KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS VOL. 8, NO. 11, Nov. 2014

A Survey on Spectrum Sharing in Cognitive Radio Networks

Tangwen Xu[1], Zhenshuang Li[2], Jianhua Ge[1] and Haiyang Ding[3]
[1] State Key Laboratory of Integrated Service Networks, Xidian University
Xi'an, 710071 - China
[e-mail: tangwxu@hotmail.com]
[2] Nanyang Normal University
Nanyang, 473061 - China
[3] Xi'an Communication Institute
Xi'an, 710065 - China
[e-mail: dinghy2003@hotmail.com]
*Corresponding author: Tangwen Xu

Received June 1, 2014; revised August 13, 2014; accepted September 10, 2014; published November 30, 2014

Abstract

With the rapid development of wireless communication, the confliction between the scarce frequency resources and the low spectral efficiency caused by the stationary spectrum sharing strategies seriously restricts the evolution of the future mobile communication. For this purpose, cognitive radio (CR) emerges as one of the most promising inventions which can overcome the spectrum shortage. As the key technology and main objective of CR, spectrum sharing can make full use of the limited spectrum, alleviate the scarcity of frequency resources and improve the system utilities, playing thereby an important role in improving the system performance of cognitive radio networks (CRNs). In this survey, the spectrum sharing in CRNs is discussed in terms of the sharing process, mainstream sharing technologies and spectrum sharing models. In particular, comparisons of different spectrum sharing strategies are concluded, as well as that of different spectrum sensing schemes in sharing procedure. Moreover, some application examples of the spectrum sharing in CRNs, such as smart grid, public safety, cellular network and medical body area networks are also introduced. In addition, our previous related works are presented and the open research issues in the field of spectrum sharing are stated as well.

Keywords: Cognitive radio network, spectrum sharing, dynamic spectrum access, game theory

---

This work was supported by the National High Technology Research and Development Program of China (863 Program, No. 2012AA011701), the National Science and Technology Major Project of the Ministry of Science and Technology of China (2012ZX03001014-004), the Natural Science Foundation of Shannxi Province (Grant No. S2014JC13058), the National Natural Science Foundation of China (Grant No. 61301135) and the open research fund of the State Key Lab. of ISN under grant ISN15-05.

http://dx.doi.org/10.3837/tiis.2014.11.006

1. Introduction

It is well-known that wireless spectrum is a non-renewable resource, which is managed by radio regulatory commission according to the characteristics and bandwidth requirements of the radio services. However, with the rapid evolutions of wireless communication techonologies and the fast growth of radio services, the limited spectrum resources become more and more crowded. Especially, the applications and developments of wireless technologies, such as Wi-Fi, 3G, Wireless Personal Area Network (WPAN), Wireless Local Area Network (WLAN) and Wireless Municipal Area Network (WMAN), occupy so many frequency resources that only a small amount of spectrum is left for the Internet of things [1] [2], 4G and so on in the future. Accordingly, the increasing requirements of the wireless services make the shortage of the spectrum resource become a bottleneck which restricts the evolutions of the future mobile communications.

The main reasons for the insufficiency of spectrum are the imperfect spectrum management and allocation strategies [3-6]. Most current spectrum policies are static, that is to say, the frequency band is assigned to the given service inherently. Although the spectrum management by a static metric is very simple and can avoid the interference among different wireless systems, it also leads to the imbalance and insufficiency for the limited spectrum, and consequently results in seriously waste of the resources [4].

For now, nearly all available frequency bands have been allocated. So with the explosive growth of the communication technologies, the exclusive spectrum policy has been regarded as a primary limitation for the applications and developments of the communication devices. In response to the aforementioned problem, some scholars proposed the idea of using the licensed spectrum repeatedly, which can enhance the spectrum efficiency. Then how to reuse the licensed spectrum flexibly to realize the spectrum sharing? To solve this problem, cognitive radio (CR) technology emerges. Cognitive radio network (CRN) is a system with cognitive ability, which can identify the current network conditions and perform a cognitive cycle, i.e., sensing, analysis and decision. As the key technology and main aim of the CRN, spectrum sharing implies that the cognitive user (CU) can access the frequency bands of the primary user (PU) only if the PU's operation over the licensed spectrum can be protected from harmful interference level. The emergence of spectrum sharing breaks the monopoly of current frequency resources, improves the flexibility in utilizing the limited spectrum and proposes the novel idea for the efficient use of the spectrum resources [7], and thus become a hot research topic.

This survey firstly discusses the sharing process and the key sharing technologies of spectrum sharing in CRNs, including centralized and distributed spectrum sharing, cooperative and non-cooperative spectrum sharing and dynamic spectrum access (DSA), and then introduces the concept of DSA in detail. In particular, comparisons of different spectrum sharing strategies are concluded, as well as that of different spectrum sensing schemes in sharing procedure. Afterwards, four spectrum allocation models are discussed, such as interference temperature, auction-based model, game theory and graph coloring. After a brief discussion of our previous related works and the introduction of application examples of spectrum sharing, some insights and potential open research issues are proposed in Section 7.

2. Spectrum Sharing Process

A cognitive cycle consists of spectrum sensing, spectrum analysis and spectrum decision. Specifically, the CUs first sense the spectrum holes by detecting the related parameters in the spectrum sensing phase, then analyze the characteristic of the detected spectrum holes, and finally select an appropriate free spectrum to transmit the data according to their own performance parameters, such as modulation modes, transmit powers, transmission bandwidth and so on. The procedure for implementing cognition in wireless communication systems can also be regarded as a process to realize the spectrum sharing. Thus, as the key technology and essential objective of a CR system, the spectrum sharing process involves five basic steps further, i.e., spectrum sensing, spectrum allocation, spectrum access, transmitter-receiver handshake, and spectrum mobility [8]. Next, we will describe the state-of-the-art technologies regarding to the spectrum sharing process in detail.

2.1 Spectrum Sensing

As an important premise to realize spectrum sharing for CR systems, the main purpose of spectrum sensing is to detect the spectrum holes which can be utilized by the CUs in time, frequency and space domains. In order to avoid interference to the PU, CUs should have the ability to detect the existence of the PU sensitively, and release the spectrum for the PU promptly or change the modulation mode/transmit power to protect the communication of the licensed user.

In general, spectrum sensing methods may fall into three categories, i.e., transmitter detection, receiver detection and cooperative detection, as shown in **Table 1**. Among them, transmitter detection means that the CUs estimate the presence of the PU by using the receiving signals on the detected channel. It can be classified into: (1) Matched filter detection can obtain the maximum SNR at the output by utilizing a matched filter [9]. Once the output SNR reaches a certain threshold, the PU would be sensed. (2) Energy detection can cumulate the energy in a certain frequency band range [10]. If the detected energy exceeds the threshold, the PU appears, otherwise, only the noise exists. (3) Cyclostationary feature detection sense the PU by distilling the features of the modulated signals [9]. The presence/absence of the PU can be detected while the spectrum correlation emerges at non-zero/zero cyclic spectrum.

On the other hand, receiver detection includes interference-based detection and leakage detection. Interference-based detection indicates the CUs prognosticate their own transmit signals which may interfere with the PU. Leakage detection senses the PU by exploring the power leakage of the local oscillator which is placed near the receiver of the PU.

In order to combat the influences of the multipath fading, shadow fading and path loss in the harsh wireless transmission environment, cooperative detection was proposed, which first requires every CU to fulfill the local detection, and then collects the acquired local detection information at the data fusion center in the sensing process [11] [12].

2.2 Spectrum Analysis

It is significant to obtain the characteristics of the available spectrum holes which are time-variant. Spectrum analysis is essentially the procedure which investigates the quality of the free spectrum, such as interference level, channel error rate, path-loss, link layer delay and holding time [8]. Only on this basis, the efficient spectrum sharing for CRNs can be achieved.

2.3 Spectrum Decision

Spectrum decision is a procedure that can select the most appropriate spectrum among multiple available frequency bands for each CU [13]. After all free spectrum bands are characterized, spectrum decision should be executed according to the user QoS requirements and the spectrum characteristics. On the basis of the QoS requirements, the data rate, tolerable error rate, delay bound, transmission mode and transmission band can be decided [8].

Table 1. Comparisions of different spectrum sensing schemes

Spectrum Sensing Schemes		Pros	Cons
Transmitter Detection	Matched filter detection	Obtains a lager gain with less computation time.	Special receiver is needed for each PU.
	Energy detection	Easy to implement; don’t need a priori information.	Cannot distinguish the types of the signals due to the uncertainty of the noise; it’s difficult to set an appropriate threshold.
	Cyclostationary feature detection	Can discriminate the noise and signals.	High computation complexity; long observation time.
Receiver Detection	Interference-based detection	High detection probability.	Precise detection of the interference temperature is necessary.
	Leakage detection	Easy operability; simple devices.	Difficult to implement; lots of sensors are needed to sense the weak local oscillator signals; narrow detection range.
Cooperative Detection		High detection accuracy; improved detection probability in a heavily shadowed environment [12].	High information overhead.

2.4 Spectrum Resources Allocation and Power Control

In CR systems, the target of spectrum resources allocation is to explore available spectrum as many as possible while protecting the operation of the PU. Spectrum allocation includes the assignment of the sensing time, the selection of the detected channels and CUs, the allocations of available bandwidth and channels, power assignment, rate allocation, access control, routing selection and congestion control, etc. It is necessary to take the fairness into account when there are multiple CUs competing for the available spectrum. Generally speaking, it’s hard to attain fairness and efficiency at the same time, improved fairness is always achieved at the cost of sacrificing efficiency and vice versa. Consequently, how to seek compromise strategies to enhance the resource efficiency while satisfying the fairness is an important issue in spectrum resources allocation.

On the other hand, power control is another major technology to prevent interference to the PU and enhance the throughput of the CUs, improving therefore the spectral efficiency [14]. Reference [15] introduced the classical water-filling algorithm, which allocated the channels to the CUs by inner iteration and find the minimum transmit power by outer iteration. The authors of [16] proposed a novel power control model based on a non-cooperative game and an ameliorative power control algorithm by utilizing cost function was discussed in [17]. Taking account of the link gain, [18] presented a modified power control model.

2.5 Spectrum Access and Transmitter-receiver Handshake

In general, there may be many CUs trying to access the available frequency bands, thus it is necessary to coordinate the spectrum access to prevent multiple CUs from colliding in the overlapping portions of the spectrum [8].

Transmitter-receiver handshake, which is essential for efficient communication, indicates the receiver of the communication about the selected available frequency when part of the spectrum is determined for communication. It is worth noting that the handshake occurs not only between the transmitter and the receiver. A third party such as a centralized station may also be involved [8].

2.6 Spectrum Mobility and Spectrum Handoff

Spectrum mobility is defined as the process when a CU changes its operation frequency. Enabling QoS in the time domain and guaranteeing the continuous allocation of the spectrum in the space domain are major challenges for spectrum mobility [19]. The CU will abdicate its occupied spectrum for some reason. However, in order to keep the ongoing communication, it’s necessary to change the operation spectrum smoothly and as soon as possible, which is named as spectrum handoff [8]. The spectrum handoff occurs in the following scenarios: (1) the occurrence of the PU; (2) the QoS of the CU cannot be guaranteed; (3) the location of the CU varies; (4) the CU accesses another wireless network; (5) inaccurate spectrum sensing.

3. Spectrum Sharing Strategies in Cognitive Radio Networks

Considering the non-equilibrium of spectrum utilization in time and space, on the premise of guaranteeing the priority of the PU, CUs are allowed to sense and analyze the spectrum holes by monitoring the licensed user, according to which proper frequency band in the spectrum pool can be acquired and accessed dynamically. That is to say, the licensed spectrum is shared by the CUs, and the efficient use of the frequency resources is achieved. A comparison of the main spectrum sharing schemes is made in **Table 2**.

3.1 Centralized and Distributed Spectrum Sharing Schemes

Based on the network structure, spectrum sharing in CRNs can be sorted as centralized and distributed strategies [7] [20].

For the centralized spectrum sharing strategy, there exists a central controller in the network, such as the base station (BS), which is used to collect and allocate the available spectrum for CU in the considered cognitive network [21] [22]. It is required for the CU to sense the spectrum information and feed them back to the central controller instantaneously. Then an idle spectrum resources map can be created, on which basis the central control unit acquires the whole free spectrum information and allocates them to the CU according to its own requirements. The decision-making of the centralized controller should be informed to the CU through broadcasting, however the collection and exchange information on the central controller would also be taken into account at the same time, which in turn leads to considerable overhead. Moreover, if multiple CUs intent to share the same licensed band, it is needed to introduce a spectrum broker to participate in the sharing cooperatively.

Different from the aforementioned centralized strategies, it is not necessary for the distributed policy to make use of a central control unit to accomplish the spectrum sharing [23]. For such a case, each secondary node should take part in the spectrum sensing and allocation, and make a decision depending on the local spectrum sharing strategy. The distributed scheme is usually applied in the situation without infrastructure. Compared with the centalized policy, the transceiver of the CUs need more computing resources by using the distributed strategy, however, the corresponding control overhead can be meliorated. In addition, since all CUs select the channel relying on the local information, the optimal spectrum allocation scheme is difficult to be realized.

Table 2. Comparisions of different spectrum sharing strategies

Class	**Sharing Strategies**	**Key Features or Descriptions**	**Pros**	**Cons**
Network structure	Centralized	Centralized entities are needed.	Easier to develop and maitain.	High computational expense.
	Distributed	All the nodes participate in the sharing.	Faster; more flexible.	High information interaction overhead.
Allocation behavior	Cooperative	Global method	Fairness; improved throughput	Information exchanges are necessary; more complex; higher overhead.
	Non-cooperative	Selfish method	Few requirements for the other nodes' communications.	Higher power consumption; lower spectrum utilization.
Access technology	Overlay	Accurate spectrum sensing is crucial.	The interference to the PU is minimum.	Much narrow available bands.
	Underlay	The transmit powers of the CUs should be restricted severely.	Not rely on detection and exploitation of the spectrum holes.	Not suitable for CUs with high transmit power; the optimal allocation scheme is difficult to be realized.

3.2 Cooperative and Non-cooperative Spectrum Sharing Strategies

According to the spectrum allocation behavior, spectrum sharing can be classified as cooperative and non-cooperative policies [7].

For the cooperative case, each CU should not only consider its own spectrum requirement, but also take into account of its interference and influence to other CUs in the considered systems. Thus, in order to exchange the coorperative information among the CUs, public coordination protocols and communication links are required, which leads to an increasing complexity and overhead as a result.

As a comparison with the cooperative scheme, non-cooperative spectrum sharing is a “selfish” solution, which does not consider the impact to the other secondary nodes. Although the spectral efficiency of the non-cooperative policy is lower than that of cooperative case in general, information interaction is not necessary, and thus the overhead can be reduced.

3.3 Dynamic Spectrum Access

Berger introduced open spectrum in [24], which promotes the emergence of novel, flexible and efficient spectrum access techonology, i.e., DSA. Contraty to the traditional static spectrum access, the DSA no longer grants the PU a monopoly on the frequency band occupation, but permits the CUs to access the licensed spectrum opportunistically, thereby achieving the coexistence of the PU and CUs. Zhao *et al* .proposed the models of the DSA in DySPAN in 2005. Based on the property right of the spectrum, DSA can be classified as dynamic exclusive use model and open sharing model, on the basis of the hierarchical access structure of the users, DSA can be sorted as spectrum underlay and spectrum overlay.

3.3.1 Dynamic Exclusive Use Model

Dynamic exclusive use model [25] [26] adjusts the spectrum policy momentarily to allocate the exclusive spectrum band for the sercive. For such a model, the basic framework of the spectrum management method has not been changed, and the spectral bands are still granted for exclusive sercive.Two ways can be utilized to realize the dynamic exclusive use model, i.e., spectrum property rights [27] and dynamic spectrum allocation [28].

Spectrum property rights permit the PU to sell the spectrum to the CUs, and then the spectral efficiency can be achieved by modulating the deals between the PU and CUs adaptively in accordance with the rule of the market. Whereas dynamic spectrum allocation assumes the spectrum allocation as an optimization problem with multi-parameter. And the spectrum efficiency can be obtained by adjusting the parameters of the objective function.

3.3.2 Open Sharing Model/ Spectrum Commons Model

Open sharing model, i.e., spectrum commons model, releases frequency band to all users, in other words, all CUs are allowed to access the licensed spectrum without a licence if the transmit powers of the CUs can not cause harmful interference with their neighbours [29] [30]. Due to lacking exclusive use privilege, open sharing model emphasizes particularly on interference suppression and collision prevention, as well as the fairness among the users. Moreover, the spectrum commons model merely suits the short-distance communications owing to the low transmitting power of the CUs.

Open sharing model can be evolved into the following three cases: (1) Non-controlled sharing model opens the spectrum for all users and services, and permits the CUs transmitting with the maxi-power, however, the interference among the CUs would exist consequentially due to the lack of priority within the users. (2) Management sharing model assumes the spectral resources will be manipulated by a regulation established by a set of users. For such a strategy, although the interference in the aforementioned case can be avoided, the protocol misbehavior may exist. (3) In contrast to the management sharing model, the accessing regulation of CUs in the private sharing model is drafted by the licensed user, and then be informed to the CUs. After hearing the command from the PU, the unlicensed users can sense and access the spectrum opportunistically.

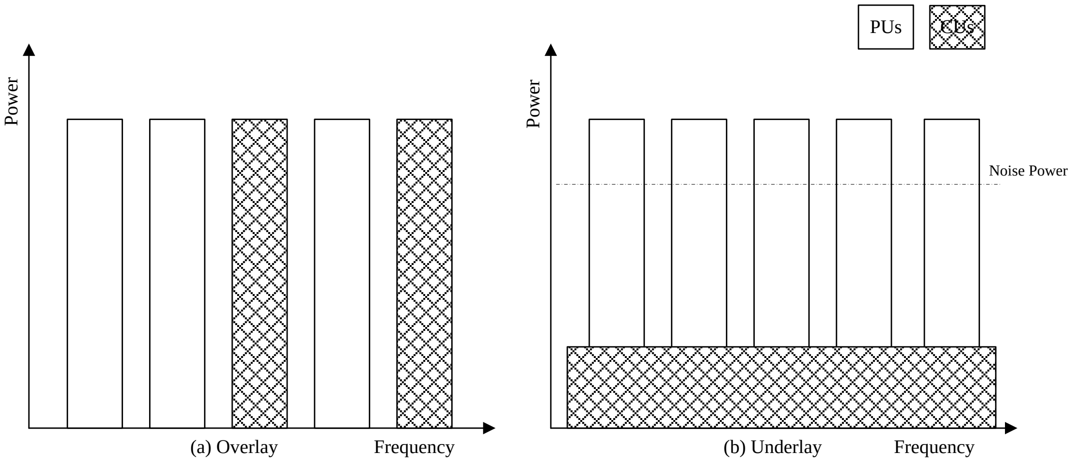
3.3.3 Hierarchical Access Model

Hierarchical access model can be regarded as the combination of dynamic exclusive use model and open sharing model. The basic idea is to allow the CUs to access the unoccupied or partial unoccupied licensed spectrum without causing harmful interference to the PU. For such a case, the PU and CUs should comply with the master-slave relationship strictly. That is to say, the

PU has the priority in accessing the spectrum. Hierarchical access model can be classified into spectrum underlay and spectrum overlay [27].

Spectrum overlay, as shown in **Fig. 1 (a)**, indicates that the CUs can access the licensed spectral band opportunistically only when the spectrum for the PU is free. Overlay is proposed by Dr. Mitola on the basis of spectrum pool [28], and then be extended as opportunistic spectrum access (OSA). In order to achieve the overlay, it is necessary for the CUs to sense the spectrum hole before sharing the licensed band with the PU. Once the spectrum holes have been acquired, CUs will readjust their parameters to access the appropriate spectrum holes. At the same time, the CUs should also monitor their own occupied frequency bands periodically to ensure the priority of the PU. Since the occupied spectrum of the PU and CUs are independent, the research of the overlay emphasizes particularly on designing accurate and fast spectrum sensing algorithm and efficient spectrum hole allocation method rather than controlling the transmit power of the CUs. Furthermore, the actions of the CUs (i.e., the access or release of the free spectrum) make the discrete spetrum hole more fragmental, which may interrupt the communication and deteriorate spectral efficiency. Therefore, how to pack up and reuse these fragments plays an important role in the overlay. In addition, it is obvious that while there exist a mass of idle spectrum, a more efficient use of the licensed spectrum will be obtained by overlay scheme.

On the other hand, the CUs share the same spectrum with the PU only if the PU’s operation over the spectrum band can be protected from intolerable interference level in the underlay case [31] [32] [33], as shown in **Fig. 1 (b)**. For such a strategy, the transmitting power of the CUs should be limited severely, due to the overlaps of the spectrum allocated to the CUs and PU.



(a) Overlay (b) Underlay

Fig. 1. Spectrum overlay and spectrum underlay.

4. Spectrum Sharing Model

Most current spectrum sharing models are on the basis of mathematical theory or microeconomics theory, such as interference temperature model, auction-based model, game theory and graph coloring. Typical spectrum sharing models in CRNs are briefly discussed next.

4.1 Interference Temperature Model

Interenference temperature metric was proposed by FCC in 2003 [34]. Different from the traditional opportunistic spectrum sharing model, the CUs and PU can coexist in the same frequency band. The main idea is that CUs firstly estimate the tolerable interference of the PU and setup an appropriate interference threshold, according to which CUs can then make a decision on accessing the licensed spectrum or not, and adjust their transmitting powers automatically to satisfy the interference limitation [32] [33] [35]. It is obvious that the interference temperature model belongs to spectrum underlay, and its allocation algorithm is always combined with power-control scheme. For such a model, how to evaluate surroundings exactly to avoid the interference to the PU, how to design the scheme with low complexity and overhead, and how to optimize the performance of the cognitive systems under the interference limitation are very crucial in practice.

In addition, interference temperature model can be classified into the following two models: (1) Perfect Model: In oder to limit the CUs' interference to the PU, the perfect model takes into account the bandwidth of the PU rather than the measurement of the interference temperature. (2) Universal Model: There is no prior information in this model, so it is needed for the CUs to sense the whole licensed frequency band, and the interference threshold should also be limited in this scale.

4.2 Auction-based Model

Referring to microeconomics theory, spectrum auction permits the PU to sell the free licensed spectrum to the CUs initiatively for some profits [36] [37] [38]. In contrast to the interference temperature model, auction-based model is a proactive spectrum sharing pattern, which is always applied in centralized framework. The access point (AP) or the BS would serves as an auctioneer, while the CUs act as bidders. In one auction, every CU bids for multiple spectrum resources according to their requirements, and reports the results to the auctioneer. Then, the auctioneer sells the resources to bidder which can produce the greatest benefits for the considered system.

All the bidders are independent in the auction-based sharing model, that is to say, the CUs bid for the resources without any information interaction. However, the CUs should sense the channels before bidding for the available spectrum, and the auctioneer should collect all CUs' bids, both of which result in additional execution time and algorithm cost. Furthermore, although all the bidders are selfish, the signaling overhead of the auction-based model may be very small due to the non-cooperative relationship among the CUs and the completeness of the information interaction between the PU and CUs.

When multiple CUs coexist with one PU, a forward auction which is illustrated in **Fig. 2 (a)** occurs. For such a case, the PU will sell its licensed resource to the CU which can result in greatest benefits [36] [39]. If there are multiple PUs intent to sell the spectral bands, which is regarded as a reverse auction (see **Fig. 2 (b)**), the spectrum sharing strategy evolves into a bid among the PUs [40]. Moreover, while there are multiple PUs sharing spectrum with multiple CUs, a double auction should be introduced [41] [42], as shown in **Fig. 2 (c)**.

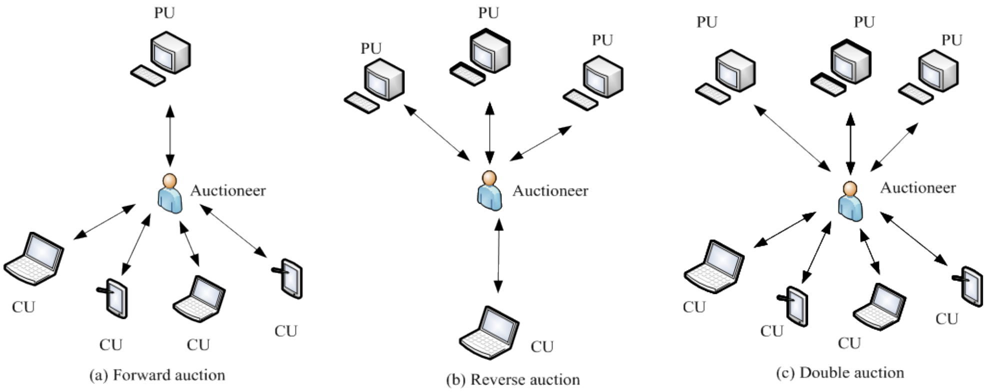


Fig. 2. Auction-based Model.

4.3 Game Theory

Traditional wireless communication system assumes all users are static and can cooperate with each other freely. However, the users with intelligence in the CRNs can sense the spectrum environment and consequently make a spectral decision. In order to obtain the limited frequency resources, more competition rather than cooperation will exist among the users. Thus, it is appropriate to utilize game theory to analyze the rational and selfish behavior of the users in dynamic CRNs.

Game theory aims to study the corresponding countermeasure and reach equilibrium when the interactions occur within the players in the game. Common process using game theory is shown in **Fig. 3**. Investigating the power control and interference limitation of the CRNs by game theory can handle the competition in the distributed spectrum allocation problems [43]. The CUs, which act as the players in the game process, would be responsible for the result of a game. The auction set contains the strategies which may be selected by the CUs. Different game conditions correspond to different auction set, and different players may choose different schemes even in the same game condition. If there are multiple players particitating in the game, in order to ensure the fairness of the game, all the CUs should make a spectral decision simultaneously. Information plays an important role in the game for the CUs. Acquiring more information can help the players to win the game more initiatively. A CU's benefit, which can be obtained from the selected strategy, is the utility of the game. According to the required performance of different applications, different utilities will be selected, such as maximizing frequency efficiency, minimizing system interference and guaranteeing the fairness of the allocation for the CUs.

4.3.1 Static Games of Complete Information

Static game assumes all the players take actions simultaneously and make the decision to earn most benefits selfishly. Cournot game can be used to analyze the CRNs with multiple CUs and only one PU [44]. In contrast to the traditional Cournot pattern, the price in the spectrum sharing is not a constant but a function. By adjusting the parameters of the price function, the CUs can choose the right spectrum and the utility of PU will be maximized at the same time. If there are multiple PUs coexisting with multiple CUs in the system, the PUs can be regarded as a whole, and then the considered network can be simplified to the aforementioned Cournot model with one PU and multiple CUs. For such a approach, both the benefit acquired by the PU and the QoS of the CU would be improved [45]. On the other hand, Bertrand model is more appropriate for the CRNs with multiple PUs and merely one CU.

4.3.2 Bayesian Game

The players are selfish and rational, and will not notify their information to others unless some benefits can be obtained, that is to say, the players can only acquire incomplete information. In order to overcome the above drawback, Bayesian game has been proposed. Owing to the incomplete information, Bayesian game aims to maximize the average utility [46].

4.3.3 Repeated Game

To describe long-term information interactions in spectrum sharing, repeated game, which is composed by multiple even infinite games, can be established [47]. In every game period, the strategy of one player depends on the past behaviors of the others. Considering long-term profits, any player may not try to maximize its own earning in current game round, but take the other players' benefits into account. Consequently repeated game is a cooperative scheme, and can maximize the gross earnings of the spectrum sharing system. However, it is difficult to obtain the Nash-equilibria for the repeated game, especially in the distributed network. Thus, the users should monitor and adjust the strategy continually until convergence is attained.

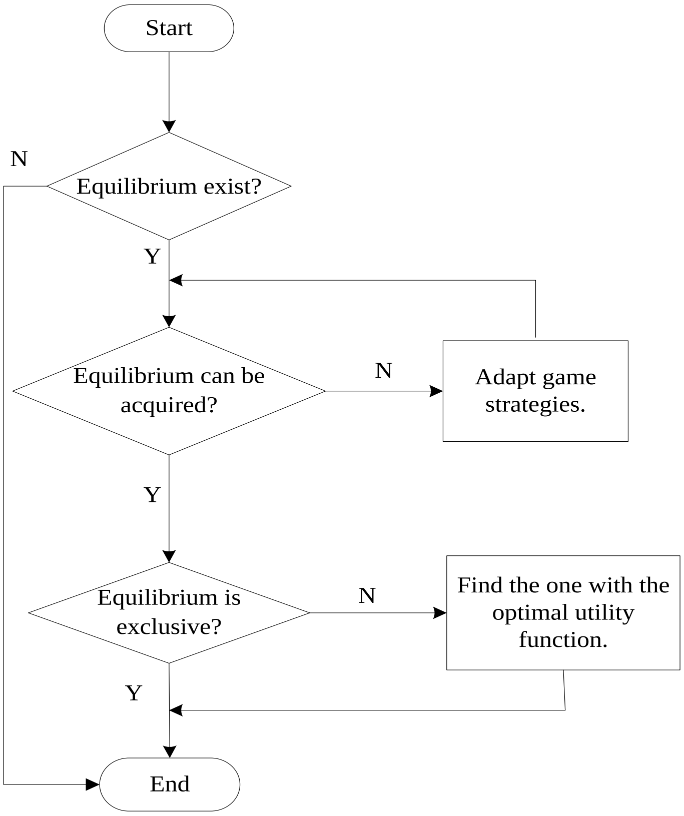


Fig. 3. Common process using game theory.

4.3.4 Evolutionary Game

Due to the difference among the players and the complexity of the game theory, the player may not obtain perfect information and some unexpected cases will also appear. To address these problems, evolutionary game emerges in time. Different from traditional game theory, it is not necessary for the players to be absolutely rational and own complete information in evolutionary game [48]. By this kind of game in spectrum sharing, the CUs can continually update the system parameters according to the variational wieless enviroment, and guarantee the system's stability.

4.3.5 Auction-based Game

In spectrum sharing system, if the PUs intent to sell the free spectrum to earn benefits, and the CUs would like to pay for these idle licensed spectrum, an auction-based game theory can be used to investigate the network. For such a strategy, the PUs and CUs act as seller and buyer respectively. The spectrum allocation on the basis of aution is regarded as an efficient sharing approach without a mass of information [41] [49] [50].

4.3.6 Cooperative Game

The essential difference between cooperative and non-cooperative games is whether there exists a binding agreement among the players. Since the PU and CU have common but not exactly same interests, the cooperative game approach with a binding agreement can combine the fairness with maximizing benefits for the users. Compared to selfish non-cooperative game, the cooperative game takes the interactions among the users into account, which makes the spectrum sharing more efficient and fair [51] [52]. If there are merely two players participate in the game, bargaining game theory should be applied. Otherwise coalition game is more suitable for the system with three or more players.

4.4 Graph Coloring

Graph coloring model abstracts the network topology consisting of the PU and CU as a graph, where the vertices represent the CUs, the edges denote the interference between the vertices. The coloring for the vertices can be viewed as a spectrum allocation process. Obviously, two vertices of one edge should not occupy the same frequency band, and every vertice can utilize different colors to indicate the number of idle channels that can be employed by the CUs [53-56].

Due to the uncertainty of the PU's arriving, and the variety of the wireless communication enviroment as well as the network topology, the available channel of the CU changes all the times. Therefore, CU should monitor the network topology periodically, and exchange the information constantly to update the topology information.

5. Our previous related works

In this section, several previous related researches will be discussed in brief. It should be noted that both our previous related papers adopt the interference temperature model to share the licensed frequency band with the spectrum underlay.

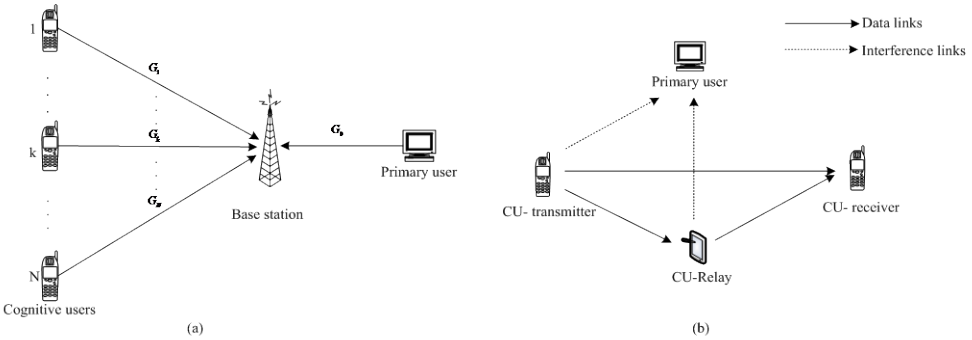


Fig. 4. System models of the previous related works

5.1 Opportunistic Scheduling for Uplink Cognitive Cellular Networks

In reference [22], we proposed a novel and efficient opportunistic scheduling strategy for an uplink cognitive cellular network (see **Fig. 4 (a)**), as considered in [32, 57, 58]. Different from previous proposals, the proposed strategy selects the CU with the best instantaneous channel quality in addition to guaranteeing the PU's operation without any degradation. Under the same outage protection threshold for the PU, numerical results manifest that our proposal yields an improved performance in terms of average rate and average bit error rate (BER) of the secondary system, as shown in **Fig. 5** and **Fig. 6**, respectively. This actually overthrew the previous observations on the considered spectrum-sharing framework, where it was deemed that the user with the weakest channel quality should be scheduled [57]. Moreover, with an increase in the number of CUs, both the average rate and the average BER of the proposed strategy are ameliorated, which are respectively illustrated in **Fig. 7** and **Fig. 8**. In contrast, the counterparts of the "weakest-channel-quality selection rule" remain unchanged. In addition, as depicted in **Fig. 9**, both numerical and analytical results indicated that in comparison with the strategy in [57], a much lower secondary transmit power is sufficient for the proposed strategy to achieve superior system performance under the same outage protection threshold for the PU, especially for a large number of CUs.

An intuitive explanation for the above advantages of our proposal is as follows: the average rate and the average BER of the secondary system are determined by the received signal-to-interference ratio (SIR) at the BS from the scheduled CU, which relies not only on the secondary transmit power but also on the channel gain of the selected CU. Although the "weakest-channel-quality selection rule" could lead to a higher secondary transmit power, the product of a high secondary transmit power and a low channel power gain is not necessarily larger than our proposal, i.e., "best-channel-quality selection rule". Inspired by this important observation, we propose to schedule the CU with the "best-channel-quality", which is in sharp contrary to the previous proposal. Moreover, extensive numerical results show that our proposal indeed leads to superior performance for the secondary system, while a much lower secondary transmit power is adequate. These merits render our proposal a very attractive solution for practical scenarios.

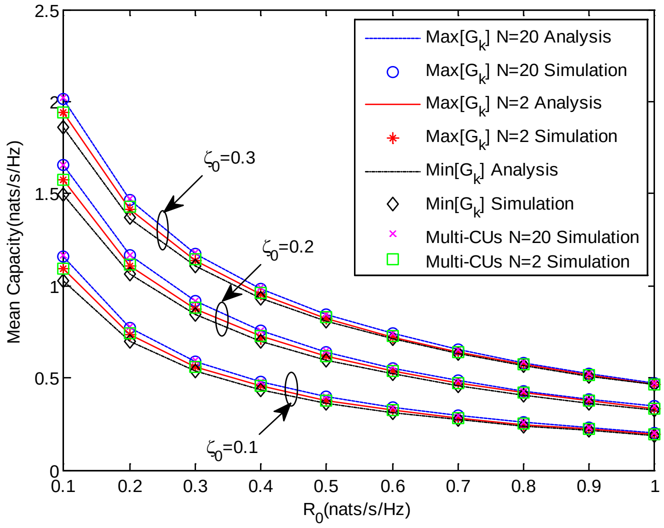


Fig. 5. Mean capacity of the cognitive system versus the target transmission rate R_0 for different scheduling schemes.

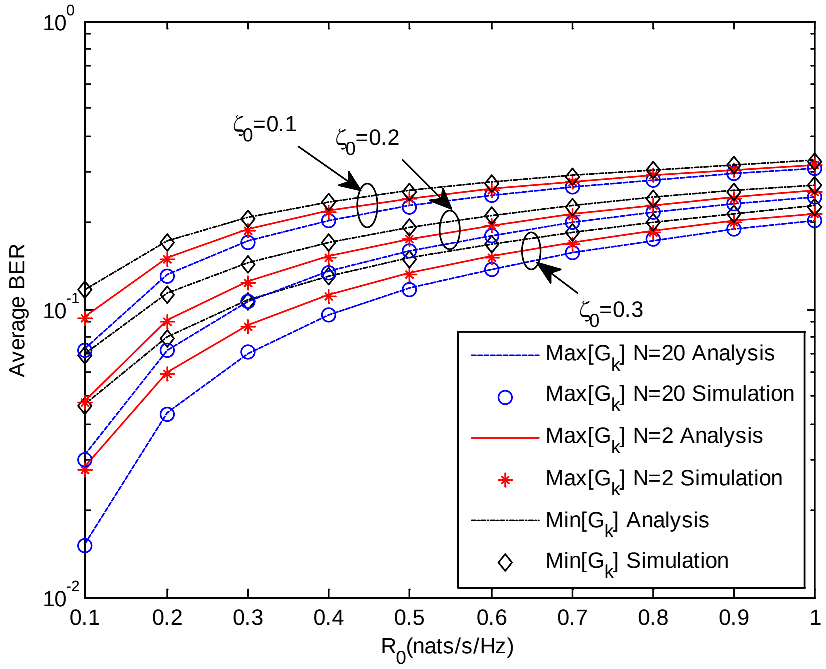


Fig. 6. Average BER of the selected CU versus the target transmission rate R_0 for different scheduling schemes.

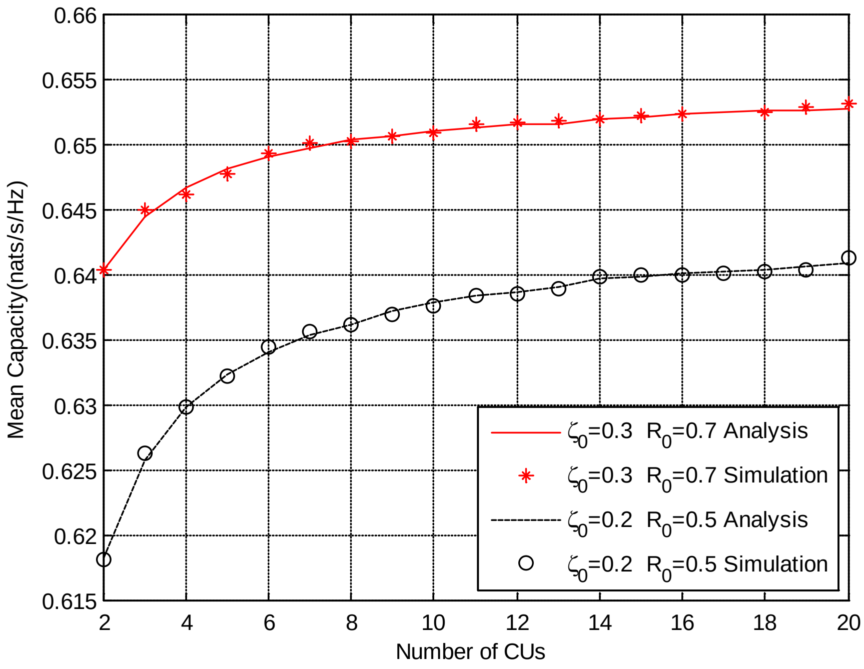


Fig. 7. Mean capacity of the scheduled CU of the proposed strategy versus the number of CUs.

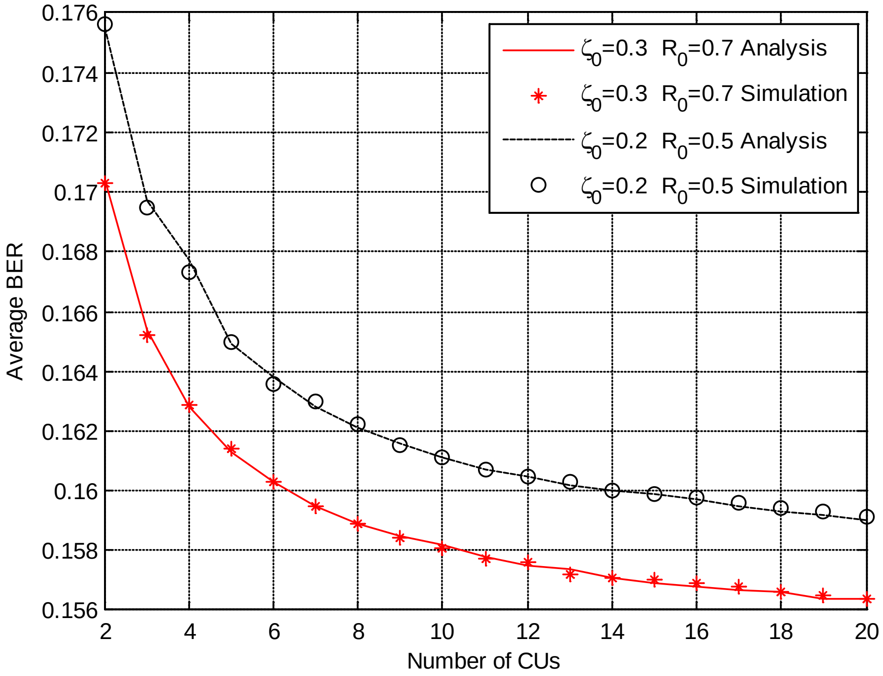


Fig. 8. Average BER of the scheduled CU of the proposed strategy versus the number of CUs.

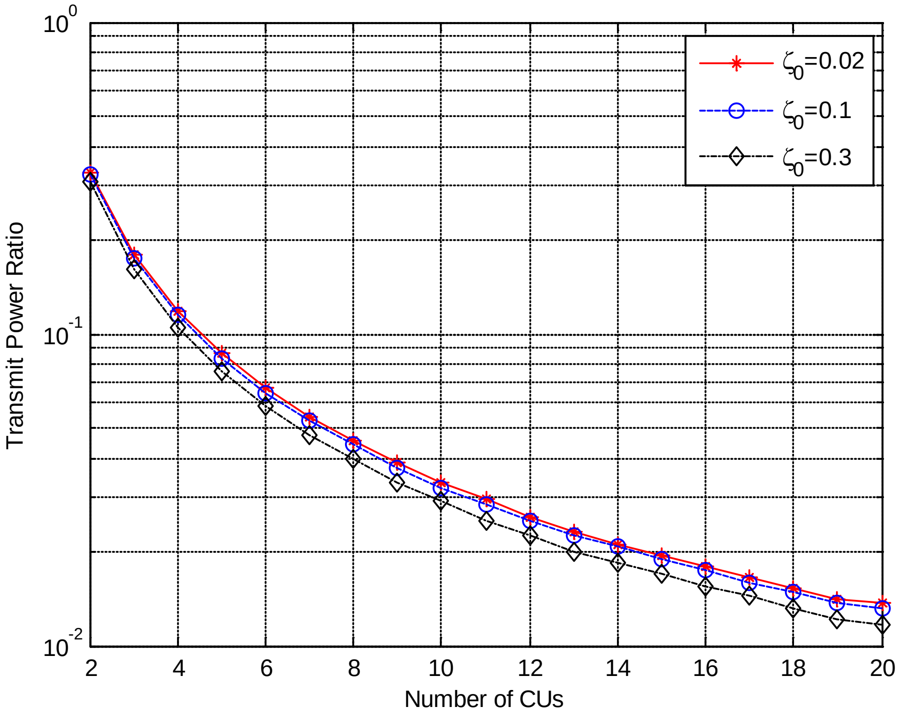


Fig. 9. Transmit power ratio of the proposed strategy to the previous proposal in [57] versus the number of CUs.

5.2 Distributed Link Selection Scheme for AF-based Cognitive Selection Relaying Networks

Inspired by the remarkable performance advantages in ameliorating the reliability and throughput of wireless systems utilizing cooperative relaying, we proposed a distributed link selection scheme for a cognitive amplify-and-forward (AF) relaying network in [33], as shown in **Fig. 4 (b)**. The importance of this work lies in that: this is the first attempt to design high-efficient link selection schemes for cognitive cooperative relaying systems. Before our work, the traditional link selection schemes in cognitive relaying systems employed a centralized link decision mechanism to schedule the transmission routes. Since the link scheduling in cognitive relaying systems involves not only the channel state information (CSI) of the secondary relaying systems but also the CSI between the secondary nodes and the primary receiver, the centralized scheduling will incur significant signaling overhead to collect the global CSI in the cognitive relaying environments. As a result, a problem naturally appears: can we make a more efficient link selection for cognitive relaying systems without collecting the global CSI? After much deliberation, we realize that it is indeed feasible to design a high-efficient link selection scheme, and the core idea of the proposed scheme is to use local CSI decision and decision feedback to replace the centralized link scheduling.

By using the above core idea, the proposed high-efficient distributed link selection scheme only consumes extremely low signaling feedback overhead to achieve almost the same system outage performance, as compared with previous centralized link selection scheme, which is depicted in **Fig. 10**. To be more specific, by replacing the 4-bit quantization feedback of the instantaneous link SNR pertaining to the second-hop γ_{RD} with the "success/fail" local decision feedback, the distributed protocol yields merely 2-bit signaling overhead even in the worst case, i.e., when the local decision at CU-transmitter S is inadequate to make a link selection. On the other hand, the best case appears when S can make link selection based on its local CSI γ_{DT} and γ_{SR}. In this case, the direct link will be chosen without the need of any signaling feedback.

Moreover, **Fig. 11** shows when the relay R lies between CU-transmitter S and CU-receiver D, the signaling overhead of the distributed scheme decreases with an increasing distance between S and R, as shown in **Fig. 11(a)**. The foregoing phenomenon can be explained as follows. Placing R closer to D can improve the average channel quality of the $R \to D$ link while deteriorating that of the $S \to R$ link. For the distributed scheme, a lower quality of the $S \to R$ link makes the event $\{\gamma_{DT} \geq \gamma_{SR}\}$ happen with a high probability, which by its turn leads to a lower feedback overhead. On the other hand, while R slides outside the link $S \to D$, the signaling overhead of the distributed scheme decreases with an increase in the distance between S and R, as shown in **Fig. 11(b)**. For such a case, the average channel quality of the $S \to R$ link is better than that of the $R \to D$ links, which yields a low signaling feedback overhead since most of the time S can make link selection based on its local CSI and no signaling feedback is required. Particularly, no more than 1-bit feedback overhead is sufficient for our proposal to make an effective link selection. All the above advantages make our strategy very attractive in practice.

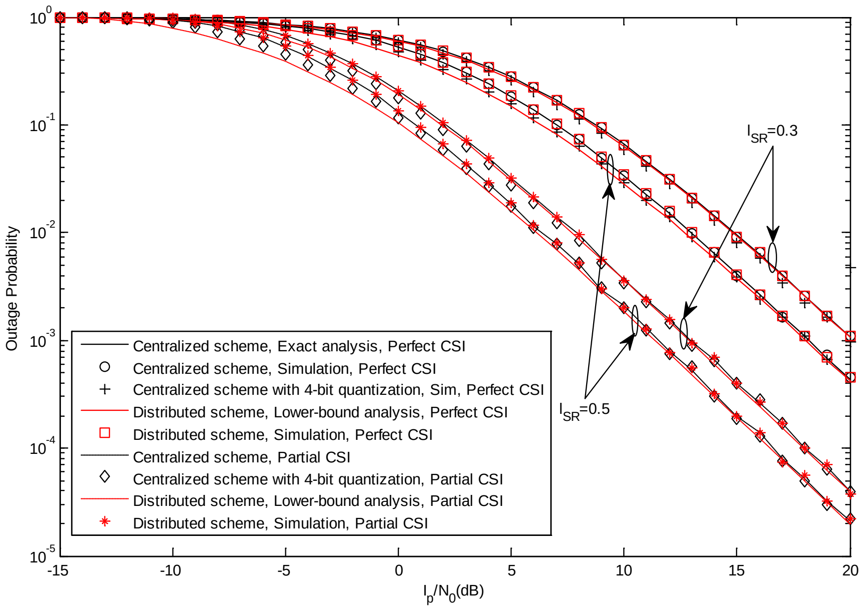


Fig. 10. Comparisons of the outage probability between the distributed scheme and the centralized scheme [59].

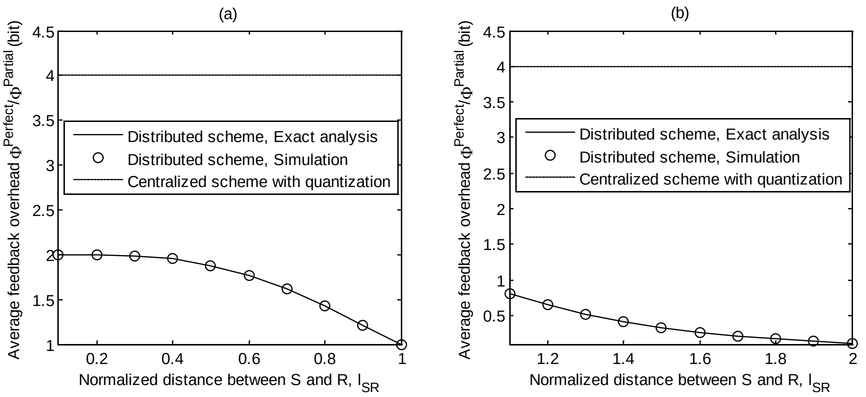


Fig. 11. Average feedback overhead of different schemes versus the distance between *S* and *R*. Herein, **Fig. (a)** shows the case of $l_{SR} = l_{SD} - l_{RD}$, l_{SD}=1, while **Fig. (b)** describes the case of $l_{SR} = l_{SD} + l_{RD}$, $l_{SD}=1$.

6 Applications of Spectrum Sharing in CRNs

Spectrum sharing in CRNs significantly improves the spectrum efficiency, and thus can be utilized in a variety of emerging applications [60], such as smart grid, public safety, broadband cellular, medical applications, etc.

6.1 Smart Grid

Smart grid, also named as intelli grid or modern grid, is established on the basis of the integrated and high-speed two-way communication networks, and can achieve the integration of electricity flow, information flow and service flow. The smart grid consists of Home Area Networks (HANs), Field Area Networks (FANs) and Wide Area Networks (WANs), in which HANs can utilize WiFi, ZigBee or HomePlug, and WANs can be the fiber-based IP backbone or the broadband cellular network, while appropriate technologies for FANs are still under consideration.

Currently, merely 900MHz unlicensed spectrum can be used by smart grid, which will become more and more crowded with the increasing unlicensed devices such as smart meters. Although IEEE 802.15.4g, the Smart Utility Networks Task Group, has suggested the FANs to use the 700MHz-1GHz and 2.4GHz license-exempt spectrum bands, there still exists other service in these bands. The cellular network is an alternative as well. However, the spectrum resource is also scarce for the cellular networks and high investment and operating costs could be introduced. Thus, it is effective to adopt spectrum sharing technologies to deal with the aforementioned problems. In other words, FANs with spectrum sharing have the advantages of lower interference and operating costs, as well as larger coverage area, which can satisfy the performance requirements of the smart grid and improve the spectrum efficiency.

6.2 Public Safety

Wireless communications are widely utilized in public safety networks to conduct the police, fire and emergency medical services. In order to deal with the accident as soon as possible, wireless laptops, handheld computers, and mobile video cameras would be carried with the public safety workers to transmit/receive the voice messages and emails, brow the webs, access the databases, transfer the pictures and so on, which consequently enhances the work efficiency. However, the allocated spectrum for the public safety network is already very crowded, especially in urban areas. In addition, different emergency service cannot communicate with each other, the standardization is lacking, both of which lead to inefficiency of the public safety network. Adopting the spectrum sharing technology of the CR, public safety workers can access the network anytime and anywhere, thereby providing reliable service for the public safety.

6.3 Broadband Cellular Network

Along with the rise of new devices (i.e., ereaders) and services (i.e., smartphones, social networks, media sites), cellular communication network would not only serve the traditional E-mail, simple voice service and web browsing. Broadband data services attract the users' attention, and bring opportunities as well as challenges for the operators. To satify the users' requirements, heterogeneous network is deployed by 3GPP LTE, IEEE 802.16m WiMAX and 4G LTE-Advanced. Moreover, hot spots and femtocell networks have also been designed to provide high speed and reliable data traffic for the users. However, recent report [61] reveals that the broadband spectrum deficit would approach 300 MHz by 2014. Thus, sharing available free spectrum can not only bring the new available spectrum resources, but also solve the interference in heterogeneous networks.

6.4 Medical Applications

Recently, wireless communication technologies have been implemented in medical body area networks (MBANs). In MBANs, on-body sensors can be used to monitor the patients' vital signs such as temperature, pressure, blood oxygen, and electrocardiogram (EGG), which would be sent to the doctors by wireless communication networks. Since the quality of medical services is very important for the patients, the requirements of QoS for the MBANs is strict. For this reason, a relatively clean and less crowded frequency band is necessary for the MBANs. The allocated 2.4 GHz spectrum band can not satisfy the QoS of MBANs due to the interference and congestion of wireless networks. To ensure the QoS requirements of MBANs, FCC proposes that spectrum sharing technologies of CR can be utilized for the MBANs to access the 2360-2400 MHz band opportunistically.

7. Open research issues

As an intelligent solution for the frequency shortage, the present research of spectrum sharing in CRNs is still in the initial development stages, and many theoretical and application issues remains to be addressed.

(1) In order to acquire better resource sharing solutions or more flexible schemes, seamless combination of auction and other non-auction approaches is worthwhile to investigate. Moreover, in a spectrum auction, the following problems should be studied in depth: (i) How much spectrum should be sold by the PUs? (ii) Which CU will obtain the free frequency band? (iii) The CUs can occupy the idle spectrum under what circumstances? (iv) How many costs should be paid for the CUs to get the spectrum to maximize their own utility?

(2) Besides maximizing the system benefit, as a key technology of CR, spectrum sharing still faces another challenge, i.e., the QoS of the CUs. To satisfy the different QoS requirements of the CUs, some proposals have been presented. Under the guarantee of the user's QoS, the authors of [62] introduced a sharing scheme which earns the maximum benefit of the network by sacrificing the fairness of the allocation. Reference [63] proposed an adaptive strategy which was a fairness spectrum sharing method and can acquire the maximum benefits of the system at the expense of the QoS of the users. Consequently, an important problem appears: how to keep a higher system benefit and a lower algorithm complexity, and simultaneously guarantee the fairness of the spectrum allocation on the premise of satisfying the users' QoS?

(3) The existing investigations of spectrum sharing in CRNs often assume some simple and ideal system configurations, which may not reflect practical scenarios. Thus, there still exist many practical spectrum sharing issues for us to address in CRNs. For example, different from many state-of-the-art works [50] [64], if there exist multiple CUs in the considered system or more complicated/practical channel fading environment are assumed, how to improve the bargaining powers of the CUs to guarantee the fairness and efficiency of the cooperation among the PU and CUs?

(4) In general, CRN is a dynamic system, due to the time-variation nature of communication environment, the accuracy of information, the movement of users and the variety of the users' operation. Especially, the practical topology of the CRN will change with the updated information of the spectrum sensing and allocation of the CUs. That is to say, the spectrum sensing results influence the subsequent spectrum sharing directly. However, since the current spectrum sensing technologies are not perfect enough, the CUs may only obtain the incomplete information of the licensed spectrum [65] [66]. To tackle this problem, combining the spectrum sharing with sensing information should attract the researchers' attentions. In particular, how to reduce the system's signal overhead when the sensing information is taken into account in spectrum sharing process?

(5) While the QoS of the PU cannot be satisfied, the service will intermit. In this case, the PU may offer some licensed spectrum to the CUs to realize cooperative transmission. Afterward, the CUs can transmit their own data [67] [68]. This kind of cooperation between the CUs and PU can enhance the PU's QoS as well as the spectrum efficiency of the CRNs. However, owing to the selfish characteristic of the CUs, most collaboration of the CUs would not satisfy the PU's expectation. Thus, how to inspire the CUs to participate in the cooperation?

(6) It is well-known that, cooperative relaying can provide remarkable performance in

ameliorating the reliability and throughput of wireless communication systems. Recently, incorporating relays into CRNs have received tremendous attentions due to its aforementioned merits [33]. The cooperative relay technologies are comparatively mature nowadays, so applying more relay technologies into CRNs are worthy studying in the future for the combinational advantages of the cooperative relay and CR technologies.

7. Conclusion

With the rapid development of wireless communication, existing frequency resources obviously cannot satisfy the increasing needed any more. Owing to the flexibility and high efficiency, dynamic spectrum sharing in CRNs provides a novel idea to deal with the scarce spectrum in conventional static spectrum sharing strategy. This survey discussed the spectrum sharing procedure and the key technologies of spectrum sharing in CRNs, such as centralized and distributed spectrum sharing, cooperative and non-cooperative spectrum sharing and DSA. Subsequently, four spectrum sharing models, i.e., interference temperature, auction-based model, game theory and graph coloring were investigated in detail. Several applications and open research issues have been also discussed in brief.

References

[1] J. P. Conti, “The Internet of things,” *Communications Engineer*, vol. 4, no. 6, pp. 20-25, 2006. Article (CrossRef Link)

[2] M. Martsola, T. Kiravuo, J. K. O. Lindqvis, “Machine to machine communication in cellular networks,” in *Proc. of IEEE International Conf. on Mobile Technology, Applications and Systems*, pp.1-6, 2005. Article (CrossRef Link)

[3] W. Tuttlebee, *Software Defined Radio: Origins, Drivers and International Perspectives*, NewYork: Wiley, 2002.

[4] Federal Communications Commission, Spectrum Policy Task Force, Rep. ET Docket no. 02-135, Nov. 2002.

[5] F. Capar, T. Weiss, I. Martoyo and F. Jondral, “Analysis of coexistence strategies for cellular and wireless local area networks,” in *Proc. of IEEE Vehicular Technology Conference*, pp. 1812-1816, Oct. 2003. Article (CrossRef Link)

[6] R. W. Broderson, A. Wolisz, D. Cabric and S. M. Mishra, CORVUS：A cognitive radio approach for usage of virtual unlicensed spectrum. Berkeley Wireless Research Center (BWRC) White paper, 2004.

[7] Q. Zhao and B. M. Sadler, “A survey of the dynamic spectrum access,” *IEEE Signal Processing Magazine*, vol. 24, no.3, pp. 79-89, May 2007. Article (CrossRef Link)

[8] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran and S. Mohanty, “Next generation/dynamic spectrum access/ cognitive radio wireless networks: A survey,” *Comput Netw*., vol. 50, pp. 2127－2159, Sep. 2006. Article (CrossRef Link)

[9] D. Cabric, S. M. Mishra and R. W. Brodersen, “Imprementation issues in spectrum sensing for cognitive radios,” in *Proc. of ASILOMARSSC*, vol. 1, pp. 772-776, 2004. Article (CrossRef Link)

[10] F. F. Digham, M. -S. Alouini and M. K. Simon, “On the energy detection of unknown signals over fading channels,” *IEEE Trans. Commun*., vol. 55, no. 1, pp. 21-24, 2007. Article (CrossRef Link)

[11] G. Ganesan and Y. G. Li, “Cooperative spectrum sensing in cognitive radio networks,” in *Proc.of IEEE DySPAN* 2005, pp. 137-143, Nov. 2005. Article (CrossRef Link)

[12] A. Ghasemi and E. S. Sousa, “Collaborative spectrum sensing for opportunistic access in fading environment,” *IEEE DySPAN* 2005, pp. 131-136, Nov. 2005. Article (CrossRef Link)

[13] W.-Y. Lee and I. F. Akyildiz, “A spectrum decision framework for cognitive radio networks,” *IEEE Trans Mobile Comput*., vol. 10, no. 2, pp. 161–174, 2011. Article (CrossRef Link)

[14] Y. Chen, G. Yu, Z. Zhang, H. Chen and P. Qiu, "On cognitive radio networks with opportunistic power control strategies in fading channels," *IEEE Trans. on Wireless Communications*, vol. 7, no. 7, pp. 2752-2761, July, 2008. Article (CrossRef Link)

[15] W. Yu, Competition and Cooperation in Multi-user Communication Environments, Ph.D. dissertation, Stanford University, Stanford , CA, 2002.

[16] D. Goodman and N. Mandayam, "Power control for wireless data," *IEEE Personal Communication*, vol. 7, no. 2, pp. 48-54, Apr. 2000. Article (CrossRef Link)

[17] Cem U. Saraydar,Narayan B. Mandayam, David J. Goodman, "Efficient power control via pricing in wireless data networks," *IEEE Trans Commun.*, vol. 50, no. 2, pp. 291-303, Feb. 2002. Article (CrossRef Link)

[18] X. Wang and Q. Zhu, "Power Control for Cognitive Radio Base on Game theory," *IEEE Wireless Commun.*, pp. 1256-1259, Sep. 2007. Article (CrossRef Link)

[19] I. F. Akyildiz, W-Y Lee, M. C. Vuran and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40-48, Apr. 2008. Article (CrossRef Link)

[20] G. Salami, O. Durowoju, A. Attar, O. Holland, R. Tafazolli, and H. Aghvami, "A comparison between the centralized and distributed approaches for spectrum management," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 2, pp. 274-290, Second Quarter 2011. Article (CrossRef Link)

[21] S. Sankaranarayanan, P. Papadimitratos, A. Mishra and S. Hershey, "A bandwidth sharing approach to improve licensed spectrum unilization," in *Proc. of IEEE DYSPAN*, pp. 179-288, 2005. Article (CrossRef Link)

[22] T. Xu, J. Ge and H. Ding, "Opportunistic scheduling for uplink cognitive cellular networks with outage protection of the primary user," *IEEE Commun. Lett.*, vol. 17, no. 1, pp. 71-74, Jan. 2013. Article (CrossRef Link)

[23] J. Zhao, H. Zheng and G. Yang, "Distributed coordination in dynamic spectrum allocation networks," in *Proc. of IEEE DYSPAN*, pp. 259-268, 2005. Article (CrossRef Link)

[24] R. J. Berger, "Open spectrum: a path to ubiquitous connectivity," ACM Queue, vol. 1, pp. 60-68, May 2003. Article (CrossRef Link)

[25] D. N. Hatfield and P.J. Weiser, "Property rights in spectrum: taking the next step," in *Proc. of IEEE DYSPAN*, pp. 43-55, 2005. Article (CrossRef Link)

[26] L. Xu, R. Tonjes, T. Paila, W. Hansmann, M. Frank and M. Albrecht, "DRiVE-ing to the inernet: Dynamicradio for ipservices in vehicular environments," in *Proc. of IEEE LCN*, pp. 281-289, 2000. Article (CrossRef Link)

[27] A. Goldsmith, S. A. Jafar, 1. Marie and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: An information theoretic perspective," in *Proc. of IEEE*, vol. 97, no. 5, pp. 894-914, 2009. Article (CrossRef Link)

[28] J. Mitola, "Cognitive radio for flexible mobile multimedia communications," in *Proc. of IEEE Mobile Multimedia Conf.*, pp. 3-10, 1999. Article (CrossRef Link)

[29] Y. Benkler, "Overcoming agoraphobia: Building the commons of the digitally networked environment," *Harvard Journal of Law & Technology*, vol. 11, no. 2, 1998.

[30] W. Lehr and J. Crowcroft, "Managing shared access to a spectrum commons," in *Proc. of IEEE DySPAN*，pp. 420-444, Nov. 2005. Article (CrossRef Link)

[31] A. Ghasemi and E. S. Sousa, "Fundamental limits of the spectrum-sharing in fading environments," *IEEE Trans. Wireless Commun.*, vol. 6, no.2, pp.649-658, 2007. Article (CrossRef Link)

[32] H. Ding, J. Ge, D. B. da Costa and Z. Jiang, "Energy-efficient and low-complexity schemes for uplink cognitive cellular networks," *IEEE Commun. Lett.*, vol. 14, no. 4, pp. 1101-1103, Dec. 2010. Article (CrossRef Link)

[33] T. Xu, J. Ge and H. Ding, "An efficient distributed link selection scheme for AF-based cognitive selection relaying networks," *IEEE Commun. Lett.*, vol. 18, no. 2, pp. 253-256, Feb. 2014. Article (CrossRef Link)

[34] Federal Communications Commission, "Establishment of interference temperature metric to quantify and manage interference and to expand available unlicensed operation in certain

fixed mobile and satellite frequency bands," *ET Docket 03-289. Notice of Inquiry and Proposed Rulemaking*, 2003.

[35] T. Duong, D. B. da Costa, T. A. Tsiftsis, C. Zhong and A. Nallanathan, "Outage and Diversity of Cognitive Relaying Systems under Spectrum Sharing Environments in Nakagami-*m* Fading," *IEEE Commun. Lett.*, vol. 16, no. 12, pp. 2075-2078, Dec. 2012. Article (CrossRef Link)

[36] Y. Chen, Y. Wu, B. Wang and K. J. R. Liu, "Spectrum auction games for multimedia streaming over cognitive radio networks," *IEEE Trans. on Wireless Commun.*, vol. 58, no. 8, pp. 2381-2390, Aug. 2010. Article (CrossRef Link)

[37] S. Gaurav, Kasbekar and S. Saswati, "Spectrum auction framework for access allocation in cognitive radio networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 18, no. 6, pp. 1841-1854, 2010. Article (CrossRef Link)

[38] M. Khaledi and A. A. Abouzeid, "Auction-based spectrum sharing in cognitive radio networks with heterogeneous channels," in *Proc. of Information Theory and Applications Workshop (ITA)*, pp. 1-8, 2013. Article (CrossRef Link)

[39] Y. Liu, X. Liu, Z. Li and H. Zhang, "Collusion-resistant dynamic spectrum resource renting and offering mechanism," *Journal of Jilin University (Engineering and Technology Edition)*, vol. 41, no. 5, pp. 1497-1502, Sep. 2011.

[40] Y. Xing, R. Chandramouli and C. Cordeiro, "Price dynamics in competitive agile spectrum access markets," *IEEE J. Select Areas Commun.*, vol. 25, no. 3, pp. 613-621, 2007. Article (CrossRef Link)

[41] Y. Liu, J. Cai, Z. Li, H. Zhang and Q. Liu, "Dynamic spectrum allocation based on continuous double auctions in cognitive radio networks," *Journal of Xidian University*, vol. 36, no. 6, pp. 996-1002, Dec. 2009.

[42] G. Sun, X. Feng, X. Tian, X. Gan, Y. Xu, X. Wang and G. Mohsen, "Coalitional Double Auction for Spatial Spectrum Allocation in Cognitive Radio Networks," *IEEE Trans on Wireless Commun.*, vol. 13, no. 6, pp. 3196-3206, June 2014. Article (CrossRef Link)

[43] M. Voorneveld and P. Borm, "Congestion Games and Potentials Reconsidered," *International Game Theory Review*, pp. 283-299, 1999. Article (CrossRef Link)

[44] D. Niyato and E. Hossain, "A game-theoretic approach to competitive spectrum sharing in cognitive radio networks," in *Proc. of IEEE WCNC*, 2007. Article (CrossRef Link)

[45] S. Hoda and A. Bahman, "Optimal quality competition for spectrum sharing in cognitive radio networks," in *Proc. of ICEE*, 2010. Article (CrossRef Link)

[46] J. Martyna, "Power Allocation Games for Cognitive Radio Networks with Incomplet Information," *Processing of Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, pp. 1-4, July 2012. Article (CrossRef Link)

[47] R. Etkin, A. Parekh, and D. Tse, "Spectrum sharing for unlicensed bands," *IEEE Journal on selected areas in communications*, vol. 25, no. 3, pp. 517–528, Apr. 2007. Article (CrossRef Link)

[48] D. Niyato, E. Hossain and Z. Han, "Dynamics of multiple-seller and multiple-buyer spectrum trading in cognitive radio networks: A game-theoretic modeling approach," *IEEE Trans, Mobile Comp.*, vol. 8, no. 8， pp. 1009-1022， Aug. 2009. Article (CrossRef Link)

[49] Y. Teng, Y. Zhang, C. Dai, F. Yang and M. Song, "Dynamic spectrum sharing through double auction mechanism in cognitive radio networks," in *Proc. of IEEE WCNC*, pp. 90-95, Mar. 2011. Article (CrossRef Link)

[50] S. Vassaki, M. I. Poulakis, A. D. Panagopoulos and P. Constantinou, "An auction-based mechanism for spectrum leasing in overlay cognitive radio networks," *Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 2733-2737, 2013. Article (CrossRef Link)

[51] H. Xu and B. Li, "Efficient resource allocation with flexible channel cooperation in OFDMA cognitive radio networks," *Prvc. IEEE INFOCOM*, 2010. Article (CrossRef Link)

[52] C. G. Yang, J. D. Li and Z. Tian, "Optimal power control for cognitive radio networks under coupled interference constraints: A cooperative game-theoretic perspective," *IEEE Trans. Veh. Technol.*,vol. 59, no. 4, pp. 1696-1706, May 2010. Article (CrossRef Link)

[53] E. Driouch and and W. Ajib, "Downlink Scheduling and Resource Allocation for Cognitive Radio MIMO Networks," *IEEE Trans. Vech. Technol.*, vol. 62, no. 8, pp. 3875-3885, Oct. 2013.

Article (CrossRef Link)

[54] P. Hu, J. Ye, F. Zhang, S. Deng, C. Wang and W. Wang, "Downlink Resource Management Based on Cross-Cognition and Graph Coloring in Cognitive Radio Femtocell Networks," in *Proc. of Vehicular Technology Conference (VTC Fall)*, pp. 1-5, Sep. 2012. Article (CrossRef Link)

[55] Y. Wang, Z. Wei, H. Du, L. Sang and D. Yang, "A Spectrum Allocation Algorithm Based on Bandwidth Matching and Interference Avoidance in Cognitive Radio Networks," *Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 950-955, Sep. 2012. Article (CrossRef Link)

[56] E. Driouch, W. Ajib and A. B. Dhaou, "A Greedy Spectrum Sharing Algorithm For Cognitive Radio Networks," *Computing, Networking and Communications (ICNC)*, pp. 1010-1014, 2012. Article (CrossRef Link)

[57] D. Li, "Performance analysis of uplink cognitive cellular networks with opportunistic scheduling," *IEEE Commun. Lett.*, vol. 14, no. 9, pp. 827-829, Sep. 2010. Article (CrossRef Link)

[58] L. Fan, X. Lei, "A Comment on 'Performance analysis of uplink cognitive cellular networks with opportunistic scheduling'," *IEEE Commun. Lett.*, vol. 14, no. 4, pp. 361-361, Apr. 2010. Article (CrossRef Link)

[59] T. Q. Duong, V. N. Q. Bao, G. C. Alexandropoulos, and H. -J. Zepernick, "Cooperative spectrum sharing networks with AF relay and selection diversity," *Electron. Lett.*, vol. 47, no.20, pp. 1149-1151, Sep. 2011. Article (CrossRef Link)

[60] J. Wang, M. Ghosh and K. Challapali, "Emerging cognitive radio applications: A survey," *IEEE Communications Magazine*, vol. 49, no. 3, pp. 74-81, Mar. 2011. Article (CrossRef Link)

[61] Federal Communications Commission, "Mobile Broadband: The Benefits of Additional Spectrum," OBI tech. paper no. 6, Oct. 2010.

[62] K. Hamdi, W. Zhang and K. B. Letaief, "Uplink Scheduling with QoS provisioning for cognitive radio systems," in *Proc. of IEEE WCNC 2007*, pp. 2592-2596, 2007. Article (CrossRef Link)

[63] P. Xu, J. Li, K. Xu and H. Xu, "Algorithm of adaptive switch spectrum allocation rules in cognitive radio networks," *Journal of PLA University of Science and Technology*, vol. 9, no. 6, pp. 577-581, Dec. 2008.

[64] T. Duong, D. B. da Costa, E. Maged and V. N. Q. Bao, "Cognitive amplify-and-forward relay networks over Nakagami-*m* fading," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2368-2374, June 2012. Article (CrossRef Link)

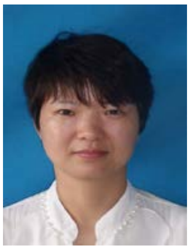
[65] Y. Chen, Q. Zhao and A. Swami, "Distributed Spectrum Sensing and Access in cognitive radio networks with energy constraint," *IEEE Trans. Signal Processing*, vol. 57, no. 2, pp.782-797, Feb. 2009. Article (CrossRef Link)

[66] K. W. Choi and E. Hossain, "Opportunistic access to spectrum holes between packet bursts: A learning-based approach," *IEEE Trans. Wireless. Commun*, vol. 10, no. 8, pp. 2497-2509, Aug. 2011. Article (CrossRef Link)

[67] H. Wang, L. Gao, X. Gan, X. Wang and E. Hossain, "Cooperative spectrum sharing in cognitive radio networks: A game-theoretic approach," in *Proc. of IEEE ICC*, pp. 1-5, May 2010. Article (CrossRef Link)

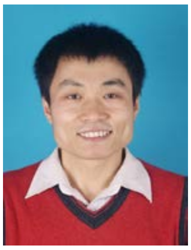
[68] W. Lu, Y. Gong, S. H. Ting, X. Wu and N. Zhang, "Cooperative OFDM relaying for opportunistic spectrum sharing: Protocol design and resource allocation," *IEEE Trans, on Wireless Commun.*, vol. 11, no. 6, pp. 2126 - 2135, June 2012. Article (CrossRef Link)

Tangwen Xu was born in Xi’an, Shannxi Province, China, in 1984. She received the B.S. degree in communication and information systems from Xidian University in July 2006. She is currently working toward the Ph.D. degree with the Department of Telecommunication Engineering, Xidian Univeraity. Her research interests focus on cognitive radio and cooperative communications.



Zhenshuang Li was born in 1978. She received the M.S. degree from Wuhan University of Technology. She works in the Department of Computer and Information Technology in Nanyang Normal University. Her research interests focus on the applications of computer.

Jianhua Ge was born in Jiangsu Province, China, in 1961. He received the B.Sc. and Ph.D. degrees, both in communications engineering, from Xidian University, Xi’an, China, in 1982 and 1990, respectively. He is currently a Professor and a Deputy Director of the State Key Laboratory of Integrated Services Networks, Xidian University, Xi’an, China. He has worked on digital television (DTV) standardization as a DTV Technical Expert. His research interests include digital video broadcasting system and multiple-input-multiple-output and mobile communication techniques.



Haiyang Ding was born in Hebei, China, in 1980. He received the B.Sc. degree in communications engineering from Xi’an Communications Institute of the PLA in 2003, the M.Sc. degree (with honors) in electrical engineering from Beijing University of Technology in 2006, and the Ph.D. degree with the Department of Telecommunications Engineering, Xidian University, in 2013. Since 2003, he has been with Xi’an Communication Institute of the PLA. At present, he is also a research fellow with the State Key Lab. of Integrated Services Networks (ISN), Xidian University. His research interests include channel modeling and characterization, cooperative communications, and cognitive radio systems.