IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 31, 2017, accepted January 29, 2018, date of publication February 5, 2018, date of current version April 18, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2802450

Full Spectrum Sharing in Cognitive Radio Networks Toward 5G: A Survey

FENG HU, BING CHEN, AND KUN ZHU
College of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Corresponding author: Bing Chen (cb_china@nuaa.edu.cn).

This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFB0802303, in part by the National Natural Science Foundation of China under Grant 61672283, and in part by the Funding of Jiangsu Innovation Program for Graduate Education under Grant KYLX15_0325.

ABSTRACT With the development of wireless communication technology, the need for bandwidth is increasing continuously, and the growing need makes wireless spectrum resources more and more scarce. Cognitive radio (CR) has been identified as a promising solution for the spectrum scarcity, and its core idea is the dynamic spectrum access. It can dynamically utilize the idle spectrum without affecting the rights of primary users, so that multiple services or users can share a part of the spectrum, thus achieving the goal of avoiding the high cost of spectrum resetting and improving the utilization of spectrum resources. In order to meet the critical requirements of the fifth generation (5G) mobile network, especially the *Wider-Coverage*, *Massive-Capacity*, *Massive-Connectivity*, and *Low-Latency* four application scenarios, the spectrum range used in 5G will be further expanded into the full spectrum era, possibly from 1 GHz to 100 GHz. In this paper, we conduct a comprehensive survey of CR technology and focus on the current significant research progress in the full spectrum sharing towards the four scenarios. In addition, the key enabling technologies that may be closely related to the study of 5G in the near future are presented in terms of full-duplex spectrum sensing, spectrum-database based spectrum sensing, auction based spectrum allocation, carrier aggregation based spectrum access. Subsequently, other issues that play a positive role for the development research and practical application of CR, such as common control channel, energy harvesting, non-orthogonal multiple access, and CR based aeronautical communication are discussed. The comprehensive overview provided by this survey is expected to help researchers develop CR technology in the field of 5G further.

INDEX TERMS 5G, cognitive radio, spectrum sharing, full-duplex spectrum sensing, carrier aggregation, energy harvesting.

I. INTRODUCTION

From the birth of the first generation (1G) mobile communication system, people's work, life style and the development trends of various industries have been profoundly affected. In order to cope with the explosive growth of mobile data traffic, massive device connection and continuous emergence of new business and application scenarios more effectively in the future, the fifth generation (5G) mobile communication system comes into being. Mobile Internet and Internet of Things (IoT) will be the major driving force for 5G development. In the future, 5G will not only meet the diverse needs of people in various regions such as residence, work, leisure, and transportation, but also will permeate the IoT and meet the various professional domains such as industry, medical, transportation and other industries to realize the true interconnectedness of all things [1].

With the rapid development of broadband wireless access and mobile terminal technology, people are eager to obtain information and services from the Internet at anytime, anywhere and even in the process of moving, and the mobile Internet has been developed rapidly in such a background [2]. It is mainly oriented to human-centered communication, focusing on providing the better user experience. In the future, the demand for communication experience will be more and more higher in various applications, such as remote areas, crowded stadium, and high-speed rail.

As the most up and coming technology, the IoT is increasingly receiving more and more attention from the academic and industrial circles [3], [4], and is considered one of the most important technologies that leads to an evolution of the network in the future [5], [6]. MIT professor Kevin Ashton and his colleagues first proposed the concept of IoT

TABLE 1. New requirements and challenges in 5G.

Application Scenario		Requirements & Challenges
Mobile Internet	*Wider-Coverage*	• To provide seamless, high-speed service experience at anytime and anywhere in harsh environments such as remote areas and high-speed mobile environments.
	Massive-Capacity	• To provide users with extremely high data transmission rate, and meet the network extremely high flow density requirements.
IoT	*Massive-Connectivity*	• To provide more than one hundred million connection support capabilities, and ensure ultra-low terminal power consumption.
	Low-Latency	• To provide users with millisecond end-to-end delay and near 100% service reliability Assurance.

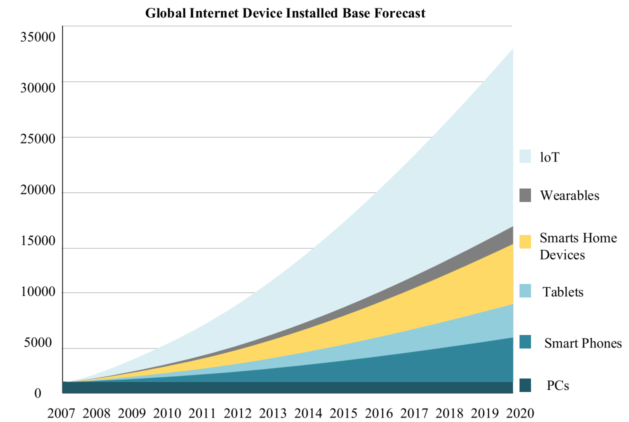


FIGURE 1. The IoT and connected devices in 2020.

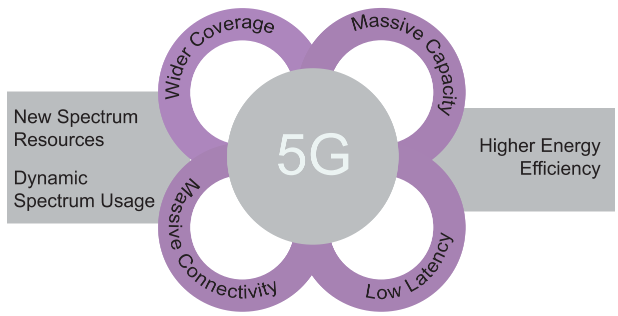


FIGURE 2. The network will be changed radically in 5G.

in 1999 [7]. They advocated to combine the radio frequency identification (RFID) technology with Internet technology successfully, and then achieve product information identification and management through the Internet. The central idea of IoT is to make object recognition, sensor networks, public communications networks and the Internet form one network which connects all objects [8], where people can communicate with the objects and can get variety information of them everywhere. Thanks to the rapid development of the cheaper small sensors, ubiquitous network, efficient cloud computing and big data, IoT has the potential to connect almost all things to the Internet. As illustrated in Figure 1, nearly 12 billion internet-connected devices have been used worldwide at the end of 2014, according to the research from Strategy Analytics [9]. That is equivalent to 1.7 devices for every person. As it can be seen, by the year 2020, when 33 billion devices like machine to machine (M2M), smart objects, smart grid, smart home, smartphones, PCs, tablets and wearable devices will be in use [10], [11]. With the development of information technology, the IoT will permeate all levels of the economy such as smart transportation, environmental protection, public safety, smart home, smart firefighting, industrial monitoring, geriatric care, personal health, water system monitoring, food traceability, reconnaissance and smart gathering.

The mobile Internet has subverted the traditional mobile communication service model and provided an unprecedented experience for users. IoT integrates the physical world and the virtual world, and affects people's behaviour and lifestyle through better connectivity and functionality. Owing to the rapid development of mobile Internet and IoT, 5G system will face new requirements and challenges in *Wider-Coverage*, *Massive-Capacity*, *Massive-Connectivity*, and *Low-Latency* four application scenarios as described in Table 1, furthermore these new requirements cannot be met in 4G and pre-generation technology. In order to address the challenges posed by differentiated performance indicators in diverse application Scenarios (see Figure 2), the network will radically change, such as new spectrum exploration, dynamic spectrum usage, and higher energy efficiency.

- **New spectrum exploration:** In the future, there must be a large number of smart terminal access to the Internet, by then, the scale of data generated by IoT will be much larger compared to the data generated by mobile communication and wireless access for communication between people [12]. In addition, the device/user data, routing, and control information are performed through the Industrial Scientific Medical (ISM) bands or mobile communication network [13]. Since the ISM bands (including RFID, Bluetooth, WIFI, ZigBee, NFC, UWB and so on) are the non-licensed frequency bands, devices can use them for free. Moreover, with the increase of IoT applications, ISM bands will become more congested. For the mobile communication bands (including 2G, 3G and 4G network), the spectrum requirement and allocation are based on the goal of communication between people, and it does not consider the traffic model of communication between people and things, and communication among things [14]. It may cause network congestion and unbalanced resource allocation. Consequently, the static spectrum allocation mechanism can no longer satisfy the growing demand for spectrum resources from various devices. If we do not attach great importance to these problems, the spectrum scarcity will become an insurmountable bottleneck in the development of 5G in the future.

- **Dynamic spectrum usage:** With the rapid growth of IoT users and terminals, the infrastructure and network framework are facing great challenges. In addition, the hardware and software of the device perform the data receiving, storing and forwarding tasks in the existing TCP/IP protocol [15]. The bigger of the amount of data, the harder in control and use will be. Therefore, using the existing Internet to carry on the IoT data transmission, it cannot adapt to the network dynamics and the complexity of the protocol and bring some difficulties to manage the large scale of IoT devices.
- **Higher energy efficiency:** As the continuous development of IoT, it will be a huge network that connects almost every aspect of our lives. Generally, IoT devices are powered by batteries, and the installation, maintenance, and replacement of the battery are not only difficult but also often costly [16]. Furthermore, in some industrial equipments, these devices are often placed in the areas that are difficult to access or inaccessible. Consequently, energy efficiency is critical facing such special applications. Aiming at the characteristic of IoT devices, the optimal energy management algorithm should be designed to realize the long-running and normal operation of devices.

The emergence of CR technology has been regarded as an efficient approach to cope up with the spectrum shortage and low utilization problems by dynamically re-use the frequency bands assigned to the licensed users [17], and seems to be the perfect answer to address the challenges and requirements that the 5G system will face [18]. The themes of CR have been given a lot of attention from the research community. Various aspects of several traditional sensing methods and cooperative sensing methods are outlined in [19], under the premise of giving multi-dimensional radio spectrum space and transmission opportunities. In order to satisfy the needs of cognitive users to detect spectrum opportunities reliably in a wide frequency range in the future, [20] summarized various wideband spectrum sensing algorithms and discusses the advantages and disadvantages of each algorithm and their challenging problems. [21] provided a survey of the state-of-the-art resource allocation algorithms for *Underlay* cognitive radio networks (CRNs) from the aspects of adopted approaches, criteria, techniques, and network architectures. On the basis of performance optimization criteria, [22] provided an overview of the recent advances in radio resource allocation in CRNs, and summarized these allocation schemes on the basis of performance optimization criteria including energy efficiency, throughput maximization, QoS assurance, interference avoidance, fairness and priority consideration, and hand-off reduction. Reference [23] presented an up-to-date survey of spectrum decision in CRNs based on spectrum characterization, spectrum selection, and CR reconfiguration. In [24], the *Overlay* spectrum access schemes in the cooperative CRNs, as well as in the non-cooperative and cooperative game model of the *Overlay*-based CRNs were reviewed. Reference [25] studied the concept of dynamic spectrum sharing, and investigated various existing spectrum sharing scenarios with different network topologies, features, challenges, and probable use cases. The summary of existing survey works on CR is shown in Table 2.

In this paper, our focus is to provide a comprehensive survey on full spectrum sharing in CR networks towards 5G. In spite of the extensive literature on CR, there are few papers to discuss the available spectrum exploration issues toward 5G, while several studies separate overview the spectrum sensing [20] and spectrum access [26] in CR networks. Reference [27] provided a comprehensive survey of CR, full-duplex communication and Long Term Evolution on unlicensed spectrum, as well as the multiple spectrum sharing techniques and identify potential challenges in 5G. Reference [28] outlined the spectrum sharing mechanism for the next generation cellular networks to overcome the energy crisis, and the spectrum sharing between satellite telecommunication networks and terrestrial has been surveyed in [29], which focuses on the investigation of the feasibility of spectrum sharing between geostationary orbit and non-geostationary orbit satellite systems. Compared with previous survey papers, our survey presents a comprehensive overview of full spectrum sharing in CR networks including the new spectrum utilization, spectrum sensing, spectrum allocation, spectrum access & spectrum handoff, and other research issues. The contributions of this paper are summarized as follows:

- We outline the spectrum resources that can be utilized by CR in 5G, as well as the recent focus on the new spectrum exploration.
- We present a comprehensive taxonomy of spectrum sharing in CR networks from the perspective of *Wider-Coverage*, *Massive-Capacity*, *Massive-Connectivity*, and *Low-Latency* four application scenarios. Particularly, the key enabling technologies that may be closely related to the study of 5G in the near future are summarized in terms of full-duplex spectrum sensing, spectrum-database based spectrum sensing, auction based spectrum allocation, carrier aggregation based spectrum access.
- We outline issues associated with the implementation of CR, such as common control channel, and provide an in-depth overview of the non-orthogonal multiple access and energy harvesting technologies from the perspective of improving spectrum efficiency and energy efficiency in CRNs.

The organization of this paper is shown in Figure 3. Section II elaborates on the background and motivation. In Section III, we present the recent advances and on-going

TABLE 2. Summary of existing survey works on CR.

Survey Papers	Aspects	Contributions
[19]	Spectrum Sensing	An overview of multi-dimensional radio spectrum space and transmission opportunities, and various aspects of several traditional sensing methods and cooperative sensing methods.
[20]		A detailed discussion of the advantages and disadvantages of various wideband spectrum sensing algorithms, as well as the use of sub-Nyquist techniques.
[21]	Resource Allocation	An overview on the resource allocation techniques for *Underlay* CRNs, as well as several comparisons between different approaches.
[22]		A summary of the recent advances in radio resource allocation in CRNs, and summarizes these allocation schemes on the basis of performance optimization criteria.
[23]	Spectrum Decision	A survey of spectrum decision in CRNs based on its three key functions including spectrum characterization, spectrum selection and CR reconfiguration.
[24]	Spectrum Access	A comprehensive summary of *Overlay* spectrum access schemes in the cooperative CRNs, as well as in the non-cooperative and cooperative games model of the *Overlay*-based CRNs.
[26]		A survey of the challenges of DSA and the future DSA model should be considered in terms of the political, social, economic, and technological factors.
[25]	Spectrum Sharing	An investigation of various existing spectrum sharing scenarios with different network topologies, features, challenges and probable use cases.
[27]		A comprehensive survey of CR, full-duplex communication and Long Term Evolution on unlicensed spectrum, as well as the multiple spectrum sharing techniques and identify potential challenges in 5G.
[28]		An overview of the spectrum sharing mechanism for the next generation cellular networks to overcome the energy crisis.
[29]		A comprehensive survey of the spectrum sharing between satellite telecommunication networks and terrestrial.

research directions in spectrum sensing relevant to 5G. Section IV describes the new advancements in spectrum allocation, and Section V discusses the spectrum access & spectrum handoff in full spectrum sharing. Section VI elaborates other research issues in full spectrum sharing including common control channel, energy efficiency, non-orthogonal multiple access, and aeronautical communication. Finally, we conclude our work in Section VII. For convenience, the list of abbreviations used in this paper are summarized in Table 3.

TABLE 3. Summary of abbreviations.

Abbreviation	Definition
5G	fifth generation
IoT	internet of things
RFID	radio frequency identification
M2M	machine to machine
ISM	industrial scientific medical
NFC	near field communication
UWB	ultra wide band
CR	cognitive radio
CRNs	cognitive radio networks
FDMA	frequency division multiple access
TDMA	time division multiple access
CDMA	code division multiple access
MIMO	multiple-input multiple-output
PU	primary user
SU	secondary user
UHF	ultra high frequency
AWGN	additive white gaussian noise
FH	frequency hopping
CP	cyclic prefix
HD	half-duplex
FD	full-duplex
OFDM	orthogonal frequency division multiplexing
LAT	listen and talk
BFS	brute-force search
PSO	particle swarm optimisation
BS	base station
D2D	device to device
IWNs	industrial wireless networks
SINRs	signal to interference plus noise power ratios
ADC	analog to digital converters
MWC	modulated wideband converter
SBL	sparse bayesian learning
TSO	TV spectrum owner
NIO	network infrastructure owner
DSA	dynamic spectrum access
CCC	common control channel
SVC	spatial variation control
NPG	non-cooperative power control game
NPGP	non-cooperative power control game via pricing
RF	radio frequency
NOMA	non-orthogonal multiple access

II. BACKGROUND & MOTIVATION

A. COGNITIVE RADIO NETWORKS

The radio spectrum management departments in different countries have something in common on the management of radio frequency spectrum resources, where the spectrum allocation method adopts the "fixed allocation" principle [30],

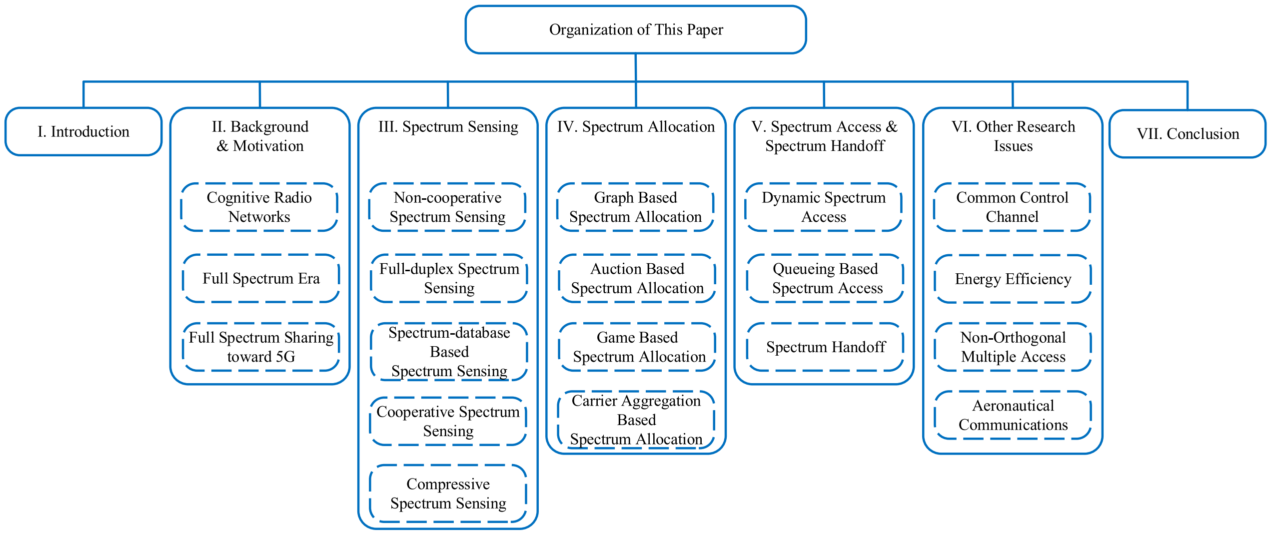


FIGURE 3. Organization of this paper.

in which spectrum is divided into several parts, where each part is assigned to different users while other users have no right to use it. The corresponding spectrum and user are called the licensed band and licensed user, respectively. However, with the rapidly and widely development of wireless communication technology, as a non-renewable resource, the spectrum resource has become extremely valuable [1]. Furthermore, a survey of the spectrum usage from Federal Communications Commission (FCC) [31] showed that a large number of spectrum resources have different degrees of idleness in time and space dimension because of the fixed allocation policy, even in some crowded bands, while only a small portion of the spectrum is used frequently. In order to improve the utilization of licensed spectrum as much as possible, various multiplexing technologies such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Multiple-Input Multiple-Output (MIMO) techniques are used to support more users on the limited spectrum resources [32], but they cannot fundamentally solve the problem of spectrum resources scarcity caused by fixed allocation policy.

In 1999, the concept of CR was first proposed by Dr. Mitola [33], and then Haykin defined the CR from the communication point of view [34], pointing out that it is an intelligent wireless communication system, and can automatically sense the usage of the surrounding spectrum and use the idle spectrum without affecting licensed users' normal communication. Generally speaking, the licensed users referred to as primary users (PUs) and the unlicensed users known as secondary users (SUs) or cognitive users. According to the definition of CR, as we have seen SU not only should have the ability of spectrum sensing to detect whether there existed available idle spectrum, and exit the spectrum immediately when the PU accesses again, but also should have the ability of reconfiguration to adjust the software and hardware parameters and working parameters, according to the spectrum sensing results.

B. FULL SPECTRUM ERA

The spectrum resources used in CR mainly include two categories, one is unlicensed bands, they don't belong to a particular user, and the use of such spectrum resources does not require licensed, furthermore SUs have the same priority of spectrum usage. The other is idle licensed bands, also known as ''spectrum holes''. The use of such spectrum resources is limited by the activities of PUs. Since PUs have the highest priority of spectrum usage, SUs are required to ensure that they do not interfere with the communication of PUs. Currently, the available spectrum resources are concentrated below 6GHz. The spectrum resources in this part have been basically allocated, especially the frequency bands below 3GHz. Compared with the licensed bands, the unlicensed bands are much less, and there are the ISM band and 5GHz WLAN band. For the ISM band, which is open to three major institutions of industry, science, and medicine, it can be used without license, as long as each user follows a certain transmit power and does not interfere with other frequency bands. WLAN, Bluetooth, ZigBee and other wireless communication technologies can work on this band. For the sake of solving the problem of fewer channels, more signals and serious interference in ISM band, the 5GHz band was officially identified for WLAN at the WRC-03 conference [35].

5G will face higher data transfer rates, richer business requirements, more rigorous user experience, and highly heterogeneous network architectures compared with 4G, consequently, the spectrum supply and demand contradictions will become increasingly prominent in the future. However, the frequency bands below 6GHz are already very crowded, and it is difficult to find abundant spectrum to meet

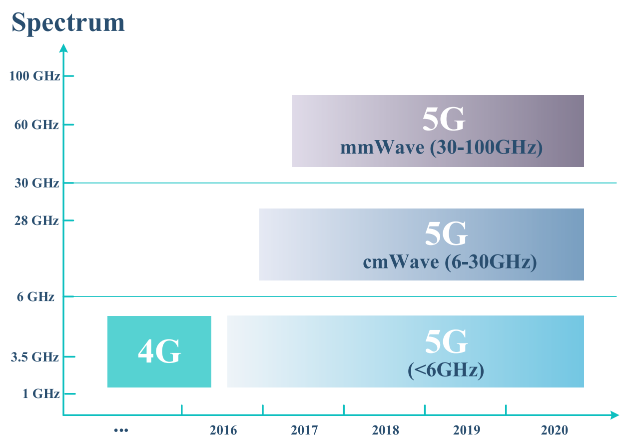


FIGURE 4. **The diagram of full spectrum era.**

the increasing spectrum demand. Comparatively speaking, the business division and usage of the spectrum above 6GHz are relatively simple, and it can provide continuous large bandwidth band. Therefore, in order to extend the capacity of the system and support the transmission of the higher data rate, the spectrum range used in 5G will be further expanded into the full spectrum era, possibly from 1GHz to 100GHz, as shown in Figure 4. The full spectrum involves low frequency bands below 6GHz and high bands over 6GHz, in which the low frequency bands are the core band in 5G, and the high-frequency bands are mainly used for local compensation due to the limitation of propagation characteristics.

According to the research, most licensed spectrum resources have not been fully utilized. Therefore, it is the heart of current research to solve the problem of spectrum resource scarcity through spectrum reallocation.

1) TV WHITE SPACES

The UHF band used in broadcasting and television is located in the same frequency band as the mobile communication system and has good propagation characteristics. However, with the digitization of analogue TV, the idle rate of frequency bands allocated to analogue broadcast TV is getting higher. Research in [36] showed that the current UHF band is very inefficient, and its average utilization rate is 4.54% in Singapore and 17.4% in Chicago. In order to make more effective use of the increasingly intense spectrum resources, the idle frequency bands used for analogue broadcast television (called "TV White Spaces") are allocated to mobile communications at the WRC-07 conference. The United States is actively promoting super WiFi [37], which is not the true sense of the WiFi, but refers to the TV White Spaces that is utilized to carry out data transmission. It is especially important to achieve high-speed Internet access in rural areas and geographical blind region where the wireless network is unavailable while the television signal is available.

2) 60GHz MILLIMETER WAVE

With the rapid development of IoT, short distance wireless communication among terminals is more frequent, and some new businesses and demands continue to emerge, such as uncompressed high definite and high quality video streaming, interactive games, massive download and ultra fast wireless data transmission, and these applications require data transfer rates up to Gbps. Traditional short distance wireless communication spectrum (such as 2.4GHz, 5GHz band) has been fully occupied by 802.11, Bluetooth, microwave and other applications. Due to the scarcity of low frequency wireless resources, the data rate is limited to further upgrade, even if the extremely high complexity communication technology are used to obtain a higher spectrum utilization.

With the continuous development of semiconductor technology such as CMOS. Many countries, including the United States and Europe, have divided 60GHz band into 5GHz $\sim$ 7GHz unlicensed continuous spectrum resources for general use [38]. The 60GHz has been widely studied in the academic and industrial fields due to its characteristics of large bandwidth, high transmission rate, high security and anti-interference [39]–[42]. The higher frequency of electromagnetic waves, the less the wavelength, furthermore, the diffraction ability of electromagnetic wave in the process of space transmission is even weaker. The results showed that the transmission distance of 60GHz millimeter wave is only 1m $\sim$ 10m due to the serious loss of the path [39], [40]. However, the unlicensed continuous large bandwidth is about seven times as much as the sum of other low frequency bands. Consequently, the 60GHz band has a great advantage in the high-speed indoor short distance communication. The IEEE 802.11ad defines a novel MAC architecture that 60GHz can be compatible with WiFi [41]. Since the 60GHz wireless signal direction is very strong, the interference among 60GHz communication signals in different directions are very small, which is beneficial to the space division multiplexing. In [42], the technology of beamforming antenna gain has been used to realize 60GHz high directional communication.

C. FULL SPECTRUM SHARING TOWARD 5G

CR technology makes it possible to reuse valuable spectrum resources without changing the existing spectrum allocation policy, thus addressing the problem of low utilization rate. The core idea of CR is to realize spectrum sharing through dynamic spectrum access, and the implication of spectrum sharing is that SUs can use the idle spectrum of PUs, but only if they cannot interfere with the communication of PUs. Typically, spectrum sharing includes four steps, as shown in Figure 5.

1) **Spectrum sensing**
   Spectrum sensing is the first step of spectrum sharing, which is the fundamental to ensure PUs from interference, to complete spectrum sharing, to improve spectrum utilization, and to realize various CR applications. SUs continuously detect the frequency bands that are being used by PUs in multi-dimensional space (such as time domain, spatial domain, frequency domain, etc.). Spectrum sensing is utilized to detect whether a PU

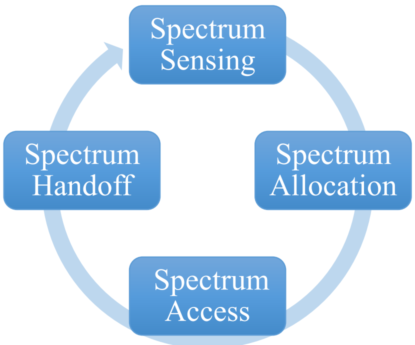


FIGURE 5. The spectrum sharing process.

appears and to determine if the spectrum hole is available. Therefore, the accurate perception of spectrum holes is the first step in spectrum sharing.

2) **Spectrum allocation**
Spectrum allocation is based on the availability of spectrum holes and distributes the spectrum to SUs. Since the number of spectrum holes is not fixed, SUs need to use them through competition while the QoS of SUs are different. Therefore, the spectrum holes have to be used fairly and efficiently. The key of spectrum allocation is to design efficient spectrum allocation algorithms and rules, which can improve the efficiency of spectrum utilization in the case of conflict minimization or conflict-free, preferably as close to the optimal target as possible.

3) **Spectrum access**
PU has the priority access rights of the frequency band, while the SU as subordinate relationship access it. Therefore, spectrum access requires an efficient access algorithm to coordinate multiple SUs access spectrum holes, avoiding conflicts between PUs and SUs.

4) **Spectrum handoff**
SU must switch to the appropriate spectrum when one of the following three situations occurs. First of all, when the SU using a current spectrum hole, the appearance of PU will cause collisions between them, thus SU must quit this frequency band, and then switch to the other spectrum holes for communication. Secondly, when the geographical location of the SUs changes, while the PU's geographical location does not change, the optional spectrum holes for the SUs will be different, and they need to switch to the appropriate frequency band. Finally, when the frequency bands used by SUs cannot meet their communication requirements, they must switch to other frequency band that can meet their communication needs.

Relatively speaking, the spectrum resources over 6GHz are more abundant, and the service division is relatively simple and can provide continuous large bandwidth spectrum. Therefore, the utilization of new spectrum resources over 6GHz has become the focus of current research. In order to meet the higher 5G spectrum requirements, it will be effective to utilize all kinds of spectrum resources, including low and high frequency bands, licensed and unlicensed frequency bands, and continuous and discontinuous frequency bands. Compared with the existing limited spectrum sharing, this is a kind of full spectrum sharing. Different frequency bands and multiple application scenarios pose some challenges to the implementation of full spectrum sharing such as the spectrum hole in the high frequency channel may not be accurately detected by using the conventional spectrum sensing algorithms, how to allocate low/high and continuous/discontinuous frequency bands for SUs to meet their needs, and energy consumption needs to be considered while maximizing spectrum efficiency. Next, we will make a comprehensive survey of several key technologies for implementing full spectrum sharing aiming at different application scenarios.

III. SPECTRUM SENSING

CR technology provides the possibility to improve the spectrum utilization as much as possible under the current spectrum resource allocation policy. SUs cannot only sense the spectrum environment around and access spectrum hole in the opportunity way, but also need to sense the presence of PUs constantly during they occupying the licensed spectrum and to terminate communications immediately when the PU reaccesses due to their priority are lower than the PUs. Hence, spectrum sensing is the key technology in CR and foundation of spectrum sharing. In this section, we first present the classical spectrum sensing approach, and then investigate the latest spectrum sensing algorithms for the multiple application scenarios in 5G. The summary of existing survey works on spectrum sensing approach is shown in Table 4.

A. NON-COOPERATIVE SPECTRUM SENSING

As illustrated in Figure 6, the purpose of spectrum sensing is to find the spectrum holes. In general, the spectrum being used (which is called "busy spectrum") contains the user signal and noise, so it has high power, while the spectrum hole has low power because it only contains noise. Consequently, spectrum sensing algorithms needs to be able to accurately determine which is the spectrum hole first. The spectrum sensing problem can be expressed as a two element hypothesis detection model [19]:

$$\begin{cases} H_0 : x(t) = n(t), \\ H_1 : x(t) = s(t) + n(t), \end{cases} \tag{1}$$

where $n(t)$ is an Additive White Gaussian Noise ($AWGN$), and $s(t)$ is the signal of PU in target channel. H_0 and H_1 are the two hypotheses of non-existence or existence of $s(t)$.

The first proposed spectrum sensing algorithms are based on the user's transmitter, like energy detection, matched filtering detection, and cyclostationary detection approaches [19], [43]–[45]. This kind of algorithm has the advantages of high technology maturity, low design difficulty, and easy realization. Thereinto, energy detection algorithm is the most simple

TABLE 4. The summary of existing survey works on spectrum sensing approach.

Technical Approaches	Description	Reference	Key Points
Full-duplex Spectrum Sensing	Each SU can use the spectrum holes uninterruptedly and mean while detect spectrum continuously.	[46–48]	Canceling the self interference of transceiver.
		[49–51]	Listen-and-Talk (LAT) protocol.
		[52]	Optimal detection thresholds.
		[53]	Considering the low SNR situations.
		[54]	A joint mode/rate adaptation strategies for WiFi/LTE-U.
Spectrum-database Based Spectrum Sensing	Each SU uploads the sensing result to BS, and then it will be compared with historical information in the spectrum data to find all available spectrum holes.	[55–57]	Exploiting spectrum table for spectrum sensing.
		[58]	A framework for determining the topology of vehicular network.
		[59]	A mobile crowd sensing-driven geolocation spectrum database for D2D communication.
		[60]	An iteratively developed history processing database.
Cooperative Spectrum Sensing	Combining the sensing results of multiple SUs to improve the detection reliability.	[61–63]	Proposing the fusion algorithms.
		[64]	Useing a directional antenna.
		[65]	Reliability-based cooperative decision fusion.
		[66]	Integrates quickest detection and belief propagation framework.
		[67–70]	Guaranteeing the high sensing accuracy in IWNs or vehicular networks.
		[71–75]	Suppressing malicious interference.
Compressive Spectrum Sensing	Each SU can extract and detect the wide band signal directly to achieve efficient wide band sensing with much lower sampling rate than the Nyquist criterion.	[76, 77]	Proposing the wideband spectrum sensing scheme.
		[78]	Considering the real-time signal.
		[79]	Improving processing speed and reducing sensing errors.
		[80, 81]	Analyze the sparsity of the wideband spectrum.
		[82, 83]	Reflecting the reality of spectrumoccupation.

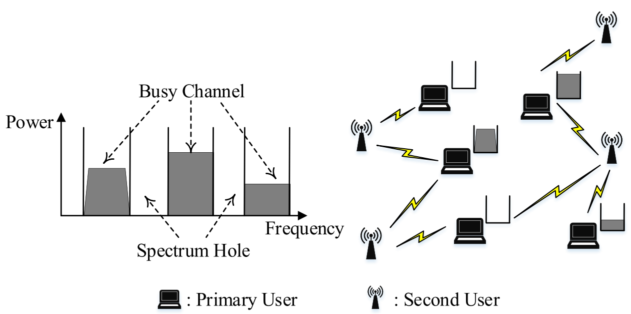


FIGURE 6. The diagram of spectrum sensing.

and widely used in the spectrum sensing algorithms [43], [44] since it does not require the prior information of the PU. The performance of the matched filtering detection algorithm is well, but it is closely related to the prior knowledge of the signal [19]. Cyclostationary detection algorithm [45] can detect the activity of PU based on the theory that signal statistical parameters (such as carrier frequency, power frequency hopping (FH) sequences, and cyclic prefix (CP)) have a certain periodicity to distinguish between signal and noise. It has a high recognition rate, but its computational complexity is prohibitive.

B. FULL-DUPLEX SPECTRUM SENSING

Most existing SUs deploy half-duplex (HD) mode to receive and transmit signals as shown in Figure 7, in which SUs sense the spectrum before transmission. It will not only sacrifice transmission time for spectrum sensing, but also lead to a collision when PUs arrive and spectrum waste when PUs leave owing to SUs cannot detect the change of PUs' status (active or inactive) during data transmission. If the PU re-accesses the channel again during the time of SU transmission, it can cause conflicts between them, and if the PU is in active state during the sensing period while is in inactive state during the transmission period, SU will not be able to detect the activity of PU in time, thus resulting

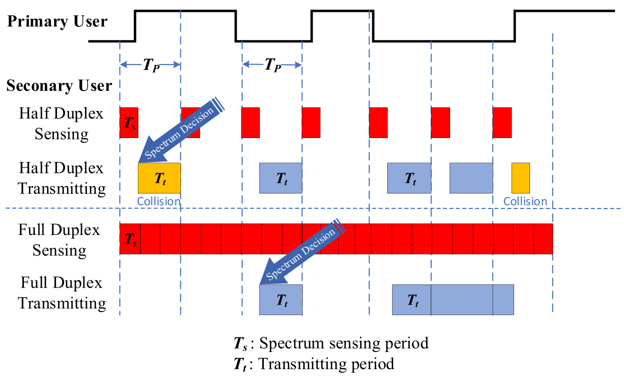


FIGURE 7. **The sensing frame structure between half-duplex (HD) mode and full-duplex (FD) mode.**

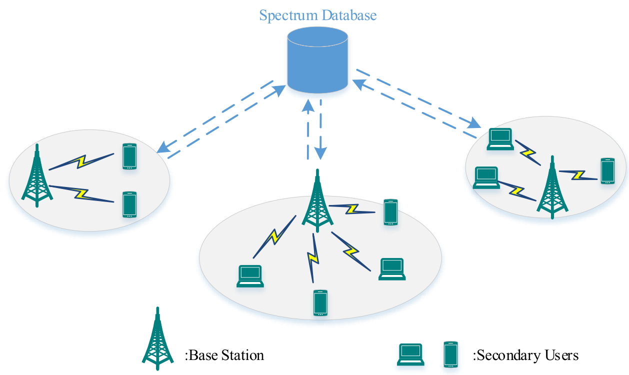


FIGURE 8. **The spectrum-database based spectrum sensing model.**

in the waste of spectrum resources. Furthermore, in order to offer higher data transmission rate for users to meet the network extremely high flow density requirements in the *Massive-Capacity* application scenario, SUs need to detect the available spectrum holes quickly and accurately. Consequently, it is hoped that the SUs can use the spectrum holes uninterruptedly and meanwhile sense spectrum continuously, i.e., the full-duplex (FD) mode. As can be seen from Figure 7, SU can simultaneously perform spectrum sensing and data transmission by using the full duplex spectrum sensing algorithm, which can not only reduce the probability of collision with PUs, but also improve the efficiency of spectrum usage.

One of the bottlenecks to realize the FD communication is how to cancel the self interference of transceiver [46]. That is, when the transmitter sends a signal, some energy can be received by the receiver itself, therefore, there will be interference when the signal is transmitted and received at the same time. Reference [46] realized a FD wireless communication system through three antennas, simulation, and digital elimination techniques, in which two antennas used for signal transmitting, and one antenna used for receiving. The realization of the zero interference of receiving antenna is based on the theory that when the distance between the two transmitting antennas and the receiving antenna is an odd number of half wavelength, the phase of the two transmit signals is opposite. Reference [47] proposed a FD system using two antennas and Balun cancellation technique, and it can also be used for wideband interference cancellation. In the same year, the OFDM FD communication system with two antennas was achieved [48].

With the recent development of the FD technology, several studies derived the "listen-and-talk" (LAT) protocol [49]–[51], in which SUs can sense the spectrum and transmit data at the same time and the same frequency. Reference [51] also designed an adaptively sensing threshold for energy detection, in which the SUs can achieve higher throughput. For a FD-CR network, optimal detection thresholds for single-user and cooperative spectrum sensing were derived through the brute-force search (BFS) and particle swarm optimisation (PSO) method [52]. Reference [53] considered the low signal to noise ratio (SNR) situation and designed a power function based weighting scheme for energy detection to improve the sensing performance. Furthermore, [54] proposed a joint mode/rate adaptation strategies for WiFi/LTE-U (i.e. extend the LTE-A services to the unlicensed spectrum) coexistence, where a FD enabled WiFi station can transmit and receive data simultaneously to improve the throughput, or transmit and sense simultaneously to monitor the LTE-U activity.

C. SPECTRUM-DATABASE BASED SPECTRUM SENSING

Continuous wider area coverage will be the inevitable trend to meet the needs of users in the future, which need to ensure the mobility of users and provide seamless high-speed service experience. Although many research works have concentrated on the development of effective spectrum sensing approach, the sensing overhead is large and the performance is limited in some existing sensing algorithms. Moreover, in order to protect the communication of PUs, the complexity of sensing algorithm will be obviously increased and the transmission power will be restricted. Recent years, the spectrum-database based spectrum sensing algorithm was proposed by some spectrum regulators such as FCC and Ofcom, which is suitable for the *Wider-Coverage* application scenario well. The spectrum database is utilized to store the historical spectrum information and to generate a new available spectrum table based on the current spectrum state information [55].

Figure 8 shows the spectrum-database based spectrum sensing model. Each SU uploads the spectrum sensing result (including the false alarm and missing detection probability, the sensing period, the sensing time, and the PUs' exit time, etc.) to Base Station (BS), and then the sensing result will be compared with historical information in spectrum database to find all available spectrum holes. Finally, BS controls SUs' sensing and access operation according to the available spectrum list. A spectrum sensing scheme with geolocation database is proposed to improve the sensing accurate [56]. Since the spectrum database makes not all SUs need to detect spectrum continuously, it will not only reduce the risk of interference to PUs, but also decrease the energy consumption [57].

Based on the spectrum database, a framework for determining the topology of vehicular network is presented in [58], including the spectrum data, multiple BSs and moving vehicles in different traffic conditions. The spectrum database minimizes the cost of analyzing the vehicular environmental parameters such as vehicular density and BS road coverage effectively, and reduces the resulting error in spectrum sensing. A mobile crowd sensing-driven geolocation spectrum database for device-to-device (D2D) communication used the TV white space is built in [59], in which mobile devices detect lots of spectrum usage information, and then the cellular base station performs data mining algorithms to bulid the geolocation database. Reference [60] employed an iteratively developed history processing database to make decisions for SUs' spectrum sensing, and they import the energy detection and cyclostationary feature detection results into spectrum database to improve the energy efficiency and reduce spectrum scanning.

D. COOPERATIVE SPECTRUM SENSING

For the *Low-Latency* application scenario, such as vehicle networking and industrial wireless networks with extremely high requirements for time delay and reliability, it is necessary to provide millisecond end-to-end delay and nearly 100% service reliability guarantee for users. Owing to the shadow and deep fading, the sensing result by single-user is not reliable. Subsequently, the cooperative sensing algorithms [61] are proposed, which combine the sensing results of multiple users to improve the detection reliability. Reference [62] proposed the "AND", "OR" and "K rank" fusion algorithms, in which the participate nodes send their decision results to the fusion center (also known as the "center node"), and the fusion center will use fusion algorithms to make the final decision. Such approach that the fusion center only handles the detected results is called hard fusion algorithm [63]. Its implementation is relatively simple and cost is low. On the contrary, in the soft fusion algorithm, the participate nodes transmit the detected data or other useful information to the fusion node directly. The Fusion Center handles a large amount of unprocessed information, which makes the performance and accuracy of the soft fusion algorithm better than that of the hard fusion approach while it requires more bandwidth consumption. Most proposed cooperative spectrum sensing techniques use omni-directional antennas, while SUs can't determine the exact location of the sensed PUs. Reference [64] used a directional antenna for spectrum sensing to detect the PUs location more accurately and without harmful interference. Fusion center collects the sensing results including sensing period, sensing power and sensing beams from each SU, and calculates the optimized sensing parameters to maximize the sensing accuracy.

A reliability based cooperative decision fusion scheme is proposed in [65], where the reliability of the sensing decision obtained from each SU will be estimated first by comparing with the past information about local and global decisions and then the weighting of each SU's decision will reflect this difference in reliability. Reference [66] presented an integrates quickest detection and belief propagation framework for cooperative spectrum sensing to achieve a better detection performance in terms of delay and false alarm rate. Under practical and imperfect common control channel, [67] proposed a reputation based cooperative spectrum sensing approach, which is validated to be robust against attacks. For the industrial wireless networks (IWNs) which require the high real-time and reliability constraints, [68] proposed a subcarrier modulation based cooperative spectrum sensing algorithm to reduce the reporting delay, and improve the sensing algorithm accuracy and sensitivity by using a two-level decision fusion method. Reference [69] presented a belief function (BF) theory based reliability-probability decision fusion rule for cooperative sensing to improve the interference detection performance in the prerequisite of uploading data as little as possible. In vehicular communication, high mobility could reduce the performance of the spectrum sensing. To solve this problem, [70] proposed a cooperative centralized and distributed spectrum sensing algorithm based on the renewal theory. By employing the renewal theory in decision fusion center, the probability of detection of the primary channel is increased and the average waiting time for SU is decreased apparently.

The performance of cooperative spectrum sensing will be severely degraded because of the presence of malicious interferences in CRNs. In [71], the malicious interferences were suppressed by estimating the local signal to interference plus noise power ratios (SINRs) at SUs and transmitting them to a fusion center for making decision. Moreover, different SUs may have different interference plus noise owing to the presence of malicious users. Consequently, SUs are executed normalization separately to enhance the performance of the algorithm. In [72], a cooperative multiband spectrum sensing approach was proposed for the CRNs with the presence of malicious users. To maximize the aggregate achievable throughput and detection accuracy, the main parameters in cooperative spectrum sensing are set in an optimal manner in the scenarios where only one channel is sensed and multiple channels are sensed jointly and simultaneously, respectively. To tackle the security threats from internal attacks launched by internal nodes, [73] presented a transferring reputation mechanism and dynamic game model based secure collaborative spectrum sensing strategy. This strategy can resolve the reputation loss problem caused by user mobility, incentive the SUs to provide honest information, and help SUs to sense the spectrum state and make spectrum decision. Reference [74] proposed a blind reputation based algorithm for cooperative spectrum sensing in the presence of malicious users, where SUs are dynamically categorized into three states (reliable, pending, and discarded, respectively). According to SUs' reputation, the number of malicious users is minimized by optimizing settings for the four decision thresholds. Reference [75] provided trajectory privacy for vehicular network by utilizing an efficient pseudonym change strategy with multiple mix zones scheme, and presented a cheating mechanism to protect vehicles against linkability attack.

E. COMPRESSIVE SPECTRUM SENSING

With the development of smart city, smart agriculture, smart medical and other IoT applications targeting sensing and data collection, this kind of *Massive-Connectivity* application scenario which requires a wide range of terminals, large quantity, small data packet, low power consumption and mass connection has put forward higher requirements for the speed and power dissipation of spectrum sensing. Most existing spectrum sensing techniques only focus on the single channel and narrowband signal detection. However, with the mushroom of innovative services, traditional narrowband spectrum sensing can no longer meet the fast growing spectrum requirements. Subsequently, the wideband spectrum sensing is coming out [76].

The high sampling rate and the large amount of sampled data bring great challenges to the existing analog to digital converters (ADC), processors and storage devices in terms of the wideband spectrum sensing. Based on the compressed sensing theory, compressive spectrum sensing algorithm was presented in [20], [76], and [77], which can extract and detect the wideband signal directly to achieve efficient wideband sensing with a much lower sampling rate than the Nyquist criterion. In [77] and [78], an adaptively regularized iterative reweighted least squares (AR-IRLS) algorithm for real-time signal and a distributed compressive spectrum sensing approach in cooperative multihop cognitive networks were presented, in which compressive sampling is used to reduce the sampling rate requirements, and then the sparse common spectrum is recovered jointly by cooperative SUs. Simulations show that the compressive spectrum sensing can achieve high detection probability and low false alarm for wideband spectrum sensing. Reference [79] proposed a fast frequency locating algorithm, namely, Arithmetic-delay BigBand (AD-BigBand), for sparse spectrum recovery without sampling the signal by using shifted multiple channels.

At present, most research on compressive wideband spectrum sensing is based on the assumption that the sparsity of wideband spectrum is known. However, due to the limited information interaction between PUs and SUs and the dynamically changing spectrum environment, the sparsity of wideband spectrum becomes unknown. Furthermore, there may be many active PUs who occupy wireless resources at the same time in some hot areas. The sparsity of the spectrum will be reduced or even disappeared. Therefore, it is necessary to analyze the sparsity of the wideband spectrum before using the compressive spectrum sensing method. Reference [80] presented an adaptive compressed spectrum sensing scheme to detect the spectrum holes and obtain the optimal sampling rate when the sparsity of the acquired wideband signal is unknown or varing. Based on the sparse fast Fourier transform theory, [81] proposed a sub-Nyquist wideband spectrum sensing algorithm for sparse and nonsparse wideband signals to reduce runtime and implementation complexity.

In the current wideband spectrum sensing model, the continuous frequency band is represented by the discrete frequency. Nevertheless, this model is out of practice and cannot reflect the reality of spectrum occupation. Reference [82] proposed a novel wideband spectrum sensing scheme including a modulated wideband converter (MWC) and sparse Bayesian learning (SBL). A practical wideband signal's compressed measurement results can be acquired by using MWC, and then the estimated support set can be obtained by exploiting SBL. Finally, this estimated support set is regard as the test statistic to facilitate spectrum sensing. Similarly, [83] considered the heterogeneous characteristic of wideband spectrum, where different spectrum bands could have different PU occupancy patterns, and modeled this heterogeneous wideband spectrum as an inherent, block-like structure. The proposed weight recovery approach can achieve lower mean square errors and higher detection probability.

IV. SPECTRUM ALLOCATION

We then investigate the latest spectrum allocation approach for the multiple application scenarios in 5G, and the summary of existing survey works on spectrum allocation approach is shown in Table 5.

A. GRAPH BASED SPECTRUM ALLOCATION

Spectrum allocation algorithm based on graph theory is proposed based on the knowledge of graph theory, its core idea is to abstract the network topology structure which is composed of the SUs, and establish a spectrum allocation model based on graph coloring according to the corresponding interference and restriction conditions. In the graph coloring model, every vertex represents a SU. The connection between two SUs represents the interference between them, and it means that two users cannot use a network or band at the same time. Each vertex corresponds to an optional set of colors that represent the available network or band sets for the SU. Furthermore, available network sets of different vertices are different, which are determined by the location of vertices, network coverage, and type of service. Therefore, the spectrum allocation problem of each SU can be transformed to the problem of coloring each vertex by this mapping relationship. Moreover, the interference condition is that if there is one edge between the adjacent two vertices, they cannot use the same color at the same time.

Most literatures which use graph coloring model to solve the problem of spectrum allocation mainly include the following two kinds: spectrum allocation algorithm based on the coloring model of the list graph and spectrum allocation algorithm based on the coloring model of the sensitive graph. The core idea of the list-coloring based allocation algorithm is to achieve the allocate spectrum resources by maximizing the utility of system to meet the interference constraint conditions. It is a distributed network topology, which can be implemented by a greedy algorithm and allocated according

TABLE 5. The summary of existing survey works on spectrum allocation approach.

Technical Approaches	Description	Reference	Key Points
Graph Based Spectrum Allocation	Abstracting the network topology structure, and establishing the spectrum allocation model based on graph coloring according to the corresponding interference and restriction conditions.	[84]	The greater the channel interference, the less the allocated spectrum.
		[85]	Networks with higher throughput demand are allocated more channels than networks with less demand.
		[86]	Maximizing the spectrum utility.
Auction Based Spectrum Allocation	Taking full account of the economic characteristics of spectrum, spectrum multiplexing and spectrum heterogeneity to protect the interests of the PUs.	[87]	First applied the McAfee theory in spectrum auction.
		[88]	Considering multichannel demand and the spectrum reuse.
		[89, 90]	Taked into account the heterogeneity of sub-channel.
		[91]	Considering different types of spectrum bands.
		[92]	A framework of unknown combinatorial auction mechanisms.
Game Based Spectrum Allocation	Easing competition between PUs and SUs to improve the contradiction between the increasing demand for wireless services and the scarcity of spectrum resources.	[93]	A rigorous method for analyzing decision-making in CRNs.
		[94]	Validating the convergence of the game model.
		[95]	Considering the competitive problem of multiple SUs.
		[96]	Presenting an allocation algorithm based on the pricing game.
Carrier Aggregation Based Spectrum Allocation	Multiple carriers can be used to aggregate into a wider spectrum to improve the utilization efficiency of the fragmentation spectrum effectively.	[97]	Using carrier aggregation for spectrum allocation.
		[98]	Combinng multiple LTE carriers.

to the number of node connections. The number of node connections represents the number of nodes that have the same available spectrum, the number of connections for each node is calculated first, and the nodes with a smaller number of connections are assigned priority. If the number of connections is the same, the high-priority nodes are allocated and randomly assigned if the priority level is the same. Priority measurements are determined according to the number of available spectrum, QoS requirements, and so on. After the assignment, the updated node is available with a list of network and node colors, and if all nodes have no available colors, exit the assignment or continue allocation. In [84], A distributed randomized algorithm with low complexity and communication overhead was proposed to allocate a limited number of idle spectrum to the SUs with less interference. However, the channel allocated to those SUs with more interference will be reduced, thus the fairness of the spectrum allocation cannot be guaranteed. In [85], the QoS requirement was considered, which addresses the problem that the traditional list coloring greedy heuristic algorithm leads to the biased and unfair allocation. The grade of QoS is provided based on the number of channels allocated to the network, which indirectly means the bandwidth allocated to the network. Consequently, networks with higher throughput demand are allocated more channels than networks with less demand, so that the channel allocation fairness is maintained.

Because different services have different preferences for the network, the benefits of accessing different types of networks are also different. For example, the high-speed multimedia service is more inclined to the broadband network, while the low-speed voice service is more inclined to narrowband network. Therefore, it is possible to improve the overall efficiency of the system by considering the preference of the business priority. In [86], a spectrum allocation algorithm based on the coloring model of the sensitive graph was proposed with the aim of maximizing spectrum utility, in which the three-dimensional matrix is used to represent the interference constraint relationships among SUs on different spectrum, and the user utility represents the different utility obtained by SUs using different spectrum.

The time required for the whole allocation process of the graph based spectrum allocation algorithm is related to the number of available spectrum. Consequently, this algorithm does not apply to the scenarios with fast changing spectrum, while is more suitable for the *Massive-Connectivity* application scenario.

B. AUCTION BASED SPECTRUM ALLOCATION

Owing to it is unfair to PUs that SUs can use the licensed spectrum without paying any fees and may cause potential interference to PUs in the dynamic spectrum access mode.

In order to enable SUs to utilize the licensed spectrum stably in a continuous wider area coverage, it is necessary to ensure PUs' QoS and interests. Auction theory is considered to be a very effective way to protect the interests of PUs and consequently auction based spectrum allocation is more suitable for the *Wider-Coverage* application scenario. Although many traditional auction mechanisms have been designed, they are not directly applicable to spectrum auction because they fail to consider the spectrum reuse, which makes the spectrum auction unreal. Three key issues are taken into consideration in the design of spectrum auction algorithm: economic characteristics, spectrum reuse and spectrum heterogeneity. First of all, the spectrum buyers and sellers all need honest quote and real bid. Secondly, the solution to the spectrum reuse problem is usually to group the buyer by using the interference graph and divide the non-interference buyer into one group to bid for the spectrum. Finally, due to the interference distance of the low frequency band is larger than that of the high frequency band, different buyers will have different interference relationship in different frequency bands, which will affect the buyer grouping in spectrum reuse. Therefore, the spectrum auction algorithm also needs to focus on spectrum heterogeneity.

In the past few years, many proposed spectrum auction algorithms [87]–[90] were based on the McAfee theory, which is a classic double auction theory and has very low computational complexity. Reference [87] first applied the Macfee auction to dynamic spectrum auction, and considered the spectrum reuse to propose a truthful double auction algorithm, where a novel winner determination and pricing mechanism are applied to achieve truthfulness individual rationality, budget balance and user honesty. However, authors assumed that each buyer only needs one sub-channel and each seller provides only one sub-channel, and all sub-channels are homogeneous. Reference [88] taked into account the multi-channel demand and the spectrum reuse in auction algorithm, and [89] improved the double auction algorithm from the perspective of the heterogeneity of the sub-channel. Reference [90] payed attention to the profit of the auction and proposed a new discriminatory pricing strategy and a competitive double auction algorithm to improve the auctioneer's profit and the numbers of successful transactions.

As there are many different spectrum in the auction, user's quotation of the spectrum combination may no longer be a simple linear summation, some researchers proposed the combinatorial auction algorithm. In a combinatorial auction algorithm, a user can quote a combination of any number of spectrum, not just a single spectrum. The user's demand for the spectrum is either met or denied. Compared to the traditional auction, this kind of auction can reflect the diverse spectrum demand relationship between buyer and seller better, at the same time, the combination auction cannot only improve the auction efficiency more effectively, but also provide the user with more flexibility in the bidding process, while user's complex and diverse demands increases the computational complexity in the process of the bid. Reference [91] proposed a lightweight double combinatorial auction algorithm to tackle the scenario where each PU has heterogeneous spectrum resources such as WiFi and 3G, and each SU may request different types of spectrum bands. Reference [92] proposed a framework of unknown combinatorial auction mechanisms for heterogeneous spectrum redistribution to achieve strategy-proofness and approximately efficient social welfare including a revelation combinatorial spectrum auction algorithm for unknown single-minded users and an iterative ascending combinatorial auction algorithm for unknown multi-minded users.

The spectrum auction mechanism discussed above is mainly aimed at the market of PUs and SUs as the seller and buyer, and the spectrum allocation is realized through the spectrum trading. Using the method of spectrum leasing among operators to solve the problem of imbalance of time and space in different operators has become a hot topic in recent research. For instance, some operators may not only have their own licensed spectrum, but also share some unlicensed spectrum. Operators optimize the allocation of spectrum resources by leasing the licensed spectrum from other spectrum holders, or competing for the use of the unlicensed spectrum [99]. For example, operator A has to lease spectrum to operator B for lack of spectrum resources. On the one hand, operator A obtains extra profits by renting out the spectrum, while operator B leases the spectrum from operator A to meet users' demands for making greater profits. On the other hand, there is a problem of competing services between operators A and B. Therefore, a reasonable and effective mathematical model are established to study the spectrum leasing process between operators A and B for getting the best leasing strategy so that both operators A and B can achieve higher satisfaction and improve the utilization rate of spectrum resources. Reference [100] decoupled the ownership of the network infrastructure and spectrum to allocate the TV White Spaces for maximizing throughput and revenue/payment, in which the TV spectrum owner (TSO) can lease the infrastructure from a network infrastructure owner (NIO) to provide services, while the TSO can rent a portion of its TV White Spaces to the NIO for revenue, and the NIO can access this spectrum to serve its customers.

C. GAME BASED SPECTRUM ALLOCATION

Whether the opportunistic spectrum access mode with the goal of maximizing spectrum utilization or the auction spectrum access mode with the goal of maximizing PUs' and SUs' own interests, the core idea of spectrum sharing is competition and cooperation between PUs and SUs. Game theory is a major branch of operational research and has received intensive research in these years [93]–[96], which needs to predict the behavioral possibility and certainty of each participant in the game, then analyze the participants' optimal selection strategy. The introduction of game theory into CRNs to realize the reuse of non-renewable spectrum resources has opened up a new way to ease the contradiction between the increasing demand for wireless services and the scarcity of spectrum resources. On the basis of game theory, Nash equilibrium solution (optimal strategy set) is an important method to improve the utilization rate of spectrum resources under the condition of limited wireless resources. Furthermore, game based spectrum allocation is of great significance to guarantee the service reliability of multi-users in *Low-Latency* application scenarios.

The problem of spectrum allocation in CR includes the game among SUs and the game between PUs and SUs. The game is played among SUs to handle the problem of which idle spectrum to choose and how much bandwidth to choose. However, PUs and SUs play a game on which spectrum can be provided to SUs by PUs and which spectrum can be decided to utilize by SUs. There are six main game theory model, which are Stackelberg game, Cournot game, Bertrand game, repeated game, auction game and evolutionary game, respectively. In the Stanlberg game model, the players of the game take the output as the competition goal, and the competition process is the complete information dynamic game. In addition, some users take the strategy first in each game, and the strategy results can be known by late-decision users. However, in the Cournot game model, the players also take the output as the competition target, while the competition process is the complete information static game. The Bertrand game model is a static game, and the price is the competition target of the players. Similar to the Stanlberg game model, the strategies adopted by the game players in the repeated game model are in order. Moreover, repeated games are composed of multiple game stages, in which participants can adjust their strategies to gain better benefits in the next stage. Using auction game model in CR can not only improve the utilization rate of spectrum resources, but also make the PUs obtain more satisfying benefits. As a new development of game theory, evolutionary game model is based on the theory of biological evolution, which makes the game model more close to the real environment and improves the game satisfaction and convergence speed. The game participants only know part of the information and adapt to the changes in the environment through a series of dynamic learning processes. Reference [93] introduced the game theory into spectrum allocation earlier, which provided a rigorous method for analyzing decision-making in CR networks, and studied how to allocate spectrum by game theory. They also validated the convergence of the game model in CR [94] and promoted the application of game theory in spectrum allocation. In [95], an allocation algorithm based on Cournot model was proposed. It does not require a control center to solve the competitive problem of multiple SUs for idle spectrum. However, it does not take into consideration the impact of spectrum constraints. Reference [96] proposed an allocation algorithm based on the pricing game, in his proposal, every non-cooperative user is selfish and only consider their own income to select suppliers, and suppliers make the pricing of the spectrum according to the principle of maximizing revenue.

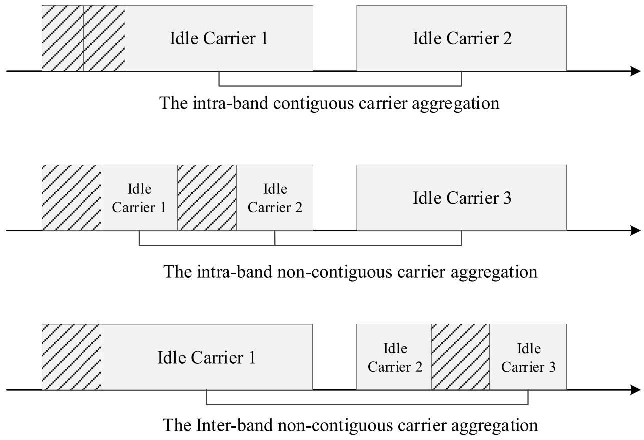


FIGURE 9. **The categories of carrier aggregation.**

D. CARRIER AGGREGATION BASED SPECTRUM ALLOCATION

In practical applications, the density of idle spectrum distribution is different, and the distribution of idle spectrum is concentrated or discrete. In the area where the idle spectrum distribution is concentrated, SUs can only perform spectrum sensing on a narrow frequency range. However, SUs will need to sense a wide frequency range when the idle spectrum distribution is discrete. In the current spectrum scarce environment, it is more and more difficult to meet the needs of users' exploding communication in the continuous spectrum resources. In addition, if the bandwidth of discrete idle spectrum is too small, the idle spectrum is not enough to meet the SU's transmission rate, which will lead to the idle spectrum still can not be utilized. Therefore, some researchers have applied the carrier aggregation technology to the spectrum allocation [97], which can effectively improve the utilization of narrowband idle spectrum and meet the network extremely high flow density requirements of *Massive-Capacity* application scenario.

Carrier aggregation can be used to aggregate multiple carriers into a wider spectrum, including continuous carrier aggregation, and discontinuous carrier aggregation, which can be usually divided into intra-band contiguous carrier aggregation, intra-band non-contiguous carrier aggregation, and inter-band non-contiguous carrier aggregation as shown in Figure 9. To meet the growing communications needs of users, the proposal clearly proposed that the requirements of spectrum expansion in LTE-advanced system needs to support the maximum 100MHz transmission bandwidth at the 53 meeting of 3GPP [98]. For extremely scarce spectrum resources, researchers in mobile communications began to consider deploying 4G in an unlicensed frequency band through carrier aggregation. Hence, the concept of carrier aggregation is formally proposed in the R10 version of LTE, which combines multiple LTE carriers into the carrier of the LTE-advanced system. After this aggregation, the available spectrum consists of the main carrier and the sub-carrier, which can work in both the licensed and unlicensed spectrum, respectively. In this way, the mobility and control of 4G terminals are still guaranteed by the licensed spectrum, that is the main carrier, and the unlicensed spectrum is responsible for the improvement of communication capacity. Thus it can be seen that the carrier aggregation cannot only make use of the physical channel and modulation coding scheme of LTE system directly to reduce the difficulty of overhead and design LTE-advanced system, but also improve the utilization of fragmentation spectrum effectively.

V. SPECTRUM ACCESS & SPECTRUM HANDOFF

A. DYNAMIC SPECTRUM ACCESS

Since most spectrum resources are divided into licensed bands, only PUs can use them. Under the current spectrum policy, the utilization of spectrum resources is uneven and inefficient. Therefore, the intelligent, dynamic and flexible access approach is the main factor to implement the spectrum sharing. At present, there are three main types of dynamic spectrum access (DSA) mode, which are *Overlay*, *Underlay* and *Hybrid* mode [101], [102], respectively. In the *Overlay* mode, SUs can opportunistically utilize the spectrum holes and exit them once sensing PUs' signals. It may not be able to obtain spectrum access opportunities when the spectrum occupancy rate is very high. As for the *Underlay*, SUs do not concern if there is the spectrum hole, and they can access the spectrum simultaneously with the PUs by reducing their transmission power, as long as the interference caused by them does not degrade the PUs' communication quality. The interference temperature is used in *Underlay* mode to indicate the degree of interference that PU can tolerate caused by SUs during the spectrum access period. More specifically, SU should first estimate the maximum interference value that this PU can tolerate, then predict the added interference value after introducing a SU, and finally determine whether this user can be allowed. Moreover, SU needs to periodically detect the interference temperature, and adjust their transmitting power adaptively to ensure that the added interference is within the tolerance range of PU. However, the transmission power of SUs will be still low even if the PUs' status becomes inactive. The *Hybrid* mode absorbs the advantages of *Overlay* and *Underlay* mode, and SUs can switch between the two modes according to the state of the PUs [103], [104]. A continuous-time markov chain was proposed to model the *Hybrid* spectrum access mode in [105]. Results showed that the *Hybrid* access mode outperforms the conventional *Overlay* and *Underlay* approach in terms of outage probability and outage capacity. In [106], Hoang *et al.* proposed a *Hybrid* access mode that each SU can opportunistically access the idle spectrum or underlay part of its signal into the portion of the busy spectrum based on the data queue state and sensing result, or access a busy spectrum to harvest radio frequency (RF) energy given its energy queue state. Ulteriorly, the cognitive stop-and-wait hybrid automatic repeat request (CSW-HARQ) protocol was represented in [107], where SU only transmits data when the spectrum is deemed to be idle, and waits for the feedback after transmission. The summary of existing survey works on spectrum access & spectrum handoff approach is shown in Table 6.

B. QUEUEING BASED SPECTRUM ACCESS

Due to the limitation of spectrum resources, it will encounter the need to wait for PU or other SU service when SU access the licensed spectrum, which leads to the increase of waiting time delay. In addition, in order to ensure the absolute priority of PU in the spectrum access process, when PU appears in the channel that SU is using, SU must be withdrawn in time, and switch to other idle channels to continue transmission or wait for the departure of the PU in the original channel. At present, there have been a large number of literatures using queuing theory to analyze the performance of dynamic spectrum access. As the queuing theory can effectively describe the effect of PU activity on the performance of SU communication, and reflect the latency of SU in different channels. Some literatures have analyzed the performance of dynamic spectrum access using queuing theory [108]–[113].

Reference [108] studied the distribution and the average waiting time of SU data packet queues in the buffer. On this basis, a queuing theory based channel access strategy is proposed, which controls the SU's access by determining the maximum allowable SU packet arrival rate to ensure its QoS demand under the given waiting time requirement. In [109], the services were divided into non-real time service and real time service, according to the SUs' different time delay requirements. For the non real-time service, when the channel being used by SU is preempted by PU and no other idle channels can be switched, SU enters the cache data queue for waiting. However, for the real time service, the transmission of SU can only be forced to interrupt. In this work, the average residence time of the non-real time service and the forced interrupt rate of real time service are presented by using preemption priority queueing model. Reference [110] presented the spectrum occupancy rate of the CRN by using the queueing analysis and reduced the computational complexity by using proposed time scaling method to approximate the average time delay, throughput and spectrum occupancy. The decision-making process of SUs that whether to queue or not and the optimal pricing strategy of the service provider were analysed in [111] by leveraging the queueing game approaches. In [112], a preemptive continuation queuing theory based spectrum access scheme was proposed, where the sensing based spectrum access algorithm is used when the quantity of service for SU is small, while the probability based spectrum decision algorithm is used when that is large, to minimize the average waiting time of SU. Reference [113] presented a novel model with coupled queues to incorporate the primary and secondary networks, and designed a penalty based framework considering the QoS of primary traffic to provide a fixed per collision compensation or to restrict the collision rate at an acceptable level for protecting the primary traffic.

TABLE 6. The summary of existing survey works on spectrum access & spectrum handoff approach.

Technical Approaches	Description	Reference	Key Points
Dynamic Spectrum Access	SUs can opportunistically use the spectrum holes in the *Overlay* mode, or access the spectrum simultaneously with the PUs by reducing their transmission power in the *Overlay* mode. Obviously, SUs can switch between the two modes according to the state of the PUs in the Hybrid mode.	[101–104]	The dynamic spectrum access mode is proposed.
		[105]	Using continuous-time markov chains proposed to model the Hybrid.
		[106]	SU can opportunistically access the idle spectrum to transmit data or access a busy spectrum to harvest RF energy.
		[107]	Stop-and-wait hybrid automatic repeat request (CSW-HARQ) protocol is represented.
Queueing Based Spectrum Access	Effectively describe the effect of PU activity on the performance of SU communication and reflect the latency of SU in different channels.	[108]	Studying the distribution and the average waiting time of SU data packet queue in the buffer.
		[109]	Using preemption priority queueing model to deal with non-real time service and real time service.
		[110]	Reducing the computational complexity by using time scaling method.
		[111]	Analysing the optimal queue decision and pricing strategy of the service provider.
		[112]	Using sensing based or probability based access algorithm to meet the SU's different QoS requirements.
		[113]	Designing a penalty based framework to restrict the collision rate for protecting the primary traffic.
Spectrum Handoff	When the communication quality of some licensed channels becomes worse or the PU has been returned to this channel, the SU must switch to other available idle channels.	[114]	Reviewing and comparing qualitatively various spectrum handoff strategies.
		[115]	Presenting a unified mobility management framework to determines a proper spectrum band or target cell.
		[116]	Considering the transmission power of SU, fading factor and bandwidth.
		[117]	Overcoming the limitations of preemptive and non-preemptive resume priority queuing models, and calculate the channel waiting time.
		[118]	Achieving the minimum energy consumption or the maximum energy efficiency/throughput.

C. SPECTRUM HANDOFF

As the characteristic parameters of the spectrum vary over time and space, the optimal channel of SU is also dynamic. When the communication quality of some licensed channels becomes worse or the PU has returned on this channel, the SU must switch to other available idle channels. Spectrum handoff is mainly restricted to the working state switching of PU and the mobility of SU, and it requires the working parameters, such as the modulation mode and the channel coding of SU, can be adapted quickly and effectively in the process of working mode change. Meanwhile, the performance of SU should be reduced as little as possible in the process of switching so as to guarantee the QoS of SU. An example of spectrum access and spectrum handoff process for a SU is illustrated in Figure 10.

According to the different trigger timing of frequency spectrum handoff, the spectrum handoff model can be divided into three kinds: passive handoff, active handoff and hybrid handoff, respectively. Their respective pros and cons are illustrated in Table 7.

- **Passive handoff.** When SU has sensed the return of PU or the communication quality of licensed channel becomes worse, it really starts to initiate the handoff request.
- **Active handoff.** By analyzing past activity rules of PUs, SU predicts the previous PUs' occupancy status at the next time and initiates spectrum handoff before PUs return.
- **Hybrid handoff.** With the combination of active handoff and passive handoff mechanism, the available idle channel list can be estimated before PU returns by using the active handoff mechanism, and the handoff delay can be reduced compared with the passive handoff mechanism.

Reference [114] reviewed and compared qualitatively various spectrum handoff strategies, and recommend that future

TABLE 7. The advantages and disadvantages of three kinds of spectrum handoff models.

Spectrum Handoff Model	Advantage	Disadvantage
Passive handoff	• Obtaining accurate target channel information.	• High handoff delay.
Active handoff	• Reducing collisions between PUs and SUs effectively.	• The lower the prediction accuracy, the higher the blind switching rate.
Hybrid handoff	• Estimating the available idle channels in advance. • Reducing handoff latency.	

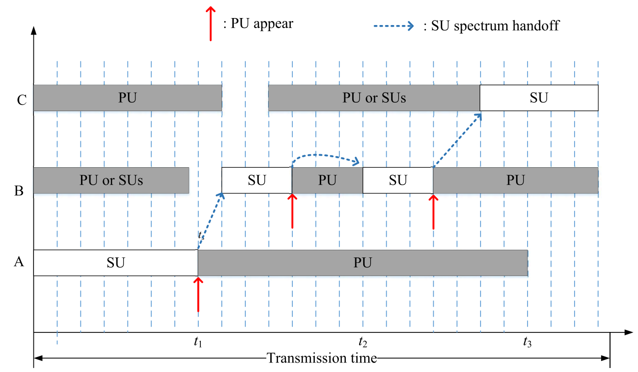


FIGURE 10. An example of spectrum access & spectrum handoff process for a SU.

spectrum handoff strategy should consider the spectrum learning factor in the design process, cross-layer link maintenance protocol, and energy efficiency to achieve optimal performance in the dynamic spectrum environment. In [115], a unified mobility management framework was developed, including spectrum mobility management, switching cost-based handoff decision mechanism, and intercell resource allocation, to determine a proper spectrum band or target cell and to minimize quality degradation caused by user mobility. An adaptive weights adjustment based spectrum handoff strategy was proposed in [116], considering the transmission power of SU, fading factor and bandwidth. The dynamic multi-attribute simple additive weight algorithm is applied to reduce the switching time of SUs and improve the effective transmission rate. A hybrid rule-based priority queuing model was presented in [117] to overcome the limitations of preemptive and non-preemptive resume priority queuing models, and to calculate the channel waiting time during spectrum handoff. Different from the extant literature, multi-teacher apprentice learning scheme is used to speed up the learning process by learning from multiple neighboring experienced SUs. In order to achieve the maximum energy efficiency/throughput or the minimum energy consumption, [118] presented a dynamic programming based optimal channel sensing sequence scheme for spectrum handoff in an *Overlay* multichannel CR networks.

VI. OTHER RESEARCH ISSUES

A. COMMON CONTROL CHANNEL

SUs must exchange public control information (including the PUs' activity, channel usability, network topology change and the route parameter and so on) with neighbor nodes in distributed CR networks. It is very important to establish a reliable common control channel (CCC) to facilitate the transmission of control information. In [119], a specified CCC was used to control the transmission of information. This scheme enables the communication between control and handshake information by selecting a specified CCC. However, it is sometimes difficult to maintain a CCC for a long time in CR networks. Because the availability of the specified CCC may change over time. Once a PU has occupied the selected CCC for a long time, all public control information will be blocked for a long time. In addition, under the high cognitive node density or high traffic flow background, a single CCC often becomes a bottleneck and causes the channel saturation problem. Hence, it is not only difficult to identify a specified CCC for all the SUs, but also this specified CCC is influenced by the PU traffic.

For the shortage of special CCC allocation scheme, the sequence hopping CCC allocation scheme is proposed. It does not require a central controller and a specified CCC, which is relatively more convenient and feasible in actual deployment. The sequence hopping CCC allocation scheme is divided into two types: stochastic hopping sequence and specified hopping sequence. The stochastic sequence hopping CCC allocation scheme means that each SU hops from one channel to another according to the hopping rate, while this kind of scheme has certain non-controllability. In the specified hopping sequence allocation scheme, each hopping sequence is generated by a specific sequence generation algorithm, so the channel hopping sequence is more regular. In [120], Yu and Ssu proposed a channel allocation algorithm based on spatial variation control (SVC), which provides a set of CCCs for mobile nodes.

B. ENERGY EFFICIENCY

1) POWER ALLOCATION

Power control is one of the key technologies to realize spectrum sharing in CR. The main purpose of power control is to guarantee that there is no excessive interference to PUs and other SUs. At present, the researches of power control are mainly based on the information theory model and game theory model [121]–[128]. The power control approach that based on information theory usually adopts the iterative water filling algorithm to solve the optimal power allocation problem, where the channel is divided into several independent subchannels, and the large gain subchannels are allocated with high power while the power allocated on the small gain subchannels are low to maximize the transmission performance.

For the power control approach which based on game theory model, [121] proposed a non-cooperative power control game (NPG) which is widely used by future researchers, and Saraydar *et al.* [122] improved the NPG from the viewpoint of power control cost, and proposed the non-cooperative power control game via pricing (NPGP). The nonlinear cost function was introduced into [123], which makes the final game strategy closer to the real environment. Reference [124] improved the NPGP model by considering the utility function and game user's SNR. Because it does not take into consideration the user's wireless access technology, it has a great advantage in CR networks. Furthermore, [125] proposed an adaptive power control algorithm based on the utility function. In recent years, the cooperative game theory has been applied to power control [126], [127]. However, due to the continuous changes in the wireless network environment and the user's mobility, the game between SUs can only be temporary. Subsequently, the stochastic game theory was applied to power control [128], which cannot only meet the requirements of the wireless environment, but also adjust the optimal power control strategy dynamically.

2) ENERGY HARVESTING

Energy supply is always a critical issue in wireless communications, and SUs need to spend more energy to detect many channels and switch among multiple channels constantly. Therefore, energy efficiency (EE), which evaluates how efficiently energy resources are consumed is another important criterion in the CR network along with the spectrum efficiency (SE). At present, the battery is still the main energy source for wireless devices. The problems of limited battery life, periodic replacement, and environmental pollution make people began to look for a sustainable, environmentally friendly power supply. Among them, the ambient energy (such as solar, heat, electromagnetic waves and other forms of energy) harvesting technology has been widely concerned. Electromagnetic waves energy harvested by CR focused by many scholars, and there have been a number of representative studies [106], [129], [130], including hardware design and efficient energy sensing algorithms, etc. The model of CR network with energy harvesting was described in Figure 11 [106]. SUs cannot only carry out the data transmission on the idle spectrum, but also can harvest RF energy from the busy spectrum which is being used by PU. It can be seen that the CR network with energy harvesting can improve the utilization of spectrum resources and increase the working time of the SUs.

In general, the SUs with energy harvesting capabilities are equipped with multiple antennas, in which some antennas are used for the traditional spectrum sensing and spectrum access, and the other part of the antenna is used to harvest RF energy. In [131], the sequential mode was used to avoid

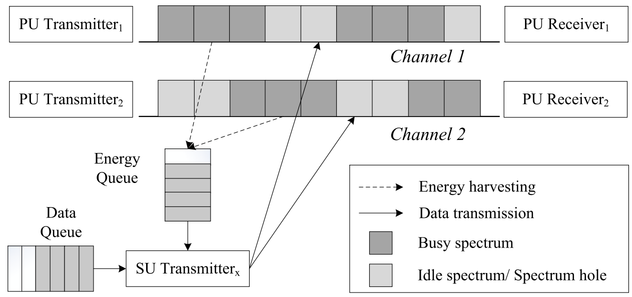


FIGURE 11. The model of CR network with energy harvesting.

mutual interference between the antennas, where SUs harvest the RF energy first and then carry out the spectrum sensing and data transmission. However, due to the energy harvesting occupy a part of time in this mode, the spectrum sensing and data transmission time are reduced and the throughput of SUs will be affected. The synchronous mode was studied in [132], including the energy reaching characteristics, the impact of energy harvest on PUs, and how to achieve the throughput maximization and optimal access strategy. The research of energy harvesting technology will be mainly focused on the following two points. Firstly, since the different spectrum environment of the SUs, the energy can be harvested is also not identical. It is difficult to rely on a single energy harvesting algorithm to obtain sufficient energy for SUs [133]. Therefore, various energy harvesting approaches can be used for different spectrum environments. Secondly, SUs with energy harvesting ability need not only detect whether there are available idle bands, but also detect whether they can harvest energy from occupied frequency bands when energy reserves are insufficient. Therefore, spectrum sensing requires more energy in the energy harvesting based CR networks. Moreover, SUs also need to switch more frequently between the spectrum holes and the busy channels. Therefore, it is necessary to study the optimize energy harvesting strategy to reduce its overhead and improve the efficiency of the whole CR networks.

C. NON-ORTHOGONAL MULTIPLE ACCESS

Non-orthogonal multiple access (NOMA) has recently been recognized as a promising multiple access technology that significantly improves the spectrum efficiency of mobile communication networks. In addition, it is also conceived as a key component in the 5G mobile communication system. NOMA is fundamentally different from the previous multiple access technology that has been relying on the time/frequency/code domain, which is a multiple users reuse technology that utilizes frequency domain, time domain and power domain. Furthermore, it adopts the superposition code at the transmitter to allocate the different user's signal power on the same subchannel according to the related algorithms, which makes the signal power of each user different. At the receiver, it eliminates interference through the serial interference cancellation (SIC) technology, so as to realize the correct

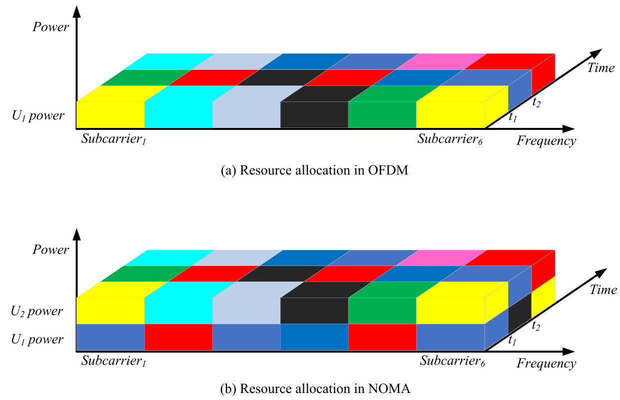


FIGURE 12. An example of resource allocation in OFMD and NOMA. (a) Resource allocation in OFDM. (b) Resource allocation in NOMA.

demodulation [134]. Figure 12 is an allocation diagram of NOMA technology and OFDM technology in the frequency domain, time domain and power domain. Obviously, compared with the OFDM technology, NOMA technology makes the power of each subcarrier channel not only to a user, but shared by multiple users. Consequently, each subchannel can carry multiple users with different signal power in the frequency domain and time domain. For the orthogonal multiple access (OMA) technology, if the subcarrier channel allocated to users with poor channel conditions, their spectrum efficiency will be relatively low. Conversely, NOMA enables each user to access all the subcarrier channels, and hence the transmission capacity and the spectrum efficiency can be significantly improved by the access of multiple users when the channel conditions are poor.

The fundamental idea of NOMA is to encourage spectrum sharing, which is similar to the concept of CR networks. Combining the NOMA with CR technology, there will be a noticeable improvement in spectrum efficiency and energy efficiency, compared with the existing OMA technology. With the help of NOMA, the information intended to PU can be decoded by SUs, and hence these SUs can serve as potential relays for obtaining the opportunity to access PU's channel to improve the performance of the CR-NOMA system. Reference [135] presented a cooperative transmission scheme to achieve the maximum diversity, which can obtain better performance when more SUs participate in relaying. In [136], NOMA was applied to large-scale *Underlay* CR networks, and the diverse order of SUs has been derived in fixed and dynamic transmit power scenario. Reference [137] studied the NOMA in multicast CR networks, and proposed a dynamic cooperative NOMA scheme, in which the performance of both primary and secondary networks can be promoted through SUs acting as relays. Reference [138] combined the application of MIMO and NOMA techniques, and proposes the precoding and detection matrices for MIMO-NOMA. To meet the predefined QoS requirement and dynamic QoS requirement, the choices for power allocation coefficients have also been presented. Through these studies we can find that unlike the conventional OMA technology which only obtains well spectrum efficiency under the good channel conditions, NOMA can achieve a good balance between system throughput and user fairness, which is more suitable for meeting the demanding requirements of *Low-Latency* and *Massive-Connectivity*.

D. CR BASED AERONAUTICAL COMMUNICATION

Air data link is an important aspect of air traffic management and Air-to-ground (A/G) communication system, which provides data link guarantee for communication, navigation, and surveillance in aeronautical communication. At present, the air data link is based on the VHF frequency band, which adopts TDMA access mode and belongs to the narrowband system, while the bandwidth and capability of communications are limited. With the continuous development of the air transport industry, air traffic will increase significantly in the next ten years and the need for space communications support of the new business is also increasing. It is urgent to study the broadband air data link technology with higher system capacity and transmission rate. The capabilities of a CR can be applied to solve the communication challenges involving spectrum allocation in various technological fields in the aeronautical domain, including the A/G communication system, air to air communication system, UAV system, aeronautical safety and in-flight entertainment system [119].

It is a new concept to apply the CR for spectrum sensing and efficient resource allocation for A/G communication. A novel frequency hopping scheme based spectrum sensing approach was proposed in [139] to deal with the low communication resource (including frequency and time) utilization rate and lacking extra ability to resist spot jamming. It utilizes the control signal to report communication status and uses the frequency spectrum sensing technology to identify and improve the anti-interference ability.

VII. CONCLUSION

CR technology is an essential measure to mitigate the contradiction between supply and demand, and it is the basic guarantee to meet the imbalance of supply and demand in the future. With the resource guarantee of spectrum sharing, the new generation of information technology can effectively accelerate the practical application and promote the healthy development of 5G. Spectrum sharing in CRNs is crucial to ensure that appropriately available spectrum bands are allocated to satisfy the heterogeneous QoS requirements of SUs. In this paper, aiming at solving the problem of spectrum scarcity towards 5G, we overview the spectrum sharing in CRNs based on the new challenges and requirements in four scenarios and the extensive studies of the existing literature. More specifically, we explore spectrum sharing scheme in the following four key steps: spectrum sensing, spectrum allocation, spectrum access, and spectrum handoff. Furthermore, they are divided into several classes on the basis of requirements of diverse application scenarios that *Wider-Coverage*, *Massive-Capacity*, *Massive-Connectivity* and *Low-Latency*.

The key enabling technologies that may be closely related to the study of 5G in the near future are presented, particularly in terms of full-duplex spectrum sensing, spectrum-database based spectrum sensing, compressive spectrum sensing, carrier aggregation based spectrum allocation. Subsequently, other issues that play a positive role for the development research and practical application of CR, such as CCC, energy harvesting, NOMA, and CR based aeronautical communication are discussed.

The future research directions of full specturm sharing will focus on the following aspects. First of all, the spectrum hole in high frequency channel may not be accurately detected by using the conventional spectrum sensing algorithms. Thus, it is necessary to study the accurate and fast spectrum sensing algorithm on the basis of fully considering the high frequency band characteristics. Secondly, although the high frequency band can provide more transmission opportunities, the transmission distance is relatively close. How to choose the best spectrum for SUs in the low and high frequency bands, and licensed and unlicensed frequency bands is an important problem to be solved in the full spectrum sharing research. Thirdly, research on the full duplex and NOMA based full spectrum sharing mechanism can not only improve the accuracy of spectrum sensing, but also significantly enhance the communication capacity. Finally, it is necessary to study the optimal spectrum sensing algorithm, spectrum allocation strategy and spectrum access mechanism which meet the different requirements of the four application scenarios in 5G to maximize the efficiency of spectrum utilization. The comprehensive overview provided by this survey is expected to help researchers develop CR technology in the field of 5G further.

REFERENCES

[1] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[2] A. Gupta and E. R. K. Jha, "A survey of 5G network: Architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, Jul. 2015.

[3] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Generat. Comput. Syst.*, vol. 29, no. 7, pp. 1645–1660, 2013.

[4] V. Gazis, "A survey of standards for machine-to-machine and the Internet of Things," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 482–511, 1st Quart., 2016.

[5] A. Ghanbari, A. Laya, J. Alonso-Zarate, and J. Markendahl, "Business development in the Internet of Things: A matter of vertical cooperation," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 135–141, Feb. 2017.

[6] D. Hortelano, T. Olivares, M. C. Ruiz, C. Garrido, and V. López, "From sensor networks to Internet of Things. Bluetooth low energy, a standard for this evolution," *Sensors*, vol. 17, no. 2, p. 372, Feb. 2017.

[7] K. Ashton, "That 'Internet of Things' thing," *RFiD J.*, vol. 22, no. 7, pp. 97–114, Jun. 2009.

[8] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[9] *Strategy Analytics News & Press Releases*. Accessed: Oct. 14, 2014. [Online]. Available: http://www.prnewswire.com/news/strategyanalytics

[10] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, "Context aware computing for the Internet of Things: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 414–454, 1st Quart., 2014.

[11] J. Gozalvez, "Samsung electronics sets 5G speed record at 7.5 Gb/s [mobile radio]," *IEEE Veh. Technol. Mag.*, vol. 10, no. 1, pp. 12–16, Mar. 2015.

[12] A. Whitmore, A. Agarwal, and L. D. Xu, "The Internet of Things—A survey of topics and trends," *Inf. Syst. Frontiers*, vol. 17, no. 2, pp. 261–274, Apr. 2015.

[13] A. Afzal *et al.*, "The cognitive Internet of Things: A unified perspective," *Mobile Netw. Appl.*, vol. 20, no. 1, pp. 72–85, Feb. 2015.

[14] H. Ning *et al.*, "From Internet to smart world," *IEEE Access*, vol. 3, pp. 1994–1999, Oct. 2015.

[15] B. R. Ray, J. Abawajy, and M. Chowdhury, "Scalable RFID security framework and protocol supporting Internet of Things," *Comput. Netw.*, vol. 67, pp. 89–103, Jul. 2014.

[16] C. Chilipirea, A. Ursache, D. O. Popa, and F. Pop, "Energy efficiency and robustness for IoT: Building a smart home security system," in *Proc. IEEE 12th Int. Conf. Intell. Comput. Commun. Process. (ICCP)*, Sep. 2016, pp. 43–48.

[17] E. Z. Tragos, S. Zeadally, A. G. Fragkiadakis, and V. A. Siris, "Spectrum assignment in cognitive radio networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1108–1135, 3rd Quart., 2013.

[18] P. Rawat, K. D. Singh, and J. M. Bonnin, "Cognitive radio for M2M and Internet of Things: A survey," *Comput. Commun.*, vol. 94, pp. 1–29, Nov. 2016.

[19] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 1, pp. 116–130, First Quarter 2009.

[20] H. Sun, A. Nallanathan, C.-X. Wang, and Y. Chen, "Wideband spectrum sensing for cognitive radio networks: A survey," *IEEE Wireless Commun.*, vol. 20, no. 2, pp. 74–81, Apr. 2013.

[21] M. E. Tanab and W. Hamouda, "Resource allocation for underlay cognitive radio networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 1249–1276, 2nd Quart., 2017.

[22] A. Ahmad, S. Ahmad, M. H. Rehmani, and N. Ul Hassan, "A survey on radio resource allocation in cognitive radio sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 888–917, 2nd Quart., 2015.

[23] M. T. Masonta, M. Mzyece, and N. Ntlatlapa, "Spectrum decision in cognitive radio networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1088–1107, 3rd Quart., 2013.

[24] W. Liang, S. X. Ng, and L. Hanzo, "Cooperative overlay spectrum access in cognitive radio networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1924–1944, 3rd Quart., 2017.

[25] R. H. Tehrani, S. Vahid, D. Triantafyllopoulou, H. Lee, and K. Moessner, "Licensed spectrum sharing schemes for mobile operators: A survey and outlook," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2591–2623, 4th Quart., 2016.

[26] M. Song, C. Xin, Y. Zhao, and X. Cheng, "Dynamic spectrum access: From cognitive radio to network radio," *IEEE Wireless Commun.*, vol. 19, no. 1, pp. 23–29, Feb. 2012.

[27] L. Zhang, M. Xiao, G. Wu, M. Alam, Y.-C. Liang, and S. Li, "A survey of advanced techniques for spectrum sharing in 5G networks," *IEEE Wireless Commun.*, vol. 24, no. 5, pp. 44–51, Oct. 2017.

[28] P. Gandotra, R. K. Jha, and S. Jain, "Green communication in next generation cellular networks: A survey," *IEEE Access*, vol. 5, pp. 11727–11758, Jul. 2017.

[29] M. Höyhtyä *et al.*, "Database-assisted spectrum sharing in satellite communications: A survey," *IEEE Access*, vol. 5, pp. 25322–25341, Dec. 2017.

[30] Z. Zhou, D. Guo, and M. L. Honig, "Licensed and unlicensed spectrum allocation in heterogeneous networks," *IEEE Trans. Commun.*, vol. 65, no. 4, pp. 1815–1827, Apr. 2017.

[31] *Spectrum Policy Task Force Report*, document ET Docket 02-155, FCC, Apr. 2002.

[32] B. Wang and K. J. R. Liu, "Advances in cognitive radio networks: A survey," *IEEE J. Sel. Topics Signal Process.*, vol. 5, no. 1, pp. 5–23, Feb. 2011.

[33] J. Mitola and G. Q. Maguire, Jr., "Cognitive radio: Making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, Apr. 1999.

[34] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[35] Y. Kim *et al.*, "Beyond 3G: Vision, requirements, and enabling technologies," *IEEE Commun. Mag.*, vol. 41, no. 3, pp. 120–124, Mar. 2003.

[36] J. van de Beek, J. Riihijarvi, A. Achtzehn, and P. Mahonen, "TV white space in Europe," *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, pp. 178–188, Feb. 2012.

[37] T. Wang, C. Jiang, and Y. Ren, "Access points selection in super WiFi network powered by solar energy harvesting," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2016, pp. 1–5.
[38] S. K. Yong and C.-C. Chong, "An overview of multigigabit wireless through millimeter wave technology: Potentials and technical challenges," *EURASIP J. Wireless Commun. Netw.*, vol. 14, no. 4, pp. 70–78, Nov. 2007.
[39] L. Zhou and Y. Ohashi, "Hybrid precoding with data stream adaptation for high throughput mmWave MIMO systems," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2016, pp. 1–6.
[40] X. Zhao, A. M. A. Abdo, C. Xu, S. Geng, J. Zhang, and I. Memon, "Dimension reduction of channel correlation matrix using cur-decomposition technique for 3-D massive antenna system," *IEEE Access*, 2017, doi: 10.1109/ACCESS.2017.2786681.
[41] M. Kobayashi, H. Motozuka, T. Urushihara, N. Shirakata, and K. Takinami, "IEEE 802.11ad/WiGig based millimeter-wave small cell systems with adjacent channel interference suppression," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Oct. 2016, pp. 1–5.
[42] B. Li, Z. Zhou, W. Zou, X. Sun, and G. Du, "On the efficient beamforming training for 60 GHz wireless personal area networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 504–515, Feb. 2013.
[43] 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, Jan. 2007.
[44] D. Datla, R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, "Parametric adaptive spectrum sensing framework for dynamic spectrum access networks," in *Proc. 2nd IEEE Int. Symp. New Frontiers Dyn. Spectr. Access Netw. (DySPAN)*, Apr. 2007, pp. 482–485.
[45] K. Kim, I. A. Akbar, K. K. Bae, J.-S. Um, C. M. Spooner, and J. H. Reed, "Cyclostationary approaches to signal detection and classification in cognitive radio," in *Proc. 2nd IEEE Int. Symp. New Frontiers Dyn. Spectr. Access Netw. (DySPAN)*, Apr. 2007, pp. 212–215.
[46] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Proc. Conf. Rec. 40th Asilomar Conf. Signals Syst. Comput. (ASILOMAR)*, Nov. 2010, pp. 1558–1562.
[47] M. A. Khojastepour, K. Sundaresan, S. Rangarajan, X. Zhang, and S. Barghi, "The case for antenna cancellation for scalable full-duplex wireless communications," in *Proc. 10th ACM Workshop Hot Topics Netw. (HOTNETS)*, Nov. 2011, pp. 1558–1562.
[48] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4296–4307, Dec. 2012.
[49] W. Cheng, X. Zhang, and H. Zhang, "Full-duplex spectrum-sensing and MAC-protocol for multichannel nontime-slotted cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 5, pp. 820–831, May 2015.
[50] W. Afifi and M. Krunz, "Incorporating self-interference suppression for full-duplex operation in opportunistic spectrum access systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 4, pp. 2180–2191, Apr. 2015.
[51] Y. Liao, T. Wang, L. Song, and Z. Han, "Listen-and-talk: Protocol design and analysis for full-duplex cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 656–667, Jan. 2017.
[52] P. V. Tuan and I. Koo, "Throughput maximisation by optimising detection thresholds in full-duplex cognitive radio networks," *IET Commun.*, vol. 10, no. 11, pp. 1355–1364, Jul. 2016.
[53] M. Deng, B.-J. Hu, and X. Li, "Adaptive weighted sensing with simultaneous transmission for dynamic primary user traffic," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 992–1004, Mar. 2017.
[54] M. Hirzallah, W. Afifi, and M. Krunz, "Full-duplex-based rate/mode adaptation strategies for Wi-Fi/LTE-U coexistence: A POMDP approach," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 1, pp. 20–29, Jan. 2017.
[55] Y. Liu, R. Yu, M. Pan, Y. Zhang, and S. Xie, "SD-MAC: Spectrum database-driven MAC protocol for cognitive machine-to-machine networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1456–1467, Feb. 2017.
[56] Y. Ma, X. Zhang, and Y. G. Q. Mary, "An efficient joint sub-Nyquist spectrum sensing scheme with geolocation database over TV white space," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.
[57] K. B. Letaief and W. Zhang, "Cooperative communications for cognitive radio networks," *Proc. IEEE*, vol. 97, no. 5, pp. 878–893, May 2009.
[58] R. Doost-Mohammady and K. R. Chowdhury, "Design of spectrum database assisted cognitive radio vehicular networks," in *Proc. 7th Int. ICST Conf. Cognit. Radio Oriented Wireless Netw. Commun. (CROWNCOM)*, Jun. 2012, pp. 1–5.
[59] G. Ding, J. Wang, Q. Wu, Y.-D. Yao, F. Song, and T. A. Tsiftsis, "Cellular-base-station-assisted device-to-device communications in TV white space," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 1, pp. 107–121, Jan. 2016.
[60] T. S. Syed and G. A. Safdar, "History-assisted energy-efficient spectrum sensing for infrastructure-based cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2462–2473, Mar. 2017.
[61] E. C. Y. Peh, Y.-C. Liang, Y. L. Guan, and Y. Zeng, "Optimization of cooperative sensing in cognitive radio networks: A sensing-throughput tradeoff view," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 5294–5299, Nov. 2009.
[62] R. Tandra and A. Sahai, "Fundamental limits on detection in low SNR under noise uncertainty," in *Proc. Int. Conf. Wireless Netw., Commun. Mobile Comput. (IWCMC)*, Jun. 2005, pp. 464–469.
[63] C. S. Xydeas and V. Petrovic, "Objective image fusion performance measure," *Electron. Lett.*, vol. 34, no. 4, pp. 308–309, Feb. 2000.
[64] W. Na, J. Yoon, S. Cho, D. W. Griffith, and N. Golmie, "Centralized cooperative directional spectrum sensing for cognitive radio networks," *IEEE Trans. Mobile Comput.*, 2017, doi: 10.1109/TMC.2017.2768509.
[65] L. Khalid and A. Anpalagan, "Reliability-based decision fusion scheme for cooperative spectrum sensing," *IET Commun.*, vol. 8, no. 14, pp. 2423–2432, Sep. 2014.
[66] Y. Wang, H. Li, and L. Qian, "Belief propagation and quickest detection-based cooperative spectrum sensing in heterogeneous and dynamic environments," *IEEE Trans. Wireless Commun.*, vol. 16, no. 11, pp. 7446–7459, Nov. 2017.
[67] L. Ma, Y. Xiang, Q. Pei, Y. Xiang, and H. Zhu, "Robust reputation-based cooperative spectrum sensing via imperfect common control channel," *IEEE Trans. Veh. Technol.*, 2017, doi: 10.1109/TVT.2017.2763980.
[68] M. Zheng, W. Liang, H. Yu, and M. Song, "SMCSS: A quick and reliable cooperative spectrum sensing scheme for cognitive industrial wireless networks," *IEEE Access*, vol. 4, pp. 9308–9319, Jan. 2016.
[69] Z. Zhang, W. Zhang, H.-C. Chao, and C.-F. Lai, "Toward belief function-based cooperative sensing for interference resistant industrial wireless sensor networks," *IEEE Trans. Ind. Informat.*, vol. 12, no. 6, pp. 2115–2126, Dec. 2016.
[70] A. Paul, A. Daniel, A. Ahmad, and S. Rho, "Cooperative cognitive intelligence for internet of vehicles," *IEEE Syst. J.*, vol. 11, no. 3, pp. 1249–1258, Sep. 2017.
[71] M. Sun, M. Jin, Q. Guo, and Y. Li, "Cooperative spectrum sensing under ambient malicious interferences," *IEEE Commun. Lett.*, vol. 22, no. 2, pp. 432–435, Feb. 2018.
[72] M. J. Saber and S. M. S. Sadough, "Multiband cooperative spectrum sensing for cognitive radio in the presence of malicious users," *IEEE Commun. Lett.*, vol. 20, no. 2, pp. 404–407, Feb. 2016.
[73] H. Lin, J. Hu, J. Ma, L. Xu, and Z. Yu, "A secure collaborative spectrum sensing strategy in cyber-physical systems," *IEEE Access*, vol. 5, pp. 27679–27690, 2017.
[74] F. Benedetto and G. Giunta, "A theoretical analysis of asymptotical performance of cooperative spectrum sensing in the presence of malicious users," *IEEE Wireless Commun. Lett.*, 2017, doi: 10.1109/LWC.2017.2778732.
[75] I. Memon, L. Chen, Q. A. Arain, H. Memon, and G. Chen, "Pseudonym changing strategy with multiple mix zones for trajectory privacy protection in road networks," *Int. J. Commun. Syst.*, vol. 31, no. 1, p. e3437, Jun. 2018.
[76] Z. Quan, S. Cui, A. H. Sayed, and H. V. Poor, "Wideband spectrum sensing in cognitive radio networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2008, pp. 901–906.
[77] X. Zhang, Y. Ma, and Y. Gao, "Adaptively regularized compressive spectrum sensing from real-time signals to real-time processing," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.
[78] Z. Fanzi, C. Li, and Z. Tian, "Distributed compressive spectrum sensing in cooperative multihop cognitive networks," *IEEE J. Sel. Topics Signal Process.*, vol. 5, no. 1, pp. 37–48, Feb. 2011.
[79] K. Cao, P. Lu, C. Sun, Y. Zou, J. Wang, and L. Ling, "Frequency locator polynomial for wideband sparse spectrum sensing with multichannel subsampling," *IEEE Trans. Signal Process.*, vol. 66, no. 3, pp. 789–803, Feb. 2018.

[80] Z. Qin, J. Wang, J. Chen, and L. Wang, "Adaptive compressed spectrum sensing based on cross validation in wideband cognitive radio system," *IEEE Syst. J.*, vol. 11, no. 4, pp. 2422–2431, Dec. 2017.

[81] Y. Ma, Y. Gao, A. Cavallaro, C. G. Parini, W. Zhang, and Y.-C. Liang, "Sparsity independent sub-Nyquist rate wideband spectrum sensing on real-time TV white space," *IEEE Trans. Veh. Technol.*, vol. 66, no. 10, pp. 8784–8794, Oct. 2017.

[82] Y. Gao, Y. Chen, and Y. Ma, "Sparse-bayesian-learning-based wideband spectrum sensing with simplified modulated wideband converter," *IEEE Access*, 2017, doi: 10.1109/ACCESS.2017.2778699.

[83] B. Khalfi, B. Hamdaoui, M. Guizani, and N. Zorba, "Exploiting wideband spectrum occupancy heterogeneity for weighted compressive spectrum sensing," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, May 2017, pp. 613–618.

[84] W. Wang and X. Liu, "List-coloring based channel allocation for open-spectrum wireless networks," in *Proc. IEEE 62nd Veh. Technol. Conf. (VTC-Fall)*, vol. 1. Sep. 2005, pp. 690–694.

[85] M. Vishram, L. C. Tong, and C. Syin, "List multi-coloring based fair channel allocation policy for self coexistence in cognitive radio networks with QoS provisioning," in *Proc. IEEE REGION 10 Symp.*, Apr. 2014, pp. 99–104.

[86] X.-O. Song, "Utilization and fairness in spectrum assignment for cognitive radio networks: An ant colony optimization's perspective," in *Proc. Int. Conf. Wireless Commun. Sensor Netw.*, Dec. 2014, pp. 42–45.

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

[88] T. Jing, C. Zhao, X. Xing, Y. Huo, W. Li, and X. Cheng, "A multi-unit truthful double auction framework for secondary market," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 2817–2822.

[89] Y. Chen, J. Zhang, K. Wu, and Q. Zhang, "TAMES: A truthful auction mechanism for heterogeneous spectrum allocation," in *Proc. IEEE INFOCOM*, Apr. 2013, pp. 180–184.

[90] T. Zhou, B. Chen, C. Zhu, and X. Zhai, "TPAHS: A truthful and profit maximizing double auction for heterogeneous spectrums," in *Proc. IEEE Trustcom/BigDataSE/ISPA*, Aug. 2016, pp. 27–33.

[91] L. Chen, L. Huang, Z. Sun, H. Xu, and H. Guo, "Spectrum combinatorial double auction for cognitive radio network with ubiquitous network resource providers," *IET Commun.*, vol. 9, no. 17, pp. 2085–2094, Nov. 2015.

[92] Z. Zheng, F. Wu, S. Tang, and G. Chen, "AEGIS: An unknown combinatorial auction mechanism framework for heterogeneous spectrum redistribution in noncooperative wireless networks," *IEEE/ACM Trans. Netw.*, vol. 24, no. 3, pp. 1919–1932, Jun. 2016.

[93] J. Neel, R. M. Buehrer, B. H. Reed, and R. P. Gilles, "Game theoretic analysis of a network of cognitive radios," in *Proc. 45th Midwest Symp. Circuits Syst. (MWSCAS)*, vol. 3. Aug. 2002, pp. III-409–III-412.

[94] J. O. Neel, J. H. Reed, and R. P. Gilles, "Convergence of cognitive radio networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2004, pp. 2250–2255.

[95] D. Niyato and E. Hossain, "Competitive spectrum sharing in cognitive radio networks: A dynamic game approach," *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2651–2660, Jul. 2008.

[96] W. Wang and B. Li, "Market-driven bandwidth allocation in selfish overlay networks," in *Proc. IEEE INFOCOM*, vol. 4. Mar. 2005, pp. 2578–2589.

[97] Y. Xiao, T. Forde, I. Macaluso, L. A. DaSilva, and L. Doyle, "Spatial spectrum sharing-based carrier aggregation for heterogeneous networks," in *Proc. Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 2591–2596.

[98] M. Iwamura, K. Etemad, M. H. Fong, R. Love, and R. Nory, "Carrier aggregation framework in 3GPP LTE-advanced [WiMAX/LTE Update]," *IEEE Commun. Mag.*, vol. 48, no. 8, pp. 60–67, Aug. 2010.

[99] P. Maille and B. Tuffin, "Price war with partial spectrum sharing for competitive wireless service providers," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Nov. 2009, pp. 1–6.

[100] X. Xing, B. Chen, H. Liu, X. Cheng, W. Zhou, and D. Chen, "Game theoretic analysis of green spectrum and infrastructure leasing on TV bands," *IEEE Trans. Veh. Technol.*, vol. 66, no. 7, pp. 6511–6522, Jul. 2017.

[101] C. Jiang, Y. Chen, K. J. R. Liu, and Y. Ren, "Renewal-theoretical dynamic spectrum access in cognitive radio network with unknown primary behavior," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 3, pp. 406–416, Mar. 2013.

[102] Y. Yilmaz, Z. Guo, and X. Wang, "Sequential joint spectrum sensing and channel estimation for dynamic spectrum access," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 11, pp. 2000–2012, Nov. 2014.

[103] H. Saki, A. Shojaeifard, and M. G. Martini, "Stochastic resource allocation for hybrid spectrum access ofdma-based cognitive radios," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 7750–7755.

[104] P. Thakur, A. Kumar, S. Pandit, G. Singh, and S. N. Satashia, "Advanced frame structures for hybrid spectrum access strategy in cognitive radio communication systems," *IEEE Commun. Lett.*, vol. 21, no. 2, pp. 410–413, Feb. 2017.

[105] T. M. C. Chu, H. Phan, and H.-J. Zepernick, "Hybrid interweave-underlay spectrum access for cognitive cooperative radio networks," *IEEE Trans. Commun.*, vol. 62, no. 7, pp. 2183–2197, Jul. 2014.

[106] D. T. Hoang, D. Niyato, P. Wang, and D. I. Kim, "Opportunistic channel access and RF energy harvesting in cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 11, pp. 2039–2052, Nov. 2014.

[107] A. U. Rehman, C. Dong, L.-L. Yang, and L. Hanzo, "Performance of cognitive stop-and-wait hybrid automatic repeat request in the face of imperfect sensing," *IEEE Access*, vol. 4, pp. 5489–5508, Sep. 2016.

[108] M. M. Rashid, J. Hossain, E. Hossain, and V. K. Bhargava, "Opportunistic spectrum access in cognitive radio networks: A queueing analytic model and admission controller design," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Nov. 2007, pp. 4647–4652.

[109] J. Heo, J. Shin, J. Nam, Y. Lee, J. G. Park, and H. S. Cho, "Mathematical analysis of secondary user traffic in cognitive radio system," in *Proc. IEEE 68th Veh. Technol. Conf.*, Sep. 2008, pp. 1–5.

[110] W. S. Chang and W. M. Jang, "Spectrum occupancy of cognitive radio networks: A queueing analysis using retrial queue," *IET Netw.*, vol. 3, no. 3, pp. 218–227, Sep. 2014.

[111] Z. Chang, T. Ristaniemi, and Z. Han, "Queueing game for spectrum access in cognitive radio networks," *IEEE Commun. Lett.*, vol. 19, no. 11, pp. 2017–2020, Nov. 2015.

[112] L.-C. Wang, C.-W. Wang, and F. Adachi, "Load-balancing spectrum decision for cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 4, pp. 757–769, Apr. 2011.

[113] C. Joo and N. B. Shroff, "A novel coupled queueing model to control traffic via qos-aware collision pricing in cognitive radio networks," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, May 2017, pp. 1–9.

[114] I. Christian, S. Moh, I. Chung, and J. Lee, "Spectrum mobility in cognitive radio networks," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 114–121, Jun. 2012.

[115] W. Y. Lee and I. F. Akyildiz, "Spectrum-aware mobility management in cognitive radio cellular networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 4, pp. 529–542, Apr. 2012.

[116] Z. Zhi-Jin, Z. Lu-Ping, and W. Hai-Quan, "Spectrum handoff based on adaptive weights adjustment," *IET Commun.*, vol. 9, no. 5, pp. 674–680, Mar. 2015.

[117] Y. Wu, F. Hu, Y. Zhu, and S. Kumar, "Optimal spectrum handoff control for CRN based on hybrid priority queuing and multi-teacher apprentice learning," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2630–2642, Mar. 2017.

[118] C. Wu, C. He, L. Jiang, Y. Chen, and Q. Shi, "Optimal channel sensing sequence design for spectrum handoff," *IEEE Wireless Commun. Lett.*, vol. 4, no. 4, pp. 353–356, Aug. 2015.

[119] D. Willkomm, J. Gross, and A. Wolisz, "Reliable link maintenance in cognitive radio systems," in *Proc. 1st IEEE Int. Symp. New Frontiers Dyn. Spectrum Access Netw. (DySPAN)*, Nov. 2005, pp. 371–378.

[120] H. Yu and K.-F. Ssu, "Spatially varied control channel assignment in cognitive radio ad hoc networks," in *Proc. 6th Int. ICST Conf. Cognit. Radio Oriented Wireless Netw. Commun. (CROWNCOM)*, Jun. 2011, pp. 311–315.

[121] H. Ji and C.-Y. Huang, "Non-cooperative uplink power control in cellular radio systems," *Wireless Netw.*, vol. 4, no. 3, pp. 233–240, Apr. 1998.

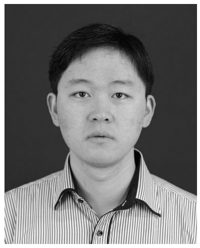
[122] C. U. Saraydar, N. B. Mandayam, and D. J. Goodman, "Efficient power control via pricing in wireless data networks," *IEEE Trans. Commun.*, vol. 50, no. 2, pp. 291–303, Feb. 2002.

[123] B. Wang, Y. Wu, and K. J. R. Liu, "Game theory for cognitive radio networks: An overview," *Comput. Netw.*, vol. 54, no. 14, pp. 2537–2561, Oct. 2010.

[124] M. Canales, J. R. Gallego, and R. Ciria, "Distributed channel allocation and power control in cognitive radio networks using game theory," in *Proc. IEEE Veh. Technol. Conf. (VTC Fall)*, Sep. 2011, pp. 1–5.

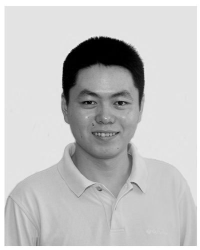
[125] M. Pirmoradian, O. Adigun, and C. Politis, "Adaptive power control scheme for energy efficient cognitive radio networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2012, pp. 6988–6992.

[126] X. Xie, H. Yang, A. V. Vasilakos, and L. He, "Fair power control using game theory with pricing scheme in cognitive radio networks," *J. Commun. Netw.*, vol. 16, no. 2, pp. 183–192, Apr. 2014.
[127] H. Zhang, C. Jiang, N. C. Beaulieu, X. Chu, X. Wang, and T. Q. S. Quek, "Resource allocation for cognitive small cell networks: A cooperative bargaining game theoretic approach," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3481–3493, Jun. 2015.
[128] J. Zheng, Y. Cai, N. Lu, Y. Xu, and X. Shen, "Stochastic game-theoretic spectrum access in distributed and dynamic environment," *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4807–4820, Oct. 2015.
[129] S. Lee, R. Zhang, and K. Huang, "Opportunistic wireless energy harvesting in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, pp. 4788–4799, Sep. 2013.
[130] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.
[131] S. Ladan, N. Ghassemi, A. Ghiotto, and K. Wu, "Highly efficient compact rectenna for wireless energy harvesting application," *IEEE Microw. Mag.*, vol. 14, no. 1, pp. 117–122, Jan. 2013.
[132] X. Gao, W. Xu, S. Li, and J. Lin, "An online energy allocation strategy for energy harvesting cognitive radio systems," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2013, pp. 1–5.
[133] I. Ahmed, M. M. Butt, C. Psomas, A. Mohamed, I. Krikidis, and M. Guizani, "Survey on energy harvesting wireless communications: Challenges and opportunities for radio resource allocation," *Comput. Netw.*, vol. 88, pp. 234–248, Sep. 2015.
[134] Z. Chen, Z. Ding, X. Dai, and R. Zhang, "An optimization perspective of the superiority of noma compared to conventional OMA," *IEEE Trans. Signal Process.*, vol. 65, no. 19, pp. 5191–5202, Oct. 2017.
[135] L. Lv, J. Chen, and Q. Ni, "Cooperative non-orthogonal multiple access in cognitive radio," *IEEE Commun. Lett.*, vol. 20, no. 10, pp. 2059–2062, Oct. 2016.
[136] Y. Liu, Z. Ding, M. Elkashlan, and J. Yuan, "Nonorthogonal multiple access in large-scale underlay cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 10152–10157, Dec. 2016.
[137] L. Lv, J. Chen, Q. Ni, and Z. Ding, "Design of cooperative non-orthogonal multicast cognitive multiple access for 5G systems: User scheduling and performance analysis," *IEEE Trans. Commun.*, vol. 65, no. 6, pp. 2641–2656, Jun. 2017.
[138] Z. Ding, F. Adachi, and H. V. Poor, "The application of MIMO to non-orthogonal multiple access," *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 537–552, Jan. 2016.
[139] L. Zhidong and Z. Xiaolin, "A novel frequency hopping scheme based on cognitive radio for aircraft," in *Proc. Green Comput. Commun. (GreenCom), IEEE Internet Things (iThings/CPSCom), IEEE Int. Conf. IEEE Cyber, Phys. Social Comput.*, Aug. 2013, pp. 1231–1236.



FENG HU received the M.E. degree in computer science from the Anhui University of Science and Technology, Anhui, China, in 2014. He is currently pursuing the Ph.D. degree with the College of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, China. His research interests are mainly cognitive radio networks, SDN, and 5G.

BING CHEN received the B.S. and M.S. degrees in computer engineering from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 1992 and 1995, respectively, and the Ph.D. degree from the College of Information Science and Technology, NUAA, in 2008. He has been with NUAA since 1998. He is currently a Professor with the Computer Science and Technology Department, NUAA. His main research interests include cloud computing, wireless communications, and cognitive radio networks.



KUN ZHU received the Ph.D. degree from the School of Computer Engineering, Nanyang Technological University, Singapore, in 2012. He was a Post-Doctoral Research Fellow with the Wireless Communications, Networks, and Services Research Group, Department of Electrical and Computer Engineering, University of Manitoba, Canada. He is currently with the College of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics, China. His research interests are in the areas of resource management in multi-tier heterogeneous wireless networks.