic spectrum access • Cognitive radio networks • Spectrum trading • Cognitive mesh assisted networks • Game theory • Auction theory

Contents

Introduction

In recent years, the popularity of smart devices, such as smartphones and tablets, and wireless services, such as mobile health (mHealth), online social networking, and mobile gaming, has led to the exponential growth in data traffic. According to the Cisco Visual Networking Index, mobile traffic has raised up to almost 400-million-fold over the past 15 years through the end of 2015 and will continue to grow by about eightfold between 2015 and 2020 [1]. This surge of data traffic will ultimately cause congestion over existing telecommunication systems, which calls for more spectrum resource. Nevertheless, current spectrum allocation adopted by Federal Communications Commission (FCC) is static and inefficient because spectrums are licensed to authorized users (a.k.a. licensed users) for long-term (often for 10 or more years with possible renewal) prespecified service provisioning across a relatively large geographical region. Licensees cannot change the type of use or transfer the right to others, and thus the current spectrum allocation policy is commonly referred to as the static spectrum access (SSA) [2]. Obviously, the SSA scheme is inflexible and leads to low spectrum utilization because the right to access certain spectrum bands is only limited to license owners even if the band is temporally or spatially unoccupied. Experimental tests in academia and measurements conducted in industries both show that even in some big cities with dense populations, many licensed spectrum bands have surprisingly low utilization (e.g., less than 20% on average in Chicago city across all bands [3]). The conflicts between high demands for spectrum resources and inflexibility in SSA have spurred government to open the discussions on intelligently sharing licensed spectrums. As reported by the President's Council of Advisors on Science and Technology (PCAST) in July 2012, exclusive licensing is not the way to stepping forward, and advanced spectrum sharing should become the new paradigm, which has the potential to transform spectrum scarcity into abundancy [4]. In July 2016, US National Science Foundation (NSF) declared an investment of over $400 million to foster advanced wireless research, and dynamic spectrum sharing, also known as dynamic spectrum access (DSA), is regarded as a promising research direction [5].

Dynamic Spectrum Access

As defined in [6], DSA can be treated as the near-real-time adjustment of spectrum usage toward varying environments, operating states (e.g., operational modes, battery life, location, etc.), and external constraints (e.g., propagation characteristics, operational policies, etc.). In general, DSA schemes can be categorized into the following three models [7].

Spectrum Commons Model

In this model, also referred to as the open sharing model, spectrum resources are openly shared among different users. All users have equal rights to access a spectrum band once they obey certain operational rules. For example, unlicensed industrial, scientific, and medical (ISM) radio bands (e.g., WiFi) are used under this open sharing model. The phenomenal success of WiFi networks has motivated mobile operators to take advantage of the spectrum commons model for traffic offloading purpose. To be specific, instead of using their cellular networks, cellular operators can offload some broadband services to WiFi networks and save precious cellular bands for more QoS stringent services. In such a way, WiFi-offloading technique could help relieve high demands on cellular bands and mitigate congestion in cellular networks. However, it mainly targets at delay-tolerant services and the quality of service (QoS) cannot be guaranteed. Having in mind that cellular networks and WiFi networks adopt different spectrum access schemes, how to effectively manage interference among accessing users in such a heterogeneous network is one of the most important issues to address for this model. Otherwise, packet collisions and retransmissions will seriously degrade the performance of these networks, particularly the WiFi networks, which will lead to low network throughput.

Hierarchical Access Model

In this model, users are classified into two types. One is the license owners, a.k.a. primary users (PUs), and the other is the unlicensed users, a.k.a. secondary users (SUs). Hierarchical access-based spectrum sharing allows SUs to access the PUs' spectrum with limited interference imposed on them, which is thus also referred to as the shared use model (note that, unlike the open sharing model, the users in this model have different priorities). Two approaches, i.e., the *underlay* and the *overlay* approaches, can be adopted by SUs when they access the PUs' spectrums [8].

In the underlay approach, SUs and PUs can transmit over the same spectrum simultaneously, but SUs should comply with restrictions on their transmit power so that the interference imposed on primary receivers does not exceed certain level (also known as interference temperature) [9]. Generally speaking, the optimal underlay spectrum sharing can be formulated as an optimization problem with a suitable objective function reflecting the performance of secondary network and a set of constraints with different considerations, such as fairness, quality of service (QoS), interference management, etc., which can be mathematically expressed as

$$\begin{aligned} &\text{Max} \quad f\left(R_1, \cdots, R_n\right) \\ &\text{s.t.} \quad R_i \geq R_{\text{th}}^i,\ \forall i \in \{1, \cdots, n\}; \quad \sum_{i=1}^{n} h_{ij} \cdot p_i \leq I_{\text{th}}^j,\ \forall j \in \{1, \cdots, m\}. \end{aligned} \tag{1}$$

Here, R_i, R_{th}^i, and p_i denote the achievable rate, the minimal guaranteed rate, and the transmit power of the i-th SU, respectively, h_{ij} is the channel gain from the i-th secondary transmitter to the j-th primary receiver, and I_{th}^j signifies the maximum tolerable interference level (threshold) on the j-th primary receiver. To satisfy the stringent limits on interferences for PUs, some sophisticated power control schemes for secondary transmitters can be adopted. Furthermore, if the constraints are too strict and/or the network load is too high, admission control mechanisms can be embedded as well to limit the number of admitted SUs. Moreover, beamforming techniques can also be jointly considered with power control to improve the performance of the secondary network. In addition to power control, SUs can also use spread-spectrum techniques (i.e., spread transmitted signals over a wide frequency band) to achieve short-range high-rate transmissions with extremely low power to avoid interference to the narrowband transmissions of the PUs.

In the overlay approach, there is no strict limits on SUs' transmission powers. Instead, SUs exploit spectrum white spaces (spectrum holes), i.e., spatially and/or temporally unoccupied parts of the spectrum, and access them opportunistically. Therefore, different from the interference control approach (underlay), to adopt the interference avoidance approach (overlay), SUs need to have the knowledge about spectrum holes so that they can ensure no interference caused to PUs. To gather the timely and accurate information about the usage of PUs' spectrum, either noncooperative or cooperative way can be employed. In the former case, SUs must have the ability to perceive and analyze the surrounding radios by using various spectrum sensing methods. This could accomplish the noninterfering communications between PUs and SUs. In the latter case, the exclusive spectrum usage information is provided by PUs. Since PUs cannot get any benefit from sharing spectrum with SUs and thus usually have no motivation to participate in the spectrum sharing process, this approach mainly applies to the government-issued cases or the spectrum trading market where PUs lease/sell their unused spectrum resources to SUs in order to create additional revenue. A typical example of overlay spectrum sharing is the approval by FCC in November 2008 of the unlicensed use of the TV white spaces (TVWS) (54–72, 76–88, 174–216, and 470–806 MHz bands, which have superior radio propagation characteristics) based on spectrum sensing as well as consultation with an FCC-mandated database. In September 2010, FCC released new rules for the use of white space for unlicensed wireless devices, which removed the mandatory sensing requirements and facilitated the use of the spectrum with geolocation-based channel allocation. In the TVWS, the TV broadcasting stations and low-power wireless microphones are PUs, and the secondary systems such as the IEEE 802.22-based WRANs, the WiFi hot-spots, and home networks can coexist in an overlay sharing manner.

Dynamic Exclusive Use Model

This model is the closest to the current spectrum regulation policy (spectrum licenses are granted for exclusive use by the corresponding licensees) but in a more flexible way and at smaller time scale, which improves spectrum efficiency. Two approaches, namely, *spectrum property rights transfer* and *dynamic spectrum allocation*, have been proposed under this model. The former approach makes the spectrum property rights transferable from one licensee to another. In order to explore the most profitable use of the spectrum resource, economic market is adopted as an important method, which leads to spectrum trading. To be specific, in general, three factors, i.e., time, geographic area, and spectrum frequency, can be used to specify the spectrum property rights. Based on this approach, the spectrum licensees are allowed to flexibly sell or lease portions of their spectrums, such as the unused bands, to SUs and authorize them to use in certain geographic areas during certain time periods, which in turn creates revenue return for themselves. Note that spectrum trading is not limited to this model. For example, the shared-use-based spectrum trading model also exists, which is very practical because in some cases it is difficult for licensees to give up their precious spectrum rights considering the unpredictable demands in the future. Such a shared-use-based spectrum trading model has been implemented by FCC on 3.5 G band [2], which will be introduced in detail in section “The State-of-the-Art of Spectrum Trading”. The latter approach is introduced by the European DRiVE project [10]. Such an approach aims to improve spectrum efficiency through dynamic spectrum assignment according to the spatial and temporal traffic statistics of different services. Similar to the current static spectrum licensing policy, this approach allocates spectrums to services for exclusive use, but the spectrum relocation occurs at a much smaller scale.

Cognitive Radios

With regard to the aforementioned DSA models, hierarchical access-based spectrum sharing has attracted increasing attention and been treated as a promising solution to the low spectrum utilization problem in the traditional SSA scheme. It allows unlicensed users to access a licensed spectrum under certain restrictions, which makes spectrum access more flexible. In such a way, spectrum efficiency can be improved significantly without losing the benefits associated with the traditional SSA scheme. However, legacy wireless devices were usually designed for a dedicated frequency band and incapable of spectrum sensing to identify spectrum holes, which makes them hardly utilize the improved flexibility provided by this sharing scheme. Cognitive radios (CRs), as smart radios, provide the adaptability and technologies for wireless transmissions and enable the spectrum sharing. Specifically, it can be regarded as a sophisticated radio device that mimics the human brain, perceives and learns the radio environment, and adjusts the transmission parameters accordingly (e.g., frequency band, modulation mode, transmission power, etc.) [8]. CR devices usually work collaboratively to form a network, a.k.a. the cognitive radio network (CRN). To achieve self-adaptive transmissions in a CRN, each CR device senses its local radio environment (distributed sensing), or a centralized sensing controller senses the whole network (centralized sensing). Then, the sensing results are processed either centrally or distributedly, which guide CR devices to control their transmission patterns, including modulation, transmission power, error control methods, etc., and establish communications accordingly.

Consequently, three main functionalities are associated with a CR device, namely, *spectrum sensing*, *spectrum management*, and *spectrum mobility* [8]. These three mechanisms can facilitate SUs to access the PUs' spectrum under the hierarchical access-based spectrum sharing. To be more specific, *spectrum sensing* can be employed to determine the status of PUs' spectrum bands. By periodically sensing PUs' activities on target spectrum bands, spectrum holes in temporal and/or spatial domain can be detected and thus leveraged by SUs (with CR devices) without causing too much interference. Then, based on the *spectrum management*, SUs can conduct their spectrum access and optimize their transmission parameters. By analyzing the sensed information, SUs can learn about spectrum access related information, such as interference estimation, available duration, collision probability, etc., and make spectrum access decisions, including frequency band, transmit power, time duration, etc., by optimizing their performance (e.g., achievable rate) under certain constraints (e.g., limited interference). When the PU returns or shifts to services with high QoS requirements, *spectrum mobility*, which is also called spectrum hand-off, plays an important role in making the SU switch to another idle spectrum band. Such a spectrum hand-off process must ensure that the parameters at different protocol layers can be adjusted to match the new frequency band so that the data transmissions of this SU can be continued.

In summary, the emergence of CR technologies makes the hierarchical access-based spectrum sharing possible. If the SU has CR ability, it can obtain and utilize the information on PUs' spectrums through spectrum sensing function, make optimal decisions on spectrum access through spectrum management function, and change the operating frequency bands in order to continue data transmissions even in the context of the unpredictable return of PUs through spectrum mobility function.

Trading-Based Spectrum Sharing Mechanism

Although the emerging CR technology could provide a strong technical support for DSA and eliminate PUs' concerns on interference imposed by SUs if they open up their licensed bands, one key issue is why PUs are willing to share their preciously owned spectrums with others. To guarantee their QoSs, if there is no incentive, PUs might even prefer to transmit bogus data to keep spectrums occupied and deter SUs from using it. Therefore, it is essential to design proper mechanisms to provide incentives for PUs to share out their spectrum bands. From the economic aspect, spectrum trading, referring to the process of selling and buying spectrum resources, has been widely advocated as a promising mechanism for DSA and attracted a lot of attention. In spectrum trading, the spectrum owners (PUs) can sell their unused spectrum resources in certain geographic areas during certain time periods to unlicensed users (SUs) for monetary gains or performance improvements, and unlicensed users can purchase them to fulfill their desired communication goals at the monetary cost or resources (e.g., serving as relays for PUs). As a result, such a secondary spectrum market can realize the DSA with a win-win situation while generating high economic profits. In what follows, along with different directions, we will discuss various spectrum trading mechanisms proposed in the current literature.

Exclusive-Use Mode vs. Shared-Use Mode

As aforementioned, DSA can be implemented in an exclusive-use mode or a shared-use mode, which corresponds to two different spectrum trading operations. These two types of trading have different characteristics with different relevant problems, which, however, are ambiguous in many existing research works. To be specific, in the former case (exclusive-use), the spectrum access rights (including specific frequency bands, available regions, and time durations) are traded for exclusive use by SUs. In other words, within the leasing duration, the SUs who have purchased the access right turn to be the PUs and can exclusively use the purchased bands at the corresponding geographic areas. In turn, the original PUs cannot use them until the end of the leasing period. As for this mode, spectrum sensing and interference management are not critical issues anymore because the spectrum is exclusively used by either PUs or SUs. One key challenge here is on the seller side (PUs), namely, how to design an optimal selling/leasing strategy. Since the spectrum owners have to guarantee the QoS for their subscribed users, they have to reserve enough resource, and it is not an easy task to determine the access right for selling due to the unpredictable traffic in the future.

In the latter case (shared-use), if SUs want to use the purchased spectrum access right, they have to obey certain rules, rather than exclusively use it as PUs. In other words, the sold spectrum access right is utilized based on spectrum sharing among both PUs and SUs where PUs have higher priority. Generally speaking, overlay-based sharing has been widely adopted, where SUs have to monitor the PUs' activities and vacate the spectrum if PUs return even though they have purchased the access right. Actually, this mode can be treated as a hybrid mode with both exclusive-use and shared-use. Between PUs and SUs, it is based on shared-use to ensure PUs' QoS; and among SUs, it is based on exclusive-use that only the SUs who have purchased the access right can opportunistically access the spectrum. In fact, in comparison with the former mode, the shared-use mode is more practical because the rational spectrum owners are usually unwilling to totally give up their access right considering their unpredictable traffic demands. In the shared-use mode, one key challenge is on the buyer side (SUs), i.e., how to valuate the reward under the uncertain risk of purchasing certain access right. Due to the hierarchical sharing mode, it is important for SUs to capture the statistical features of the sold spectrums (e.g., by taking spectrum measurements) and determine an optimal buying strategy [11].

Monetary Reward vs. Resource Exchange

It is known that the radio spectrum resource is very valuable. In 2008, the auction of 700 MHz frequency band in the United States raised $19.59 billion for the US government. Therefore, as the traditional trading market in economics, currency, also referred to as money, is widely used as the payment in the spectrum trading market as well, i.e., in the so-called money-exchange trading model. Generally speaking, this model is most effective if PUs have redundant spectrum resource to sell because in this case, SUs are transparent to PUs and high monetary revenue can be gained, which is most interesting to PUs. However, if PUs' own traffic load is heavy or the primary channels' qualities are poor (e.g., due to the severe channel fading), there might be no extra spectrum resource left for sale. In this scenario, resource-exchange spectrum trading becomes an attractive option, where PUs could share spectrum with SUs in exchange for the performance improvement, such as increasing data rate or reducing probability of outage [12]. Under the barter-like trading rule, SUs provide communication resources for PUs in exchange for the access right to PUs' certain spectrum (also known as cooperative spectrum sharing).

Serving as relays is one typical way for SUs to obtain the spectrum access right in the resource-exchange trading model [13, 14]. To be specific, direct transmission of a primary session may be at a low data rate due to poor channel condition or long transmission distance. Thus, suitable SUs could be utilized as the cooperative relays for the PU's traffic to achieve a higher data rate accordingly. If the selected SUs join the cooperation and the primary session's data rate can be increased,

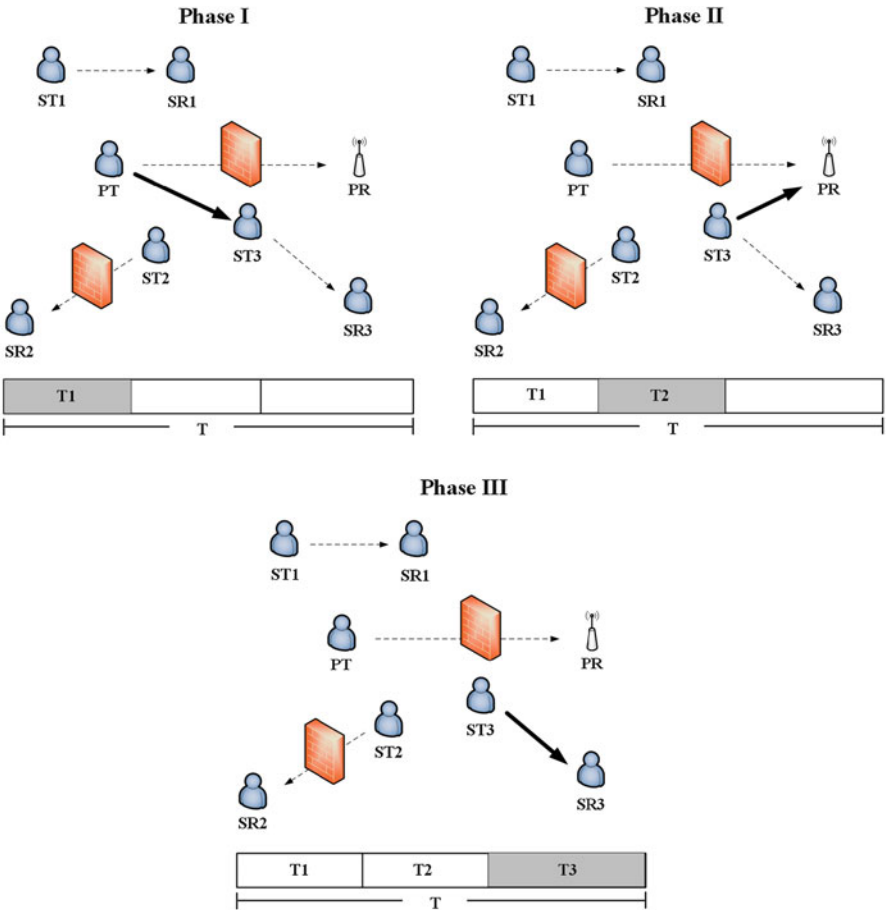


Fig. 1 A toy example of the relay-based resource-exchange spectrum trading

the time occupied by this primary session on the licensed band can be decreased. In return, the involved SUs could gain the access right for the remaining session period. Therefore, by exploiting relay-based cooperation between PUs and SUs as a resource-exchange trading mechanism, both sides can increase their own interests. Here, a toy example is presented as Fig. 1, where one primary transmission pair (PU) and three secondary transmission pairs (SU) coexist.

The PU has the exclusive access right to the licensed band with certain transmission task, but experiences a poor channel condition from its transmitter PT to its receiver PR, and the SUs have no right to use the spectrum for their transmissions unless explicitly permitted by the PU. Based on the resource-exchange trading, the PU employs some SUs to relay its traffic and allows involved SUs to use the spectrum after the primary session is completed. Suppose that the primary session is scheduled as T. In phase I, the primary transmitter PT broadcasts its data to the involved SUs who are willing to join the cooperation, by using T_1. In this example, ST1 rejects the invitation because it is quite far away from PR, and ST2 rejects as well because of its poor channel condition between ST2 and SR2. The trading agreement can be reached by bargaining between the PU and SUs or adopting a contract-based approach in which the PU can claim different reward-effort combinations and design contracts for different SUs. In phase II, the involved SUs (ST3) relay the primary traffic to PR in either amplify-and-forward or decode-and-forward manner by using T_2. In phase III, the PU rewards the involved SUs (ST3) to use the spectrum within the remaining time period, i.e., $T - T_1 - T_2$ (if multiple SUs participate in the cooperation, they can share the spectrum by using TDMA with a dedicated time allocation managed by the PU).

Auction Market vs. Open Market

Auction Market

An auction is a process of procurement via competitive bidding. It is a traditional but efficient way to distribute commodities and especially suitable for the spectrum trading market because the price of a radio spectrum is difficult to be determined precisely in advance.

First, some basic terminologies in auction theory are introduced as follows [15]. (a) *Seller and bidder*: In auctions, a seller and a bidder (buyer) are the one who owns and wants to sell commodities and the one who wants to buy them, respectively. In the secondary spectrum market, the seller is usually the spectrum owner, and the bidder is usually a secondary user or a secondary service provider who wants to obtain the spectrum access right. (b) *Auctioneer*: An auctioneer works as an intermediate agent who receives bids/asks from both bidders and sellers and hosts and directs the auction process. In general, the auctioneer could be employed by the seller or certain third-party institution such as government agencies. (c) *Valuation:* In an auction, for each commodity, a bidder/seller has a reserved valuation in his mind, i.e., the monetary estimated value of it. Different players may value commodities with different valuations depending on their preferences. (d) *Clearing price*: According to the bids from bidders and asks from the seller, auctioneer will determine winners, charge them by certain price (so-called clearing price) and clear the market. Note that, for each winner, the charging price may not be equal to his bid. Generally, it is not higher/lower than the valuation of the bidder/seller on this commodity.

After introducing some basic definitions, we next present some typical auction types, which could be embedded in the spectrum trading market. (a) *Open-cry and sealed-bid auction*: In an open-cry auction, each buyer calls out his bid, i.e., the bidding strategy of each buyer is public. This type of auction is usually held in several rounds, and each buyer could adjust his bidding strategy according to others' calls which could reach a high revenue for the seller. However, generally, it is time-consuming and needs to make all bidders stay in one room. On the contrary, in a sealed-bid auction, buyers privately submit bids to the auctioneer without knowing others' bidding strategies, which is more suitable for the dynamic spectrum trading. Specifically, first-price and second-price sealed-bid auctions are the two most important sealed-bid auctions. In both auctions, the winner is the buyer who submits the highest bid, but the charging prices are different. As for the first-price mechanism, the charging price is just his highest bid, but as for the second-price mechanism (also known as Vickrey auction), the charging price is equal to the second highest bid among all bidders. As a generalized Vickrey auction, Vickrey-Clarke-Groves (VCG) auction has attracted great attention because it can achieve the maximal social welfare due to its truthfulness property (introduced later), and many VCG-styled auction mechanisms have been proposed for the auction-based spectrum trading market. For an overview see section "The State-of-the-Art of Spectrum Trading". (b) *Single-sided and double-sided auction*: In the single-sided auction [16–19], the competition only happens on either seller side or buyer side, corresponding to the following two cases, one is that multiple sellers compete with each other to sell commodities to one buyer. In this case, Dutch auction (descending-bid auction) is usually adopted where each seller decreases the price from the initial setting ceiling price over time until the deal is completed. The other case is that multiple buyers compete for the commodity from one seller. Then English auction (ascending-bid auction) can be employed, in which the bids submitted by buyers increase monotonically until no higher bid comes out, and the buyer who offers the highest bid wins the auction. In practice, generally, multiple sellers and buyers coexist in the market, and thus double auction emerges to handle this scenario [20–23]. In a double auction, the auctioneer matches the asks from multiple sellers and bids from multiple buyers by allocating commodities from sellers to buyers and payments from buyers to sellers accordingly. (c) *Offline and online auction*: In an offline auction, the auctioneer will keep listening to asks from sellers and bids from buyers and determine the auction result at certain specified time points, i.e., the auction is based on a wait-and-clear procedure. Nevertheless, in an online auction [18, 22, 23], whenever the asks and the bids arrive, the market is cleared immediately, i.e., the auction is based on a real-time procedure. The online auction is more complicated than its offline counterpart but could reach a more flexible spectrum trading market, where the auction requests could be generated randomly and handled as soon as possible. (d) *Single-unit, multiunit, and combinatorial auction*: In single-unit auctions, each buyer bids for one commodity unit, while in multiunit auctions, each buyer bids for multiple commodities. The requested commodities may be partly or fully allocated to the buyers, and buyers can accept the case if only some of the requested commodities are received. However, in some cases, buyers may need a complete set of commodities. In other words, buyers bid for certain commodity bundles in an all-or-none mode, i.e., each bid for the whole bundle is either fully accepted or rejected. Such a scenario is common in spectrum trading market because a SU may need to use a set of bands within a large area to provide end-to-end services. To deal with such bidding requests, combinatorial auctions [24–26] can be applied. Since each buyer bids for certain bundles, the conflict relationships among different bidders will be more complicated and thus makes the optimal commodity allocation more difficult.

In general, an auction mechanism design mainly contains two components (no matter what type the auction is), namely, the winner determination and the pricing mechanism. There are many key issues to be considered.

(a) Winner determination: As for the winner determination process, social welfare maximum is usually adopted as the decision metric, which is defined as the sum of all auction participants' utilities, indicating the total profits produced in the market. By maximizing the social welfare, an auction could allocate each commodity to the buyer who values it the most, which is called allocation efficient or Pareto efficient. To be specific, for a buyer, if he wins the commodity, his utility is equal to the difference between his valuation and his payment (clearing price). For a seller who sells the commodity, his utility is the gap between the charging price and his valuation (reserved price). Then, for the auctioned commodity, the achieved social welfare is equal to the sum of all winners' valuations minus the reserved price of the sold commodity, and the optimal decision can be obtained by solving certain optimization problems. In addition to efficiency, fairness issue is also considered in some research works to ensure that different participants can benefit fairly in the auction, which could encourage buyers to join the auction. Different fairness levels can be developed, such as the basic level ensuring the equal chance for buyers to participate in an auction and the max-min fairness level to make each buyer at least receive a basic portion of commodities [27]. Generally speaking, in an auction market, efficiency and fairness cannot be achieved at the same time, and there should be trade-offs between these two metrics. Furthermore, different from the conventional auction, for the commodity which is not reusable, i.e., an auction in which commodity claimed by one buyer cannot be allocated again to others, in the spectrum auction, the radio resource can be allocated to many buyers simultaneously as long as they will not interfere with each other (e.g., sufficiently apart from each other). Such a special feature makes the winner determination process more complicated, and conflict graph model has been regarded as an effective way to handle the interference issue. Furthermore, the reusability also leads to some other interesting research works, such as the group-based auction [28] where multiple buyers targeting at the same radio resource group together as a virtual bidder and the corresponding profit sharing problem, i.e., how to share the profit among individual buyers in the same virtual bidder group [29].

(b) Pricing mechanism: With regard to the pricing mechanism design, the following three important economic properties are usually taken into account, namely, individual rationality (IR), budget balanced (BB), and incentive compatibility (IC, also known as truthfulness or strategy proof) [30, 37]. To be specific, IR property means that the charging price to certain winner cannot be higher than his bid. BB property indicates that the generated revenue of the trader should be nonnegative. These two properties are relatively easy to achieve. However, satisfying IC property, as an extremely important property to realize the maximal social welfare, is usually challenging for an auction design. In general, buyers in the market are selfish and may deceive others by submitting false information about their private valuations to gain more profit. In such a way, although some lying buyers may earn more profit, the social welfare may be impaired seriously. From this point of view, a

truthful auction design with IC feature can guarantee that each buyer will achieve the optimal utility only when he submits the truthful bid, reflecting his real valuation on the requested commodity. In other words, when IC property is satisfied, each buyer's dominant strategy (social choice) is to submit the true valuation no matter what other buyers' bidding strategies are. In such a way, the auctioneer can make the socially optimal winner determination just according to buyers' bids, which reflect their real valuations, and also prevent market manipulations. A simpler approach to achieve IC is referring to the existing auction mechanisms that have been proved to be IC, such as the typical VCG auction.

Open Market

Unlike the auction-based spectrum trading, instead of being controlled by an auctioneer, in an open market, PUs and SUs are allowed to sell and buy radio resources freely. Due to the flexibility in the open market, some new issues emerge accordingly, which lead to several interesting research directions. In the following, three popular marketing mechanisms are introduced, namely, pricing based, contract based, and bargaining based.

(a) Pricing-based mechanism: Different from the auction market, where the final price of the commodity is derived from buyers' bidding strategies (e.g., first-price or second-price mechanism), in the open market, the price of the commodity is designed by its corresponding seller. As the most important role in the open market, the pricing strategy of a seller will not only determine his revenue but also influence the decision of buyers, which usually stand on two opposite sides, e.g., a high price will increase the seller's revenue while reducing the satisfaction of the buyer. Due to the complicated relationships among different market participants, several factors will impact the price setting, such as the demand/supply of buyers/sellers, the competition among buyers/sellers, etc. Considering a typical scenario where multiple sellers and multiple buyers coexist, generally, three pricing models are involved, i.e., market-equilibrium model, competitive model, and cooperative model, corresponding to different levels of competition and cooperation among different sellers [31]. In the market-equilibrium pricing model, each seller is not aware of others, and the prices of commodities of each seller are natively set by himself according to the demand in the market. Specifically, since the price of commodities will influence the demand of buyers, the market-equilibrium price represents the price that makes the demand just equal to the supply in the market. Such a pricing strategy could ensure that there is no excess supply in the market and maximize both seller's profit and buyer's satisfaction. In general, demand function and supply function are considered in this model to derive the market-equilibrium-based solution. In the latter two models, sellers are aware of each other, and the prices are set in either a competitive or a cooperative manner. To be specific, in the competitive pricing model, each seller has its own interest to maximize his individual profit. Therefore, competition occurs in terms of pricing, and game theory can be used to deal with this situation. In general, a game formulation consists of three main components, i.e., players, actions, and corresponding payoffs. As for this situation, multiple sellers (i.e., players) offer prices (i.e., actions) to

sell commodities to buyers trying to maximize their profits (i.e., payoffs), and thus a noncooperative game can be adopted to model such a situation. The Nash equilibrium is usually considered as the solution to such a game model, where no seller can improve his payoff by deviating from the equilibrium, and the Nash equilibrium can be obtained by analyzing the best response function, i.e., the best strategy adopted by one player given others' strategies. Although more buyers could be attracted in the market through the competition among sellers, it may result in a low revenue for each seller. Therefore, instead of competing with each other, sellers may be willing to cooperate together to choose higher prices so that they can earn a higher profit than that in case of competition, i.e., the so-called cooperative pricing model. In addition to game theory (i.e., cooperative game), optimi zation approach could be employed as well in the cooperative pricing model, e.g., to achieve the highest total profit for all sellers.

(b) Contract-based mechanism: In some cases, precisely pricing commodities is inflexible or even hardly achievable for sellers (e.g., due to the limited knowledge about buyers' valuations). As a result, contract mechanism has been regarded as an effective approach in the open market [32–35]. To be specific, the seller can design a contract by offering different supply-price options to different buyers, such as different effort-reward combinations in resource-exchange market or different quality-price combinations in money-exchange market. Each buyer can choose to sign one of the contract items or reject. A typical example is the labor market, in which an employer offers a contract with several different items specifying different combinations of effort level and salary level. Each potential employee can select one of the contract items or refuse it to maximize his payoff according to his own capability and valuation. By means of the contract, buyers will gain enhanced satisfactions, and meanwhile sellers can optimally allocate their commodities to maximize own revenue or the social efficiency. Consequently, how to optimally specify the class of contracts so that both sellers and buyers are able to maximize their individual utilities is the most important issue for contract mechanism design.

(c) Bargaining-based mechanism: In the former two market mechanisms, the trading process is based on a monopoly market, in which the seller acts as a monopolist who sets prices or contracts for the sold commodities. Different from that, in the bargaining mechanism, the buyer and the seller can negotiate on the price and the requested commodities repeatedly until an acceptable solution for both sides is achieved (i.e., for certain commodity, the seller and the buyer take turns to offer and counteroffer until reaching an agreement). Such a bargaining mode is especially suitable for the multiplayer scenario, where each player prefers to reach an agreement rather than not, however, with conflicting interests. As a mathematical basis for modeling and analyzing interactive decision-making problems, game theory is commonly used for bargaining scheme design. For example, the Stackelberg game as a strategic game has attracted intensive attention, which contains two types of players, i.e., leader and followers. In the Stackelberg game, the leader moves first, and then the followers move subsequently. For the bargaining market, the seller acts as the leader, and the buyers acts as the followers, and the Nash equilibrium solution can be solved through backward induction, i.e., the leader makes the best decision

by predicting what the possible best response of the followers is and the follower moves according to the adopted strategy of the leader. In addition to the Stackelberg game, Bayesian game can also be used in the bargaining market when considering a common scenario that sellers and buyers do not have complete information about each other, in which probabilistic analysis plays an important role.

Summary

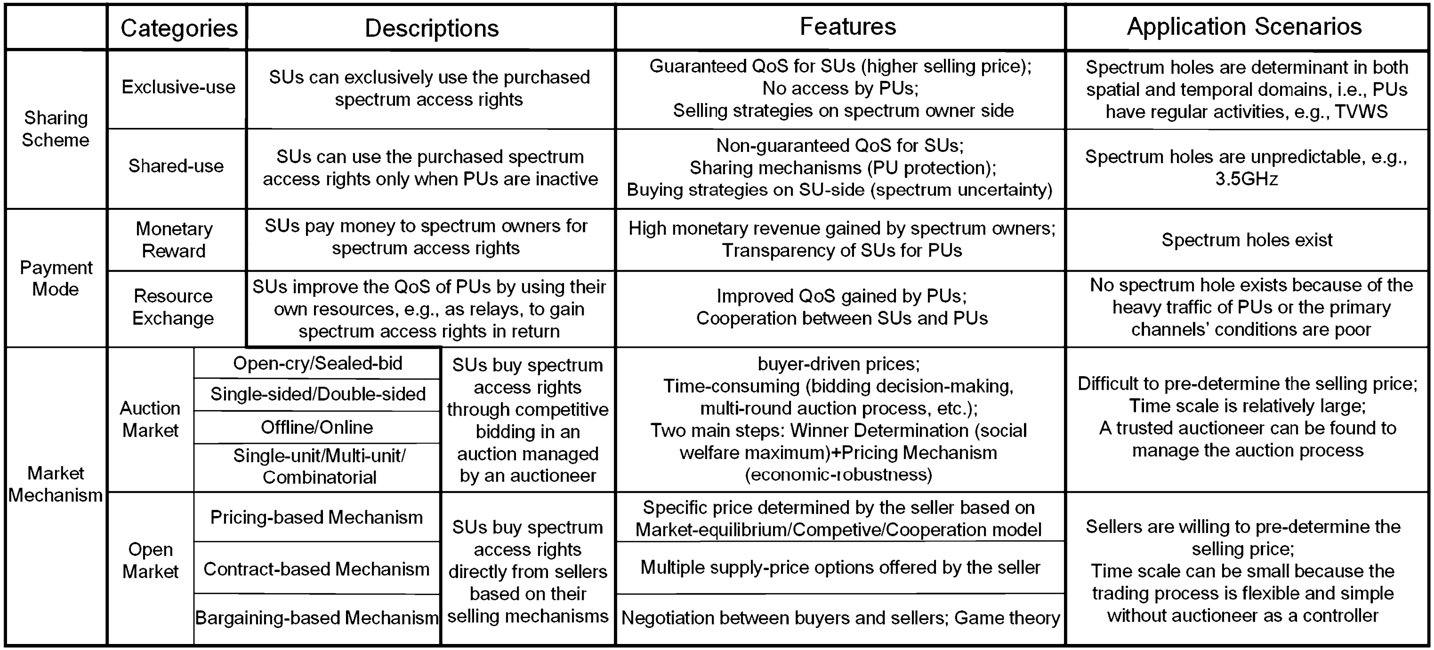
The aforementioned various classifications of spectrum trading along with different directions have been summarized as Fig. 2, including their categories, descriptions, features, and possible application scenarios.

The State-of-the-Art of Spectrum Trading

In this section, we present the state-of-the art of spectrum trading, including both practical initiatives implemented by the government and theoretical research works developed in the academic research community.

Auction-Based Spectrum Sharing Initiatives by Government

Although the dynamic spectrum trading market, where spectrum owners and unlicensed users can trade spectrum access right freely, is still in the draft, in practice, such an economic-based spectrum sharing mechanism has been implemented by the government to provide more spectrum for commercial use due to the booming growth on wireless services. In the United States, the radio spectrum is managed by two governmental agencies, namely, the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). The former is responsible for managing the non-Federal use (e.g., commercial, private internal business, and personal use) and the latter for Federal use (e.g., used by the Army, the FAA, and the FBI) of the spectrum. In order to enable various wireless broadband technologies, the Presidential Memorandum in June 2010, "Unleashing the Wireless Broadband Revolution," called for the NTIA and the FCC to make 500 MHz of spectrum available for the wireless broadband use within 10 years [36]. Generally, the traditional way to make additional frequency bands available for commercial use is based on a clear-and-relocate process, i.e., clear the target spectrum (original users are moved to other bands) and relocate the cleared spectrum to new commercial users (e.g., by an auction). For example, in 2002, the NTIA and the FCC jointly reallocated the 1710–1755 MHz band from Federal use to non-Federal Advanced Wireless Service (AWS) use, also referred to as AWS-1. The spectrum relocation, although additional spectrum could be made available for commercial use as well, is extremely expensive and time-consuming. Take the case AWS-1 as an example, 12 Federal agencies representing 173 separate



	Categories		Descriptions	Features	Application Scenarios
Sharing Scheme	Exclusive-use		SUs can exclusively use the purchased spectrum access rights	Guaranteed QoS for SUs (higher selling price); No access by PUs; Selling strategies on spectrum owner side	Spectrum holes are determinant in both spatial and temporal domains, i.e., PUs have regular activities, e.g., TVWS
	Shared-use		SUs can use the purchased spectrum access rights only when PUs are inactive	Non-guaranteed QoS for SUs; Sharing mechanisms (PU protection); Buying strategies on SU-side (spectrum uncertainty)	Spectrum holes are unpredictable, e.g., 3.5GHz
Payment Mode	Monetary Reward		SUs pay money to spectrum owners for spectrum access rights	High monetary revenue gained by spectrum owners; Transparency of SUs for PUs	Spectrum holes exist
	Resource Exchange		SUs improve the QoS of PUs by using their own resources, e.g., as relays, to gain spectrum access rights in return	Improved QoS gained by PUs; Cooperation between SUs and PUs	No spectrum hole exists because of the heavy traffic of PUs or the primary channels' conditions are poor
Market Mechanism	Auction Market	Open-cry/Sealed-bid	SUs buy spectrum access rights through competitive bidding in an auction managed by an auctioneer	buyer-driven prices; Time-consuming (bidding decision-making, multi-round auction process, etc.); Two main steps: Winner Determination (social welfare maximum)+Pricing Mechanism (economic-robustness)	Difficult to pre-determine the selling price; Time scale is relatively large; A trusted auctioneer can be found to manage the auction process
		Single-sided/Double-sided			
		Offline/Online			
		Single-unit/Multi-unit/ Combinatorial			
	Open Market	Pricing-based Mechanism	SUs buy spectrum access rights directly from sellers based on their selling mechanisms	Specific price determined by the seller based on Market-equilibrium/Competive/Cooperation model	Sellers are willing to pre-determine the selling price; Time scale can be small because the trading process is flexible and simple without auctioneer as a controller
		Contract-based Mechanism		Multiple supply-price options offered by the seller	
		Bargaining-based Mechanism		Negotiation between buyers and sellers; Game theory	

Fig. 2 Summary of various spectrum trading classifications

systems with thousands of radio equipments in hundreds of locations have to move away from the 1710–1755 MHz band. Facing the serious drawback of the clear-and-relocate process, the NTIA and the FCC have been cooperating to develop advanced spectrum sharing schemes to fulfill the 500 MHz goal. Due to the high economic revenue of the spectrum resource, auction has been considered as an effective way to grant new licenses. As a result, many auction-based spectrum sharing actions on different frequency bands have been executed recently. Next, two concrete examples are presented, namely, AWS-3 and Citizens Broadband Radio Service (CBRS) at 3.5 GHz [2].

AWS-3

In March 2014, the Report and Order makes 65 MHz available for commercial use via auction (including 1695–1710, 1755–1780, and 2155–2180 MHz) and specifies some rules for sharing with incumbent Federal users (40 MHz to be shared). The incumbent Federal users will either relocate to other bands or share with the incoming commercial systems based on the establishment of certain geographic protection zones. In January 2015, the AWS-3 auction was conducted, which raised $41.3 billion in total with 31 winning bidders granted 1611 licenses. The new AWS-3 licensees must agree on the transmission rule where the incumbent Federal users within protection zones have higher priority for operation. In other words, the sharing is based on the underlay mode where the AWS-3 licensees within protect zones need to control their transmission power in order to avoid harmful interference imposed on incumbent Federal users. By using such an auction-based underlay spectrum sharing mechanism, high economic revenue has been generated, more spectrum has been made available to carriers, and meanwhile disruptions to Federal missions can be prevented.

CBRS at 3.5 GHz

In July 2012, the President's Council of Advisors on Science and Technology (PCAST) released its report "Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth," which claims that exclusive licensing is not the way to stepping forward and the advanced spectrum sharing should become the new paradigm [4]. The report proposes a new spectrum management mode by dividing the spectrum into large blocks, called spectrum superhighways, and allowing users with compatible services to dynamically share them on a priority basis. To be specific, users are classified into three tiers with different priorities, and all users are required to register in a database, called Spectrum Access System (SAS) database, which acts as the controller to manage the dynamic spectrum access. (a) The incumbent users, also called primary access users, are at the top tier with the highest access right. They would register their actual deployments in the SAS database and obtain the guaranteed protection against harmful interference in their deployment areas. (b) Secondary access users, also called priority access licensees, are at the secondary tier, who are issued short-term operating rights in certain specified geographic areas and would be protected from interference caused by the third tier users. However, they are required to vacate the spectrum when a primary access user registers a conflicting deployment in the database. (c) General authorized access (GAA) users are at the third tier, who would be allowed to access the unoccupied spectrum opportunistically if there is no conflicting primary and secondary access users registering in the database. Particularly, the secondary access users and GAA users are required to query the SAS database to gain the permission to access certain spectrum. The implementation of CBRS at 3.5 GHz is just based on this three-tier sharing model proposed in the PCAST Spectrum Report, which enables incumbent Federal users, operating at the first tier, and CBRS users, operating at the second and third tier, to share spectrum via a dynamic spectrum access system, and the priority access licenses (PALs) at the secondary tier are allocated by an auction. Obviously, different from the AWS-3 case, the spectrum sharing for CBRS at 3.5 GHz is in an overlay sharing mode, and the auction for the PALs belongs to the shared-use trading model.

Spectrum Auction

The aforementioned spectrum auction, as a well-known economic-effective allocation mechanism, has been widely adopted for spectrum trading. Different auction models with different features have been embedded in the spectrum auction design.

VCG Auction

Vickrey-Clarke-Groves (VCG) auction is a type of truthful sealed-bid auction for multiple commodities. Such an auction allocates commodities in a socially optimal way (i.e., to maximize the total valuation of winners) based on the bidders' bids (equal to their true valuations) and charges each winner the harm he causes to other bidders. Suppose that there are $\mathscr{M} = \{c_1, \cdots, c_m\}$ commodities and $\mathscr{N} = \{k_1, \cdots, k_n\}$ bidders in the auction. For the bidder k_i, his bid for the commodity c_j is expressed as $b_i\left(c_j\right)$, which is equal to his valuation due to the guarantee of truthfulness in VCG auctions. Then, based on the VCG mechanism, the socially optimal allocation can be formulated as the following optimization problem

$$\begin{aligned} &\text{Max} \quad \sum_{j=1}^{m} \sum_{i=1}^{n} b_i\left(c_j\right) \cdot x_{ij} \\ &\text{s.t.} \quad \sum_{i=1}^{n} x_{ij} \leq 1, \ \forall j \in \mathscr{M}, \quad x_{ij} \in \{0, 1\}, \end{aligned} \tag{2}$$

in which the integer x_{ij} indicates whether or not k_i wins c_j. In some cases, each bidder only allows to win one item, then, the constraint $\sum_{j=1}^{m} x_{ij} \leq 1, \forall i \in \mathscr{N}$ can be included as well. Denote the achievable social value of this VCG auction as $V_{\mathscr{N}}^{\mathscr{M}}$, i.e., $V_{\mathscr{N}}^{\mathscr{M}} = \sum_{j=1}^{m} \sum_{i=1}^{n} b_i\left(c_j\right) \cdot x_{ij}$, and use $\mathscr{A} \backslash \mathscr{B}$ to represent the set of elements of $\mathscr{A}$

which do not belong to $\mathscr{B}$. Assume that k_i wins c_j, i.e., $x_{ij} = 1$, then, the charging price to k_i for c_j can be calculated as $V^{\mathscr{M}}_{\mathscr{N}\backslash\{k_i\}} - V^{\mathscr{M}\backslash\{c_j\}}_{\mathscr{N}\backslash\{k_i\}}$. The first term represents the total valuation of others if the bidder i does not participate into the auction, and in the second term, the commodity c_j is excluded from the available commodity set due to the participation of the bidder i. Therefore, such a gap indicates the harm that the bidder i causes to others. A simple example is presented here for a better understanding. Assume that there are two bidders with bidding values $b_1(c_1) = 10$, $b_1(c_2) = 6$, $b_2(c_1) = 7$, $b_2(c_2) = 5$ for two commodities and each bidder is allowed to get only one commodity. Obviously, the socially optimal allocation is to let k_1 get c_1 and k_2 get c_2, achieving the maximal social value 15. According to the aforementioned pricing mechanism, the charging price to k_1 for c_1 should be $7 - 5 = 2$ and that to k_2 for c_2 should be $10 - 10 = 0$.

The VCG auction guarantees the most important truthfulness property, i.e., forces buyers to bid truthfully in the sense that bidding lower than the true valuation does not gain anything advantage, and thus achieves the maximal social welfare. Therefore, it has attracted great attention and inspired many truthful VCG-styled spectrum auction development. Due to the specific feature of radio resource, i.e., spectrum reusability in different regions, the truthful design on spectrum auction is different from (and much more difficult than) that in conventional auctions. Zhou et al. developed the first truthful and computationally efficient spectrum auction scheme, called VERITAS, in [16], which consists of a greedy spectrum allocation algorithm for winner determination and a VCG-styled pricing mechanism to charge winners. Take the scenario (conflict graph) in Fig. 3 as an example. Each vertex represents a bidder, i.e., there are totally five bidders in this auction. The edge between two vertices indicates that they conflict with each other, i.e., a spectrum band cannot be allocated to these two bidders at the same time. Suppose that there are two bands auctioned in this market denoted as f_1 and f_2 and each bidder bids for one (for each bidder, either f_1 or f_2 is acceptable). The bidding values of the five bidders are shown in Fig. 3 as $b_1 = 6, b_2 = 5, b_3 = 4, b_4 = 3$, and $b_5 = 1$. First, the greedy algorithm is adopted to allocate the two bands. Specifically, it sequentially allocates spectrums to bidders from the one with the highest bid to the one with the lowest bid, considering their conflicting relationships. For each bidder, the algorithm first checks whether or not there is an available band for him. If so, it assigns him one band with the lowest available index. Consequently, the allocation process can

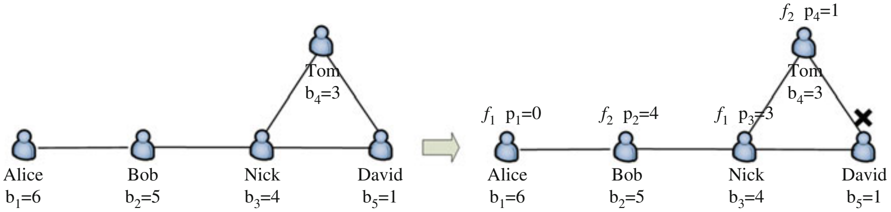


Fig. 3 An example of VERITAS scheme

be described as follows: (Alice gets f_1) → (Bob gets f_2) → (Nick gets f_1) → (Tom gets f_2) → (David gets nothing). After the greedy allocation, a VCG-styled pricing mechanism is applied on the winners to calculate their payments. To be specific, the charging price of each winner i is the bidding value of his critical neighbor (i.e., the one of the i's conflicting neighbors where if i bids lower than his, i will lose, and if i bids higher than his, i will win). Take Alice and Nick as an example. Alice does not have a critical neighbor because even if she bids lower than her neighbor Bob, e.g., 4.5, she can also win the auction with f_2, i.e., (Bob gets f_1) → (Alice gets f_2) → (Nick gets f_2) → (Tom gets f_1) → (David gets nothing). Therefore, the charging price to Alice is 0. Nick has three conflicting neighbors, i.e., Bob, Tom and David, and Tom is his critical neighbor because if he bids lower than Tom's bid 3, Tom will get f_1 based on the greedy algorithm and Nick will lose the auction. Therefore, the charging price to Nick is 3. Similarly, the charging price to Bob and Tom is 4 and 1, respectively. It is noteworthy that comparing with the aforementioned VCG pricing mechanism, the charging price to winner i in VERITAS can be denoted as $V^{\mathcal{M}}_{\mathcal{N}\backslash\{k_i\}} - \left(V^{\mathcal{M}}_{\mathcal{N}} - b_i\right)$, which can be treated as a special VCG mechanism due to the reusability of the auctioned commodity. Such an auction mechanism can be proved to be truthful, and detailed proof can be found in [16].

According to the VERITAS design, a key rule for truthful spectrum auction design is summarized here by satisfying the following two crucial factors: (a) The resource allocation process (winner determination) is monotonic, i.e., if a bidder could win/lose by certain bid, he could also win/lose if he bids higher/lower. (b) The charging price for a winner is the critical value (boundary value) of him, i.e., if he bids higher than that, he would win, otherwise, he would lose. Under different scenarios, the monotonic allocation and the critical value could be different, and readers could refer to such a design rule to develop different truthful spectrum auction schemes. For example, in [17], Li et al. considered the multi-hop scenario by modeling unlicensed users as secondary networks (SNs) with end-to-end routing service requests. A truthful heuristic auction scheme with the consideration of inter-SN interference and a truthful randomized auction framework based on primal-dual linear optimization were proposed. Also targeting at the multi-hop communication scenario, in [37], Li et al. proposed a novel economic-robust transmission opportunity auction scheme (TOA). Different from the case in [17], in [37], the bidders are the individual SUs with certain multi-hop data transmission tasks, rather than SNs, which are deployed by a secondary service provider working as a network operator. To support the multi-hop data traffic, instead of using spectrum bands as the auctioned commodities, in the TOA scheme, each SU bids for transmission opportunities (TOs), i.e., the permit of data transmission on a specific link using a certain band (link-band pair). Based on the sophisticated design on TO allocation, TO scheduling, and TO pricing, the developed TOA scheme can satisfy all the IC, IR, and BB properties. Similarly, to support the end-to-end service in multi-hop networks, Pan et al. developed a session-based spectrum trading system in [38] and [39] and further designed an economic-robust session-based auction scheme in [40] by following the aforementioned design rule. In [18], considering the dynamic CRN environment, Sodagari et al. developed a truthful online auction for expiring spectrum sharing, where the SUs are allowed to arrive and participate in the auction with expiring spectrum bands at any time. The SUs are required to submit their valuations and arrival-departure time instances, which can be enforced to be truthful. In order to enable bidders' flexible strategies in terms of demands and valuations, in [19], Feng et al. designed a novel truthful auction mechanism called Flexauc, in which each bidder can bid for any amount of demands with different valuations and will be satisfied with any possible result.

Double Auction

Double auction is also a common auction model when multiple sellers are involved, in which buyers bid for resources and sellers compete for demands. As an extension of the single-sided truthful auction design in [16], in [20], Zhou et al. proposed a framework for truthful double auctions called TRUST. To be specific, based on the conflicting relationships, buyers are formed into many groups. Then, by comparing the sellers' asks with the buyer groups' bids, several matching seller/buyer-group pairs are selected as the auction winners, and payments are made from the winning buyers to the winning sellers. In [21], Chen et al. developed a truthful double auction mechanism with the consideration of the heterogeneity of spectrum, called TAMES, in which each buyer is allowed to submit a bidding profile to express his diversified valuations for different spectrum bands. Similarly, buyer grouping, matching allocation, and VCG-styled pricing are adopted by the TAMES. In [22], Wang et al. designed a truthful online double auction (TODA) scheme because the selling/buying requests from PUs/SUs often come in an online fashion. In the TODA, once the auctioneer receives spectrum requests, it will decide and match winning SUs and PUs immediately and also determine how much SUs should pay and PUs should get. By incorporating the buyers' location information into the auction mechanism design, a location-aware online truthful double auction scheme called LOTUS was proposed in [23], which has considered the sporadic nature of spectrum requests and the geographic feature of buyers.

Combinatorial Auction

Combinatorial auction has been regarded as a widely used model for spectrum auction as well because in general, to satisfy the end-to-end QoS, the SU may need to bid for a whole bundle of frequency bands covering certain regions during an extended time period in an all-or-none mode. In [24], Zheng et al. modeled the heterogeneous spectrum allocation as a combinatorial auction, named AEGIS, with the consideration of five features, i.e., strategic behaviors of unknown users, channel heterogeneity, preference diversity, channel spatial reusability, and social welfare maximization. Specifically, two mechanisms are developed, i.e., a direct revelation combinatorial spectrum auction mechanism for unknown single-minded users (AEGIS-SG) and an iterative ascending one for unknown multiple-minded users (AEGIS-MP). In [25], Dong et al. modeled the spectrum opportunity in a time-frequency division mode and proposed a truthful combinatorial auction with the consideration of time-frequency flexibility. It consists of a polynomial-time and near-optimal winner determination algorithm and a novel payment mechanism that guarantees the truthfulness. Many-to-many matching theory was adopted in [26] to realize the combinatorial auction, in which buyers can freely express their preferences for different combinations of spectrum bands. Instead of achieving the maximal social welfare, the stable status is the main goal of the interference-free spectrum matching where both sellers and buyers are satisfied with the result.

In addition to the investigation of various auction models, there are also many other hot research directions for spectrum auction in the literature, such as the allocation objective design, the bidding strategy adaption, the multitier architecture development, etc. (a) With regard to the optimization objective for resource allocation (winner determination), in [41], Huang et al. proposed a flexible one that can be set to maximize either the overall social efficiency (social welfare) or the expected revenue. In order to prevent some bidders from starvation in the long run, in [27], Gopinathan et al. brought the fairness criterion into the objective to increase the diversity of the winners. In general, such an optimization problem involving interference-free scheduling is essentially an NP-hard graph coloring problem [15], which, therefore, attracts many research works to develop approximation algorithms. For example, in [41], a series of near-optimal mechanisms were proposed based on many approximation techniques, namely, linear programming (LP) relaxation, randomized and de-randomized rounding, monotone de-randomization, and Lavi-Swamy method. In [16] and [17], heuristic algorithms were employed to achieve the truthful auction based on the rule that combines the monotonic allocation and critical value-based pricing. In [25], a polynomial-time approximation algorithm that could reach the upper bound of the worst-case approximation ratio was developed. (b) Furthermore, as for the bidding strategy adaption, many interesting updating techniques have been proposed, which are usually based on the auction results in the past and other auction participants' statistical information. For example, in [42], Fu et al. proposed a best-response learning algorithm for bidders to improve their bidding policies based on the historical information on bidding and allocation, the current auction participants' statuses, and the estimated future auction results. In [43], Han et al. considered a repeated auction game and developed a Bayesian nonparametric belief update scheme based on the Dirichlet process. According to the proposed bidding learning algorithm, buyers can alter their bidding strategies optimally. (c) Moreover, to enable a more flexible auction market, the multitier auction framework has been studied as well. For example, in [44], Tang and Jain presented a hierarchical auction model where multiple auction markets are cascaded as multiple tiers to iteratively trade the spectrum resource. In [45], 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.

Spectrum Trading in Open Market

Different from the auction market where the trading process is hosted by an auctioneer, the open market is more flexible where sellers and buyers could freely conclude the transactions with each other by reaching certain agreement, which

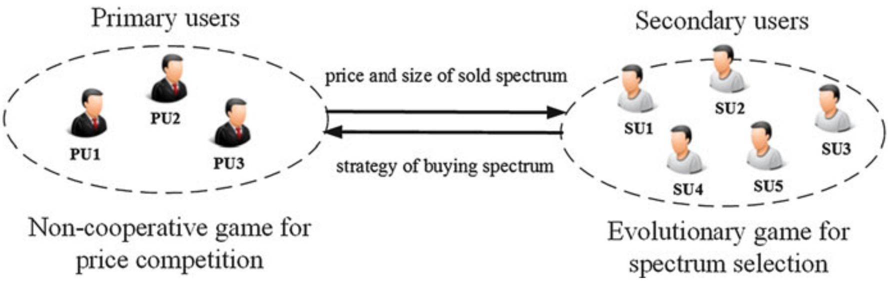


Fig. 4 A game-theoretic framework for spectrum trading in an open market

makes the relationship among the market participants more complicated. A typical open market with multiple PUs selling spectrum opportunities to multiple SUs was considered in [46], and the interactions among PUs and SUs were modeled by a game-theoretic framework. As shown in Fig. 4, in general, there are two levels of competition in such an open market. The first one happens among different PUs in terms of the size and the price on their sold spectrum bands. Denote the total bandwidth owned by PU i as B_i, the size for sale as b_i, and the number of SUs demanding that spectrum as n_i. Assume that all spectrum demanding SUs are allocated with the same size of the spectrum, i.e., b_i/n_i, and charged with the same price p_i. Then, the payoff, also called *net utility*, of PU i can be defined as

$$\gamma_i\left(\mathbf{b},\mathbf{p}\right) = \mathscr{U}\left(B_i - b_i\right) + p_i \cdot n_i\left(\mathbf{b},\mathbf{p}\right), \tag{3}$$

in which $\mathscr{U}(b)$ represents the utility function of a user when using the spectrum with bandwidth b, and it is usually defined as a logarithmic function, e.g., $\mathscr{U}(b) = u_1 \log\left(u_2 \cdot b\right)$ (u_1 and u_2 are constants that depend on the application type). $\mathbf{b}$ and $\mathbf{p}$ indicate the size and the price vectors, respectively, corresponding to all PUs, which will influence the demanded spectrum from SUs. In order to maximize its own payoff, each PU should set the size and the price carefully. If the size is small and/or the price is high, SUs may buy from other PUs. Conversely, if the size is large and/or the price is low, although many SUs may be attracted, the payoff may be low because of the low price and the poor utility of their usage. Such a competitive spectrum selling can be modeled as a noncooperative game, and the Nash equilibrium may provide an optimal solution. In this case, the Nash equilibrium can be obtained by using the best response function, i.e., the best strategy of one player given others' strategies, which can be described as

$$\left\{b_i^*, p_i^*\right\} = \arg\max_{b_i, p_i} \gamma_i\left(b_i, p_i, \mathbf{b}_{-i}, \mathbf{p}_{-i}\right). \tag{4}$$

The other level of competition occurs among the SUs. The payoff of one SU, if he buys spectrum from PU i, can be expressed as

$$\phi_i = \mathscr{U}\left(b_i/n_i\right) - p_i. \tag{5}$$

Obviously, if many SUs choose to buy spectrum from the same PU, the spectrum may become overutilized, or the price may be increased, resulting in poor performance and low payoff for each SU. Consequently, the rational SUs will buy spectrum bands with low price while achieving reasonable performance, which can be modeled as an evolutionary game. Note that the evolutionary equilibrium, i.e., the final buying strategy of each SU, will in turn influence the selling strategies of PUs, which has been considered in the best response function to achieve the Nash equilibrium.

As for the spectrum trading in an open market, the pricing strategy of PUs is usually treated as the most important design issue because it influences the benefit of each trading participant. In [31], Niyato et al. investigated three typical pricing models for spectrum trading, namely, market-equilibrium, competitive, and cooperative pricing models, which aims at satisfying spectrum demands from SUs, maximizing individual profit, and maximizing total profit, respectively. In [47], Xing et al. explored the price dynamics in the market with multiple competitive sellers. A myopically optimal strategy was developed when full information is available to the sellers, and a stochastic learning-based strategy was studied when the information is limited. In [48], by considering different states of the primary channel (e.g., good or bad), Bajaj et al. investigated the optimal pricing that maximizes the PU's payoff under three scenarios, i.e., overlay-based spectrum sharing, relaying-based spectrum sharing, and underlay-based spectrum sharing.

In addition to the pricing mechanism, contract mechanism has also been regarded as an effective mechanism for spectrum trading, in which the seller could design several options with different supplies and prices as a contract or the items in one contract for different buyers by considering their different characteristics, and each buyer could choose one to sign or reject. For example, in [32], Gao et al. designed a monopolist-dominated quality-price contract, which is offered by the PU with a set of quality-price combinations corresponding to different consumer types, and further derived the optimal contract, which maximizes PU's utility. In [33], Gao et al. investigated a hybrid spectrum market, consisting of both future market with guaranteed contracts (including the price, the guaranteed supply, and the penalty if PU violates the contract) and spot market with spot transactions (where SUs buy spectrum in a real-time and on-demand mode). They focused on the PU's expected profit maximization and addressed the problem on how to optimally allocate the idle spectrum among contract users and spot market users. Similarly, a two-stage spectrum trading market, including a long-term market and a short-term market, was studied in [34]. In the long-term market, the PU designs a set of contracts for different types of SUs, and the optimal contract is developed. In the short-term market, SUs can buy some amount of spectrum in a real-time manner, and the interaction between the PU and SUs is modeled as a Stackelberg game. In [35], Jin et al. proposed a novel insurance mechanism for spectrum trading, in which the PUs serve as spectrum sellers as well as insurers. With the insurance contracts, SUs simply purchase the spectrum or sign an insurance contract with the PU to obtain insurance for the potential accident, i.e., transmission failure incurred by the excessively poor channel quality. Such a market game was modeled as a four-stage

Bayesian game characterized by the second-best Pareto optimal allocations and the perfect Bayesian equilibrium.

Instead of the preceding monopolistic market, in which sellers as monopolists to determine prices or contracts, in some cases, buyers are allowed to negotiate with sellers, which is called the bargaining-based market. Such a market mechanism could provide more incentives for buyers to participate because they could express their intentions in the market and thus more transactions could be achieved. In [49], a two-tier market was proposed for decentralized dynamic spectrum access. To be specific, in the tier-1 market, spectrum is traded from a PU to several SUs in a relatively large time scale, which is modeled by a Nash bargain game, and the equilibrium prices are derived. The tier-2 market is set up by SUs to redistribute channels among themselves in a small time scale, which is modeled by a strategic bargain game that SUs can exchange channels with low overhead through random matching, bilateral bargain, and the predetermined market equilibrium price. Actually, such a bargaining mode is especially suitable for the resource-exchange-based spectrum trading, also referred to as cooperative spectrum sharing/trading. For example, in [13], Yan et al. studied a cooperative spectrum sharing scenario with one PU and one SU where the SU was allowed to opportunistically use the licensed band if he relays the PU's traffic. By considering the incomplete information obtained by the PU, the dynamic bargaining process was modeled as a dynamic Bayesian game, and the equilibria was investigated under both single-slot and multi-slot bargaining models. In [14], Simeone et al. considered the cooperative spectrum sharing scenario with multiple SUs. The PU leases the spectrum for a fraction of time to a subset of SUs in exchange for the cooperation, i.e., relaying. On the one hand, the PU attempts to maximize his QoS in terms of either rate or probability of outage. On the other hand, the SUs compete with each other for transmission within the leased time period based on a distributed power control mechanism.

After reviewing the state-of-art of spectrum trading, in the next section, we will discuss some related practical issues and then present a novel flexible network architecture, called *cognitive mesh assisted network*, accordingly. Furthermore, we will demonstrate how to leverage the new network architecture to design an efficient service-oriented spectrum trading scheme.

Service-Oriented Spectrum Trading

Given all these spectrum trading schemes, natural questions to ask are how much cost do they have to pay to implement such schemes and how much end-users can benefit. To address these questions, we may have to revisit our prior research on cognitive radio networks [38, 39, 50–53], particularly on practical implementation consideration. In this section, we first discuss some of the practical issues, then present our flexible network architecture developed previously, followed by our recently proposed service-oriented spectrum trading (SOST) scheme to facilitate end-users to benefit from the spectrum trading [55].

Design Issues and Concerns for CRNs

In this subsection, we first discuss several issues when end-users are directly involved in spectrum trading processes.

Decision-Making for End-Users: End-users might lack necessary expertise and intelligence to join the spectrum trading processes. Similar to its counterpart in economics, spectrum trading requires buyers to specify desired commodities (i.e., spectrum bands) with certain valuations. In contrast, what end-users exactly know is just the service they want to acquire, such as downloading an HQ-video with 1.5 Gbits from Dropbox within 10 min. To join the spectrum trading processes, end-users must convert their service requests to desired bands and the corresponding valuations. Specifically, end-users should decide how much spectrum is needed to meet the QoS, which set of bands is the best choice, how to evaluate different bands, and so on. Clearly, it is not an easy task to make these decisions without specialized knowledge in telecommunications. Even with necessary knowledge, end-users might still not be able to specify their desired bands because of difficulties in gathering intelligence. How much each end-user can gain from purchased spectrum bands depends on PUs' activities, network topology, and the decisions of other end-users, particularly when destinations cannot be reached within one hop. When end-users look for extra spectrum resources for service delivery, they have already suffered from the lack of spectrum resources and might not have enough spectrum bands to collect necessary information for decision-making.

Implementation of Spectrum Markets: Considering the large number of end-users, it will cast a heavy burden on spectrum markets if these users directly join spectrum markets. On the one hand, spectrum markets should be able to interact with substantial number of end-users. To facilitate spectrum trading, spectrum markets need to exchange various kinds of information with end-users, including spectrum band availability, reserve price for each band, and end-users' desired bands and the corresponding valuations. This implies that some exclusive reliable bands/channels must be reserved for fast information exchange, but where do they come from? On the other hand, the extremely large number of end-users will impose considerable computational complexity on spectrum markets, which may become the bottleneck, even for some heuristic algorithms to achieve an approximate maximum of social welfare. For example, unlike traditional trading in economics, since one band can be shared among many nonconflicting users in spectrum trading, spectrum markets need to figure out the conflict relationships among different users' transmissions, which is a very daunting task.

Uncertain Spectrum Availability: Other than above issues, spectrum uncertainty is also an important factor for spectrum trading, which makes it challenging for end-users to directly participate in the spectrum trading processes. The basic premise of CRNs is to protect PUs from being interfered by SUs. In other words, despite end-users' payments for spectrum access, what they obtained is actually the right to *opportunistically access* these licensed bands, rather than accessing them freely and unconditionally as PUs. End-users still need to obey the FCC ruling and immediately evacuate from the licensed band if the PU returns. This observation has two implications. First, end-users should consider potential risks (service interruptions due to the return of the PU) when purchasing a band. However, due to limited information, it is difficult for end-users to make the appropriate judgement on the potential risk. Second, end-users need to execute spectrum sensing to monitor PUs' activities when accessing licensed bands. These spectrum sensing may consume too power, imposing unbearable burdens on SUs' lightweight mobile devices in terms of energy consumptions.

Capabilities of End-Users' Devices: Even if the aforementioned issues could be well addressed and end-users could get what they need from the spectrum market, they might still not be interested in joining spectrum markets due to limitations of their communication devices. To trade and access licensed spectrum bands, end-users must have frequency-agile communication devices to search for unused licensed bands, reconfigure the RF front end, switch among a wide range of spectrum bands (e.g., from MHz bands such as TV bands to GHz bands such as 5 GHz unlicensed bands), and send and receive packets over potentially noncontiguous spectrum bands. According to [1], by 2020, nearly 50% of global devices and connections will be handheld smartphones which will account for more than four-fifths of mobile data traffic. Due to limited size, it is extremely difficult to embed cognitive radio capability into these lightweight handheld devices. Although some of the desired features could be implemented in these devices in the future, significant amount of time and efforts must be devoted to design more capable hardware devices as well as more efficient signal processing algorithms. Besides, even if it is possible to have lightweight handheld communication devices with CR capability, the prohibitively high price of these new fancy devices might discourage end-users, especially the economically disadvantaged ones, from joining the spectrum trading processes.

In view of above concerns, it would be ideal if there is a network to assist end-users to join spectrum markets, which is the theme of the next subsection.

Cognitive Mesh Assisted Network Architecture

In this subsection, we elaborate our formerly proposed flexible network architecture, called *cognitive mesh assisted network (CMAN)* or *cognitive capacity harvesting network (CCHN)*, as shown in Fig. 5, where an SSP is introduced to manage the services for end-users [38–40, 50, 53, 54]. Our CMAN consists of an SSP, a group of SUs, a set of base stations (BSs) and cognitive radio routers (CR routers), and a collection of licensed spectrum bands, i.e., *basic bands*. The SSP can be either an existing wireless service provider or an independent wireless service provider which is willing to provide better or new kinds of services to their customers. BSs

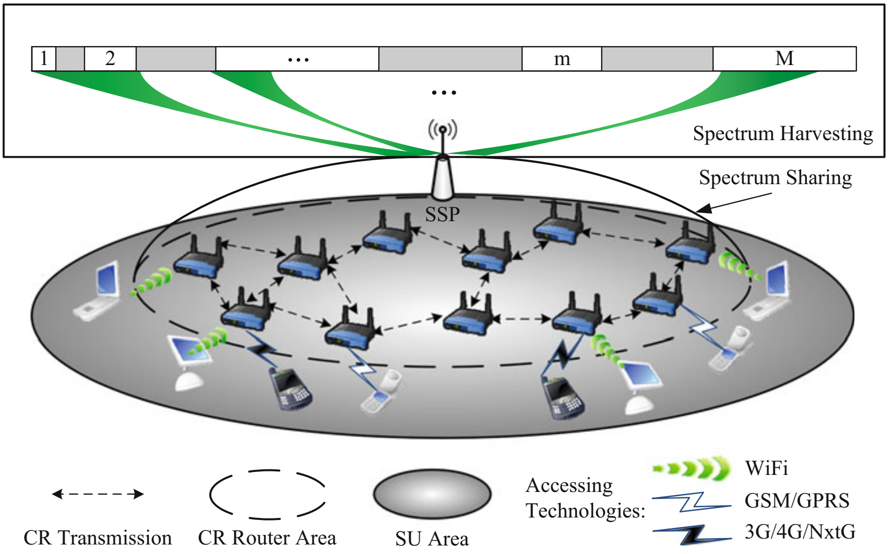


Fig. 5 The cognitive capacity harvesting network architecture for spectrum trading

are deployed by the SSP via, for example, leasing infrastructure (towers and cables) from an existing cellular operator but with its own transceivers and spectrum bands to reduce initial deployment costs. BSs are interconnected via data networks and allow the SSP to gain access to data networks. The SSP employs BSs as an agent to exchange control signaling with CR routers and SUs as well as to provide basic coverage services. CR routers are deployed by the SSP to assist BSs in service provisioning. Specifically, under the supervision of the SSP, CR routers collectively form a cognitive radio mesh network (CMN) as a backhaul network between SUs and BSs for data transportation. It should be noted that BSs and CR routers are equipped with cognitive radios and communication interfaces, including the basic band interface. The basic band is mainly used for control message exchange between BSs and CR routers, user access related control signaling, and, if possible, data delivery in both the access network and the CMN. The cognitive radio interface is mainly used for data delivery in the CMN. Depending on SUs' locations, mobility, and service requests, they connect to either BSs or CR routers for services. If SUs have cognitive capability (i.e., equipped with cognitive radios), BSs and CR routers can deliver data services to these SUs via cognitive radio interfaces. If SUs do not have cognitive radio interfaces, BSs and CR routers can tune to the interfaces which SUs normally use for service delivery. CR routers collect SUs' traffic requests via basic bands and submit the aggregated traffic requests to the SSP. After receiving these data requests, the SSP make centralized network optimization by jointly considering link scheduling, flow routing, and resource allocation and sends the coordination decisions back to CR routers via BSs. According to these decisions, CR routers in the CMN collectively deliver data services to SUs. Since this may potentially reduce the transmission range for the last-hop communications to the end SUs, the frequency reuse for the bands used for network access can be significantly increased with proper frequency planning, resulting in high spectral efficiency.

The CMAN architecture can help end-users interact with spectrum markets without knowing what the spectrum market is, which spectrum bands are needed, and how to complete their data transmissions. End-users only need to know their expected services and affordable monetary costs. They submit their service requests and their valuations of these services to the SSP, i.e., end-users bid for services from the SSP instead of spectrum resources from the spectrum markets. Once end-users' data requests are received, the SSP will search for appropriate spectrum resources in spectrum markets according to end-users' service requests and spatial distributions, prices of different bands and how these bands will be utilized, etc. As an operator, the SSP always attempts to maximize its own profits, and thus how much spectrum the SSP should purchase from spectrum markets is closely related to end-users' bids, which implies that end-users interact with spectrum markets via the CMAN. Such a spectrum trading scheme is referred to as the SOST scheme to emphasize the fact that end-users purchase services instead of directly purchasing spectrum bands in most existing research works.

Compared with end-user-based spectrum trading, the SOST scheme has many attractive features. First, in the SOST scheme, each end-user only needs to submit its service request and bidding allowance to the 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 is more trustworthy and has more bargaining power and credibility. Second, as a network operator, the SSP can collect necessary network intelligence and make centralized optimization accordingly to determine which bands to purchase. Third, the number of SSPs will be much fewer than that of end-users, which not only reduces the complexity but also improves the efficiency of spectrum markets. Fourth, since services in the CMAN are carried over the CMN, end-users are not aware of the specific spectrum allocation across the whole session (i.e., from the source to the destination). Even if an SU overhears the bids of other SUs, it is not helpful since the SU is not sure who are his competitors for spectrum usage, which simplify the spectrum trading mechanism design. Finally, this SOST scheme does not pose any additional requirements on end-users' communication devices. Even for end-users without cognitive radio devices, they can still benefit from spectrum trading, which allows the SSP to extend its services and enhance the prosperity of spectrum markets.

CMAN-Based Two-Tier Service-Oriented Spectrum Auction

In this subsection, we introduce the basic operation process of the SOST scheme by taking the auction market as a concrete example. For illustration, 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

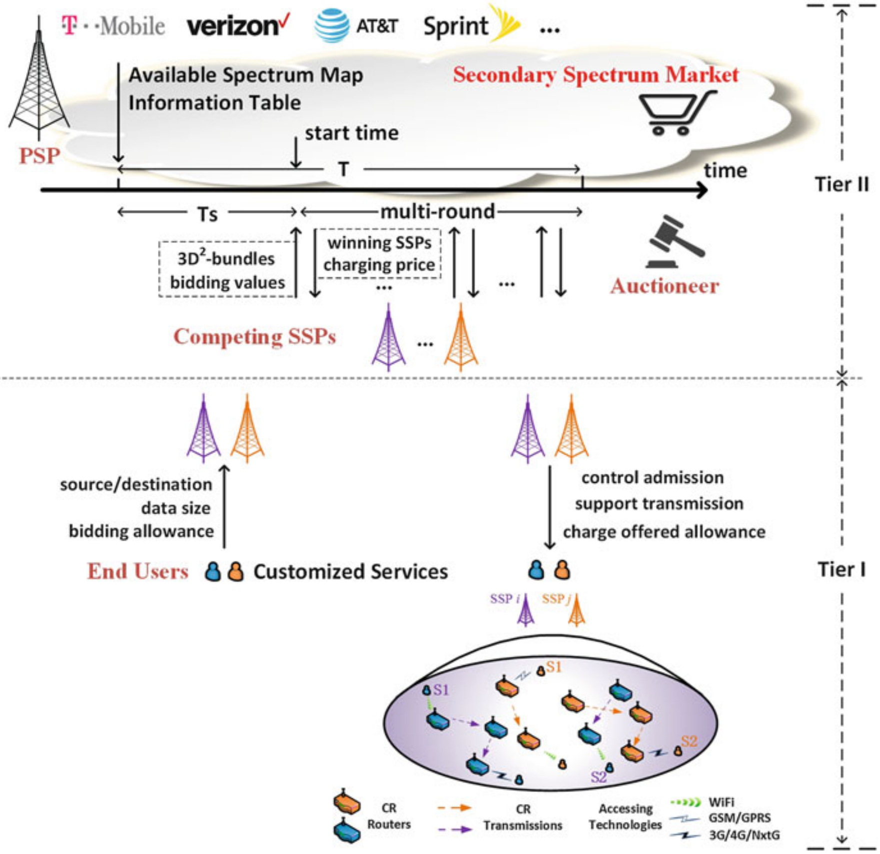


Fig. 6 Two-Tier framework for multi-round service-oriented combinatorial spectrum auction

licensed bands for economic profits, and SSPs can bid for them to support their own 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 idle within which regions in the next time period. Each SSP bids for needed bands within certain regions in an all-or-none mode, 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 their service requests, and the buyers who truly participate in the auction are the SSPs. To be specific, such a market has a two-tier framework as shown in Fig. 6.

Mesh Network of an SSP in Tier I

Tier I is between SSPs and their end-users. End-users do not need to know what the spectrum market is, which spectrum bands are needed, and how to complete their data transmissions, other than their expected services and affordable monetary costs. Each SSP acts as an admission controller, a bidding agent, and a service provider for end-users. Specifically, as shown in Fig. 6, each SSP deploys BSs and CR routers to deliver data services to end-users. 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 a group of CR routers deployed in its coverage area, which have CR capability to operate over the purchased PSP's bands. These CR routers form a mesh network to relay data traffic between the BS and end-users. If possible, end-users can access CR routers through the SSP's basic bands using any available interfaces, 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. Assume that each end-user generates a specific service request, which will be submitted to the SSP through the closest CR router. Each service request includes its source/destination, data size, and bidding allowance, and each SSP aggregates end-users' service information through CR routers via basic bands. According to the aggregated information from end-users and available bands in the market, each SSP bids for needed bands during the auction. According to the results, each SSP broadcasts its admission decisions and charges each admitted end-user its bidding allowance via basic bands and, then, provides requested services to end-users with CR routers and purchased PSP's bands according to predetermined routing and scheduling decisions.

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 opened bands in the next time period, where T is a controllable time parameter. As shown in Fig. 6, at the starting time of each auction period, the seller, the PSP, provides a fine-grained ASM and an IT to reveal available bands and regions in the next period T. An example of the fine-grained ASM is shown as Fig. 7. It has several overlapped zones, and each one represents an available region for an 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. In the considered spectrum market, for certain band m, if certain SSP wants to bid for it, he has to specify which blocks he wants to get, i.e., he has to bid for a set corresponding to all needed blocks for this band. Therefore, while bidding for the band m, the SSP needs to specify both the band's index and the block's coordinates which form a spectrum bundle as $\{m, (x, y)\}$. All the requested spectrum bundles of an SSP is called a three-dimensional desired bundle (3D^2-bundle). Note that the 3D^2-bundle is purchased in an all-or-none mode, i.e., only part of it is unacceptable.

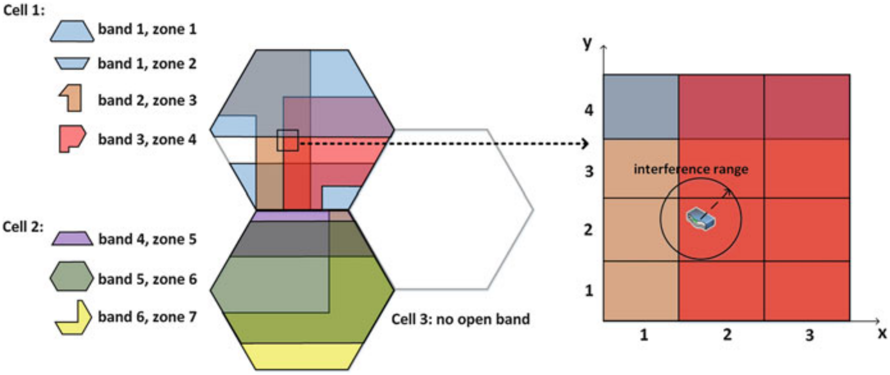


Fig. 7 An example of the fine-grained available spectrum map

IT is provided as the supplement to the ASM including multidimensional information of the sold bands. First, it contains the specific spectrum range with the bandwidth and the available blocks' coordinates. Second, for each band within certain available block, a reserved price required by the PSP is also included in the IT. Furthermore, it is noteworthy that PUs' activities are diverse in different areas during different time periods. Therefore, to capture the spatial variation in spectrum availability, the actual available bandwidth of certain band within certain available zone can be treated as a random variable. In order to help SSPs take such an uncertainty into consideration, in the IT, as a reference, historical usage data for each band is also provided (e.g., the average available bandwidth during the same time period everyday in previous several days collected via spectrum measurements).

The competing SSPs should submit their 3D^2-bundles to the auctioneer before the auction starts, i.e., within the first T_s, in each period. Considering certain CR router, if its SSP wants to obtain certain band for its data transmissions, he has to claim an exclusive area, i.e., specify certain needed blocks. On the one hand, no other SSPs can use this band within this area if it has been claimed already. On the other hand, the CR router can transmit data using this band only within this area and will not cause interference to other areas. For certain transmit power, the exclusive area can be described as a circle, with the CR router as the center and the interference range as the radius, and the desired set of blocks corresponds to the minimal set of blocks covering this circle. A band is called an available band to certain CR router only if its SSP can find available blocks to cover the corresponding exclusive area.

Summary

After aggregating end-users' service requests, according to the available bands of each router, each SSP optimally schedules its network transmissions to obtain its needed 3D^2-bundle which is submitted to the auctioneer along with certain bidding value. When the auction begins, the auctioneer determines winners and their charging prices. After that, the sold blocks of bands will be deleted from the ASM, and each losing SSP can reschedule its network transmissions according to the updated ASM and bids for desired spectrum bands during the next auction round. The auction continues multiple rounds until no available bands on ASM or no participating SSPs, or this auction period is over. In such a way, more transactions are achievable in this market and thus generate higher revenue for both PSP and SSPs. It should be noted that many other mechanisms, such as other auction models or game-based open market, can also be adapted in the CCHN based SOST scheme to fulfill different design goals.

Case Study

Next, we present a one-shot experiment as a case study to illustrate the whole process of the SOST scheme. We consider a $1000 \times 600\,\text{m}^2$ grid network with 3 SSPs owning 9 CR routers, respectively, as shown in Fig. 8.

SSP$_1$ has two end-users with request as ($7 \rightarrow 5$, $r_1^1 = 6\,\text{Mbps}$, $p_1^1 = 20$) and ($1 \rightarrow 3$, $r_2^1 = 1.3\,\text{Mbps}$, $p_2^1 = 10$), respectively. SSP$_2$ has three end-users with request as ($5 \rightarrow 1$, $r_1^2 = 6\,\text{Mbps}$, $p_1^2 = 19$), ($5 \rightarrow 1$, $r_2^2 = 4\,\text{Mbps}$, $p_2^2 = 7$), and ($5 \rightarrow 7$, $r_3^2 = 5\,\text{Mbps}$, $p_3^2 = 17$), respectively. SSP$_3$ has one end-user with request as ($6 \rightarrow 4$, $r_1^3 = 7\,\text{Mbps}$, $p_1^3 = 25$). Assume that four bands are opened by PSP and each one is available to all CR routers in all 15 blocks. The four numbers in each block in Fig. 8 represent the reserve price of the four unoccupied bands within this block, respectively, and some other information including bandwidth and 13 historical data is shown as Table 1. According to the bands' information and its own end-users' service requests, each SSP makes an optimal scheduling to

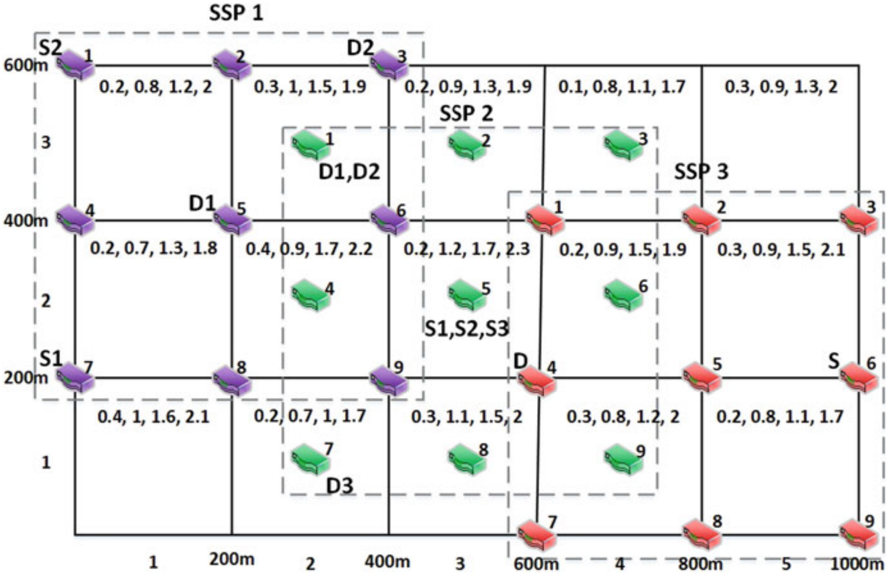


Fig. 8 Topology of the grid network for the case study

Table 1 Information of the four unoccupied bands

Band	Bandwidth (MHz)	Historical data (MHz)												
1	0.4	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	1.8	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	4.0	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	5.5	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

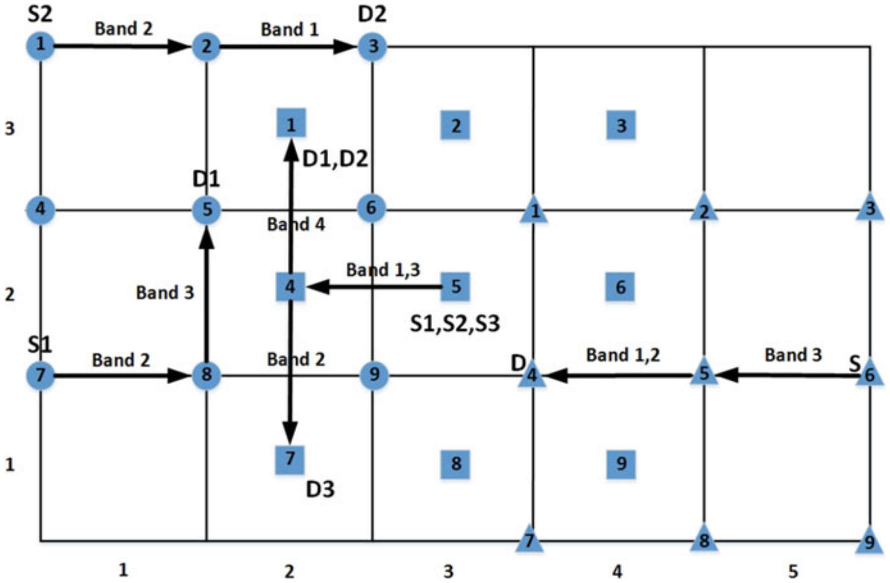


Fig. 9 The optimal transmission schedule of each SSP

determine a 3D^2-bundle (the needed blocks outside this map are not considered). For the 3 SSPs, suppose that they have the same path loss factor $\beta = 4$, the antenna related parameter $\lambda = 4$, and the noise density power at each CR router $\eta = 10^{-16}$ W/Hz. The transmission power at each CR router on each band of each SSP is assumed to be equal as 5 W with a transmission/interference range as 210 and 350 m, respectively, and the confidence level for probabilistic link capacity $\alpha = 0.8$. Then, through the optimal network scheduling, the transmission schedule of each SSP is shown as Fig. 9 (readers can refer to [55] for the details of the optimal network scheduling).

According to the optimal schedule, at the first round of the auction, SSP$_1$ has a 3D^2-bundle as $\hat{\mathscr{B}}_1^1 = \{\{m, (x_m, y_m)\}\}$, $m = 1, 2, 3$, $x_1, y_2, x_3, y_3 = 1, 2, 3$, $y_1 = 2, 3$, $x_2 = 1, 2$, with a total reserve price as 18.4 and its bidding value $b_1^1 = v_1^1 = 30$, and SSP$_2$ has a 3D^2-bundle as $\hat{\mathscr{B}}_1^2 = \{\{m, (x_m, y_m)\}\}$, $m = 1, 2, 3, 4$, $x_1, x_3 = 2, 3, 4$, $y_1, y_3, x_2, x_4, y_2, y_4 = 1, 2, 3$, with a total reserve price as 40.9 and its bidding value $b_1^2 = v_1^2 = 43$, and SSP$_3$ has a 3D^2-bundle as

$\hat{\mathscr{B}}_1^2 = \{\{m, (x_m, y_m)\}\}, m = 1, 2, 3, x_1, x_2 = 3, 4, 5, x_3 = 4, 5, y_1, y_2, y_3 = 1, 2, 3,$ with a total reserve price as 18.2 and its bidding value $b_1^3 = v_1^3 = 25$. Obviously, three SSPs conflict with each other. By taking the social welfare maximum as the metric to determine winners, since the bid of SSP_2 is the maximum, it becomes the winner. To guarantee the truthfulness property, the corresponding clearing price is set as its critical value, i.e., $\max(40.9, 30) = 40.9$. The auction only has one round 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. More detailed mechanism design and performance evaluation can be found in [55].

Conclusion and Future Directions

Facing the dramatic increase of wireless data traffic, making more spectrum available is imperative. Consequently, dynamic spectrum sharing via spectrum trading, as one promising technique with the potential to transforming spectrum scarcity into abundancy, has attracted great attentions. In order to provide incentives for spectrum owners to open up their licensed spectrum, economic perspective has been embedded to burst the spectrum trading. In the spectrum trading market, the spectrum owners could sell/lease their radio resources for monetary revenue or performance improvement, and unlicensed users could buy/rent the spectrum access opportunities for their own services. Based on different characteristics, the spectrum trading market could be categorized into many different types, such as exclusive-use based and shared-use based, money exchange and resource exchange, and auction market and open market, which have been elaborated in this chapter. By referring to the overview of the state of the art, readers could acquire a broad view of the spectrum trading on both governmental issued mechanisms and those designed by the academic research community. Furthermore, some practical issues have been summarized, and a novel service-oriented spectrum trading scheme based on a newly developed network architecture has been presented as a promising solution. As the future research direction, spectrum trading market will become more and more flexible in spatial, temporal, and frequency dimensions, which still needs lots of research efforts, including the sophisticated market frameworks to enable such an extremely dynamic trading, the superior bidding languages with low overhead, the hybrid market mechanisms to satisfy different types of users, the privacy protection for users exposed in the public market, the computational-efficient advanced strategy adaptation designs on both seller and buyer sides, etc. We hope this chapter provides the needed background for spectrum trading and inspire more deep research on this topic.

Acknowledgements This work was partially supported by US National Science Foundation under grants CNS-1343356/CNS-1602172/CNS-1343361, CNS-1409797 and CNS-1423165. The work of M. Pan was also partially supported by US National Science Foundation under grants CNS-1350230 (CAREER) and CPS-1646607. The work of P. Li was also partially supported by US National Science Foundation under grant CNS-1566479 (CAREER). The work of X. Huang was partially supported by the Joint Program of National Science Foundation of China-Guangdong under grants No. U1501255 and No. U1301256. The work of S. Glisic was partially supported by Taseen Käyttö CWC-NS Glisic Menot under 240007101 and ADTEC-2016 Menot under 2410067111.

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