Effective Wide Spectrum Sharing Techniques Relying on CR Technology toward 5G: A Survey

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Abstract —In order to overcome the spectrum scarcity in 5G networks, spectrum sharing is being studied relying on Cognitive Radio (CR) technology. Even with the new spectrum resources (millimeter-wave) for future networks, sharing the spectrum below 6 GHz and above will be necessary. The four stages as processes to achieve spectrum sharing were classified using a novel taxonomy for the latest techniques with their applicability. The proposed algorithms and studies in the literature on spectrum sharing techniques were summarized on the basis of an analytical study. According to 5G requirements several challenges need to be defeated such as large capacity, ultra-low latency, full coverage, and numerous connectivity. This paper presents a comprehensive survey on the sharing techniques which may be applicable to 5G networks. Yet, the challenges provided an open issues which attracted the interest of researchers to a key techniques such as full duplex spectrum sensing, spectrum sensing based on spectrum database, compressive spectrum sensing, spectrum allocation based on auction theory, spectrum allocation based on aggregation technologies, hybrid Dynamic Spectrum Access (DSA), and hybrid handoff mechanism. To realize the wide spectrum sharing concept, our paper focus on the efficient use of all spectrum resources by exploitation all the obtainable spectrum holes in licensed and unlicensed bands. We specify the applicability of each technique and its performance to recognize the preferable techniques for 5G networks. Finally, the potential challenges and open issues have been discussed, focusing on the spectrum sharing in small cells, also future research directions are suggested.

Index Terms—5G, aggregation technologies, cognitive radio technology, dynamic spectrum access technique, spectrum sharing, spectrum sensing techniques

I. Introduction

The cellular communications networks and its technologies have developed by generations starting from the first generation (1G) to the current fourth generation (4G), to fulfill the increasingly continued data demand as a result of the cellular communications industry growing, due to the importance of communications in our life for better world in all of domains. The development was in a gradual manner by increasing the data rate and decreasing the latency also treating with the growing in number of users. So, the generations have been working fine especially with successfully standardization achieved by 3GPP releases for various cellular systems and technologies. Unlike the previous generations and current 4G which are not sufficient for the future, the fifth generation (5G) will be different according to its requirements which have been shaped by the International Telecommunication Union (ITU) [1], typified by 10Gbps for the peak data rates, 1Gbps for average data rates, sub-one millisecond for ultra-low latency, ultra-reliability, and the minimized power consumption, to be enough for the next generation by fulfilling the needs and achieving the expectations especially that related with emerging of the Internet of Things (IoT).

IoT and the tactile mobile internet will be the main drivers for the next generation which will satisfy the tomorrow's citizens needs in everywhere, and its expected ability to connect too many devices to each other as an important procedure for achieving IoT for diverse fields such as industries, enterprises, transport, medical, and education, then realization the true interactive of every things [2].

Both of mobile technology and spectrum access techniques have been quickly developing, which led to the internet's availability with its information and services in all times, everywhere and even with movement, and according to this objective the development happened [3]. Using the communications to serve people's life require offering the best user experience which must be more importance afterward, especially in new applications like the far regions, areas of human density, and public transport.

The IoT as an attractive technology has acquired interest of many research and experiment centers, academic researchers, and some of standardization groups [4], [5], which have been seriously working on it, supported by some communications companies, vendors, and some industrialists by considering it as the future technology which motivate for emergence the next generation [6], [7].

The concept of IoT which has started in 1999 [8], is combination both the Radio Frequency Identification (RFID) technology and internet technology by successful manner, conclude with product information identification and managing it via internet. The main functions of IoT are to recognize thing and connecting approximately all things to the internet [9], which enable people to interconnect with the things and getting information

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within one network can contain more than 30 billion devices in 2020 [10]-[12].

Due to the importance of mobile internet in people's life which has very surpassed the conventional communications service, and IoT's function represented by interconnecting both the things world and real world. 5G as the revolution in communications world needs to overcome the challenges such as large capacity, ultra-low latency, full coverage, and numerous connectivity to achieve the requirements as illustrated in Table I. Thus, the most important needs for 5G networks can be addressed as shown in Fig. 1.

A. Additional Spectrum

As it is predicted, there will be so many end-points connected to the internet due to IoT, which leads to a huge amount of data in comparison with the data of mobile communications networks and wireless accessing, for conventional use between humans [13]. User Equipments (UEs) accessing the internet, either using the licensed bands of mobile networks, which are limited and allocated to communicate between users themselves, not with things [14], or sharing the Industrial Scientific Medical (ISM) bands as an unlicensed frequency bands for free data transmission, with Wi-Fi devices which originally use these bands [15], when all connect to Wireless Local Area Network (WLAN) Access Point (AP), and with emergence of IoT technology in the future, the ISM bands will be not enough. Thus, the lack of spectrum is big challenge, and additional spectrum is required.

B. Dynamic Spectrum Access (DSA)

With the large expected number of UEs and huge amount of data due to IoT in the future, the cellular infrastructure and mobile network architectures, will suffer several problems in radio resources allocation and managing the users activities, especially that all the executed users data through the internet are using TCP/IP protocol, which is complex somewhat. Hence, the spectrum sharing relying on effective DSA techniques may be the best solution [16].

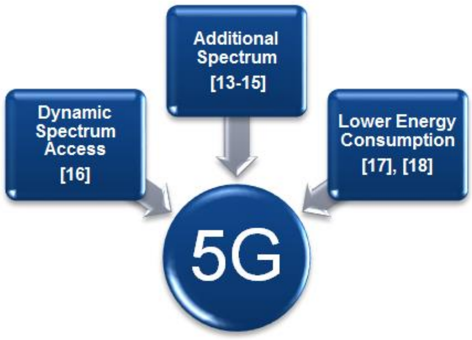

Fig. 1. Most important needs for 5G networks

C. Lower Energy Consumption

The extended future network will connect almost everything, to communicate and get information easily, which may encourage the users to utilize their equipments more. Most of UEs are working by batteries, the cost and complex procedure to replace the battery represent great challenge, requires finding new successful solutions for simplified operations lead to longer battery's life. Thus, focusing on the energy efficiency solutions for future networks is a very important matter [17], [18].

The Cognitive Radio (CR) technology has represented the successful manner to treat with the limitedness of spectrum and its inefficient use, because this technology allows reusing the particular bands [19], and can effectively contribute to determine both the technical challenges and essential requirements toward 5G [20]. Thus, the concepts of CR technology have attracted interest of many researchers.

The procedures of channel sensing techniques for different networks using various spaces of spectrum are summarized in [21]. Due to the importance of the channel access opportunities in a broadband for data transmission, [22] has discussed several mathematical solutions to obtain the channel, with the characteristics of each solution and its weaknesses.

TABLE I: CHALLENGES AND REQUIREMENTS IN 5G

Challenges	Requirements
Large capacity	Very high data transmission rates such 10Gbps for the peak data rates and 1Gbps for average data rates
Ultra- low latency	Realization sub-1ms delay between two terminals, with ultra-reliability
Full coverage	Internet's availability with its information and services in all times, everywhere and even with movement for the best user experience with seamless using the advanced mobile technology and spectrum access techniques
Numerous connectivity	Billions of the connected devices to internet for IoT's emergence, on the condition of minimized power consumption

An overview of resource allocation methods, applied in Cognitive Radio Networks (CRNs), with the explanation for the specific criterion and mechanism of each method, are covered in [23]. In the same context, [24] has highlighted on the criteria that optimize the performance of CRNs, related with the enhancements in energy efficiency and Quality of Service (QoS), throughput increasing, interference reduction and fairly usage. For dependable spectrum, [25] reviewed the latest procedures represented by studying the spectrum characteristics and its selection mechanism. A survey of spectrum access schemes in CRNs, which took into account the cooperative and non-cooperative models, are illustrated in [26]. To understand the idea of dynamic spectrum sharing, [27] reviewed several scenarios for licensed spectrum sharing, applied in different network configurations, with applicability of each scenario and its challenges. Reference [28] presented a survey on the concept of DSA with its challenges, and highlighted on the future of DSA as a flexible model for spectrum sharing after considering several factors such as the technological, economic, social, and political.

According to the above, there are many papers on the CR technology and most of these papers have adopted one important aspect related with CRNs such as spectrum sensing, resource allocation, spectrum decision, and spectrum access. The few of papers provided a comprehensive survey on spectrum sharing toward 5G networks. Reference [29] presented a brief survey on advanced techniques for spectrum sharing in 5G networks included cognitive radio, in-band full-duplex communication, device-to-device communication, Long Term Evolution on unlicensed spectrum, and non-orthogonal multiple access with the principles, research methodology, and challenges for each technique, in addition to the issues of integration multiple spectrum sharing techniques. For the GREEN cellular networks in 5G, [30] provided a survey included the techniques and technologies which will be used in the next generation networks from the green communication perspective, and focused on the spectrum sharing role in the reduction of energy consumption for longer battery's life. Reference [31] as a survey study has discussed using the databases of spectrum for spectrum sharing between the satellite and terrestrial networks, also between two satellite networks, and presented several scenarios adopted different orbits and frequencies. The summary of existing survey papers on spectrum sharing is shown in Table II.

By reviewing the previous studies, the need arises for a comprehensive study on spectrum sharing schemes in CRNs, and its role to explore the spectrum for getting it to overcome the spectrum scarcity issues to pave the way for 5G. This paper introduces a comprehensive survey on wide spectrum sharing schemes in CRNs as a procedure toward 5G networks including the technologies, techniques, and proposed algorithms used in these schemes, to answer the most important question which is: from where and how will more spectrums come?

The contributions of this paper are summarized as follows:

- Identifies the new spectrum resources, and emphasizes on exploitation all the obtainable spectrum holes in licensed and unlicensed bands which are below 6GHz and above (wide spectrum sharing) to increase the capacity of CRNs in 5G.
- Provides a comprehensive survey with novel taxonomy on the latest techniques of spectrum sharing schemes in CRNs with their applicability, to recognize the preferable techniques for 5G networks, which can face the challenges of large capacity, ultra-low latency, full coverage, and numerous connectivity.
- Provides an in depth survey on the potential spectrum sensing techniques that may be serviceable in 5G, such as full duplex spectrum sensing, spectrum sensing based on spectrum database, and compressive spectrum sensing, also the focus on the difference between Listen-Before-Talk (LBT) and Listen-And-Talk (LAT) technique.
- Provides an extensive survey on the most important spectrum allocation approaches that may be applicable in 5G, specifically spectrum allocation based on auction theory and spectrum allocation based on aggregation technologies using either Carrier Aggregation (CA) or link aggregation technology.
- Provides detailed survey on the spectrum access procedures represented by DSA technique with its modes, and the queueing for spectrum access, also investigates in the different spectrum handoff mechanisms.
- Outlines the spectrum sharing challenges and open issues which may face the implementation of DSA in DBF and IFW small cells in 5G networks when using higher frequency bands (millimeter-wave). Then, summarizes the major challenges associated with adopting in-band full-duplex (IBFD) mode, and increasing spectrum demand due to the expected numerous connectivity in 5G.

TABLE II: THE SUMMARY OF EXISTING SURVEY PAPERS ON SPECTRUM SHARING

Reference	Contribution	Description
[27]	A study on the dynamic spectrum sharing assuming several scenarios	A study about licensed spectrum only
[29]	A brief survey on the spectrum sharing techniques in 5G networks	Non-comprehensive and neglect other important techniques
[30]	A survey on the next generation techniques from green communication perspective	It only about the spectrum sharing role in energy efficiency
[31]	A survey on the spectrum sharing between satellite and terrestrial networks	A study depend only on the databases for spectrum sharing

The organization of this paper is as follows. In Section II, we demonstrate the background which is about CR technology, spectrum sharing toward 5G to exploit the spectrum resources, and the importance of using wide range of spectrum for 5G. Section III present the important manners of spectrum sensing, and explain each manner, with its applicability to particular application. In Section IV, we accurately describe the latest and effective algorithms which can be applicable for 5G networks. Section V explains the procedures of spectrum access process, and the main transmission modes of DSA technique. In Section VI, we illustrate the spectrum handoff process with its different mechanisms. Section VII discusses a number of potential challenges and open issues for wide spectrum sharing in 5G networks. In Section VIII, we conclude the paper and mention to required studies for the future.

II. Background

A. Cognitive Radio Technology

The radio spectrum resources are managed by one of the spectrum allocation techniques, and when the technique uses the fixed allocation manner [32], the spectrum divides to parts, and each part allocates to particular users, whereas other users can not use it. The user and its allocated spectrum represent the licensed user and licensed spectrum respectively, and with the advances of cellular technology, also the limitedness of spectrum resources, the existed spectrum has become very precious [2].

The fixed allocation of spectrum leads to, that the allocated spectrum may be unoccupied for some time and in some segments, which mean inefficient use even in the more importance parts of spectrum [33]. For the efficient use of limited licensed spectrum, several technologies have been adopted to achieve multiple using on the same spectrum resource, are Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA), in addition to using the techniques of Multiple Input-Multiple Output (MIMO) [34], though these technologies and techniques have improved the spectrum efficiency by serving several users, but cannot considering it as the best solution to treat with the lack of spectrum resources, due to originally unavailability, and the fixed allocation.

The proposed idea of CR technology started in 1999 [35], afterward it has been defined professionally as an intelligent wireless communication system [36], to serve the wireless communications networks, by its ability to sense the specific spectrum, for detecting the idle periods to use it, when the licensed users are inactive. The licensed user represents primary user (PU), while the unlicensed user who uses the CR is called the secondary user (SU). Notable, that the SU's functions are sensing the spectrum for use it when the PU is jobless, leaving the spectrum instantly when the PU return to the spectrum and must be adaptable by change its parameters accordance with the results of sensing.

B. Spectrum Sharing Toward 5G

To exploit the available precious spectrum which has been already allocated, sharing it represent the better procedure for efficient utilization, by applying the CR technology in cellular networks and using the advanced techniques which enable SUs to use spectrum when PUs are jobless to avoid the interference between them. Thus, the spectrum sharing scheme should complete four processes as shown in Fig. 2, are:

1) Spectrum sensing

The first process in spectrum sharing scheme is spectrum sensing, which is very important to detect the occupied spectrum bands by PUs, and recognizing each band from several aspects such as its channels, used spaces, channel use periods and idle periods. Thus, this step enables SU to be sure that the intended band is unoccupied by PUs for preventing interference with them, and the progress toward other processes to utilize the band and achieving successful spectrum sharing.

2) Spectrum allocation

Spectrum allocation as the second process depends on the available spectrum holes and the followed distribution mechanism. Because the number of holes is changeable, the SUs should compete between them based on the QoS to obtain spectrum. For fair and better spectrum usage, successful distribution mechanism is required, to manage the accurately spectrum allocation.

3) Spectrum access

So long as, the access right of band is for PU only, SU must use the band when it unoccupied (PU is idle), to prevent the interference between them. Thus, the optimal algorithm is necessary, for coordinated utilization between the SU and its allocated spectrum holes.

4) Spectrum handoff

Three reasons compel the SU to leave used band, and switching to other band, are:

- When the PU returns to utilize the band, SU leaves the band to avoid interference.
- SU's mobility may cause low quality of communication, SU needs to leave the used band and switching to other proper band within the new area.
- When the utilized band cannot fulfill the needs of SU.

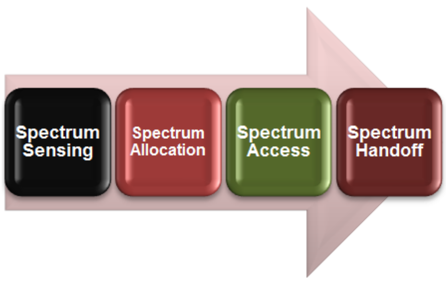

Fig. 2. The processes of spectrum sharing.

C. Wide Range of Spectrum

The CR technology is applicable with the unlicensed bands, which no need license to use it, thus all users have the same rights to utilize these bands, without priority to any user, and with the unoccupied portions of licensed bands which are called holes, in this case the priority is to PUs, and the SUs can using these licensed bands only when the PUs are jobless, to obviate the interference with them. At the present time, the obtainable spectrum bands are under 6GHz, and most of these bands are already allocated, particularly the bands which having frequencies less than 3GHz. The unlicensed bands represented by the ISM bands, which are used with several applications, especially the technologies of unlicensed access for short range wireless transmissions on 5GHz band which has been designated in the WRC-03 conference [37], for the uses of WLANs, after years the mobile communications have used this band with regulatory requirements included the fairly coexisting between users and allowed power levels depending on the area of using this band.

Unlike 4G, the 5G networks will be more heterogeneous, and loaded with a huge data rates, also strict rules of user experience, in addition to so many requirements, therefore the spectrum availability will be the most important matter to satisfy the future user's demands. So long as, the spectrum bands under 6GHz are previously allocated, and suffer from crowding, also the complexity of supplying a new spectrum due to the scarcity, the spectrum bands which having frequencies more than 6GHz can be considered to divide the tasks, especially that these bands can offer large bandwidth. Hence, the 5G need to use the so wide range of spectrum can start from 1GHz to 100GHz, to increase the capacity of networks for achieving the transmissions related with the great demand of data. The so wide range of spectrum include the bands of frequencies under 6GHz which represent the fundamental bands and the bands which having frequencies above 6GHz which will utilize as supplementary bands because of the restriction of propagation.

As mentioned in this research, the licensed spectrum usage is not ideal in both dimensions (time and space), due to the idle periods and not using of some spectrum's portions, respectively. To exploit the unused spaces of licensed spectrum, the reallocation of the spectrum parts is very important, to treat with the lack of spectrum resources. In the same context, the allocated bands for mobile networks are within the analogue TV bands, and when the digitizing of analogue TV happened, several parts of bands, which have been previously allocated for analogue TV have became idle. Thus, the used spaces became small in analogue TV bands, which led to, decreasing the rate of usage to 17.4% in Chicago and 4.54% in Singapore [38]. To benefit from these idle parts of analogue TV bands which are named TV White Spaces, or super Wi-Fi as figuratively called by United States [39], the reallocation was necessary, and has been done during the WRC-07 conference, which allocated these spaces for mobile networks, to utilize it for providing the wireless communications signal in far regions, which usually covered by the TV signal.

In the future, the wireless transmissions for short distances will be much more, due to the expected IoT with its new applications which may require high data rates. Currently, the conventional unlicensed spectrum bands used by Wi-Fi for the indoor transmission are 2.4GHz and 5GHz, both have been exploited using the advanced technologies and latest techniques, for the efficient use of available spectrum, and to get the maximum limit of data rate.

The 60 GHz band with its high frequency millimeter waves due to the short wavelength, has attracted the interest of many researchers, industrialists and specialist groups, especially that the advanced technology of semiconductors enabled them dividing this band into 5GHz-7GHz in several countries, to be the available continuous unlicensed bandwidth, which can use it by many applications [40]. Thus, the 60GHz band is very important and can considering it the superlative band, due to:

1) It can provides the large continuous unlicensed bandwidth, is approximately six times larger than the total bandwidth offered from all bands below 6GHz, which mean high data rates, and when taking into account the seriously path loss of 60GHz electromagnetic waves, the preferred distance for transmissions should be from 1m-10m [41], [42]. Hence, this band is proper for indoor use, and the new architecture of MAC layer has been defined by IEEE 802.11ad to utilize 60GHz band in Wi-Fi networks [43].
2) The precise direction of 60GHz band's signals, because the refractive index in space of this band's waves is very small, which mean that the interference between signals in diverse directions is negligible. Thus, this band has been considered as the anti-interference band and with highly directional signals using the beam forming technology for antenna gains [41]-[44].

As previously mentioned, above 6GHz band there is abundance of spectrum resources with the ability of many bands to offer large continuous bandwidth, which help to improve the capacity, for higher data rates, in addition to the role of spectrum availability to simplify work and multiplicity of services. To fulfill the 5G requirements, it is useful exploiting all the spectrum resources which are below 6GHz and above, licensed and unlicensed bands with continuous bandwidth and discontinuous, to realize the wide spectrum sharing, which will face some problems when adopting it, and applying the specific schemes to achieve this sharing, for example the current sensing techniques and existing algorithms may be unable to detect the channel's holes in high frequency bands, how to achieve the successful allocation of spectrum to distribute the spectrum according to the need of SU as possible and the challenge of power consumption. This paper will present an overall survey about the processes of spectrum sharing schemes, in addition to the required technologies, techniques, and proposed algorithms, adopted in these schemes for wide spectrum sharing.

III. Spectrum Sensing

In CRNs, the spectrum sensing represents fundamental process of spectrum sharing for better spectrum usage, the proper sensing technique enables SU detecting the hole to utilize it and awaiting the return of PU which has the priority to leave the licensed band. There are several manners of spectrum sensing, as shown in Fig. 3. Table III, illustrates the common detection methods used by the first manner (non-cooperative) as a signal processing manner, taking into account that these methods are applicable with advanced technologies. Also Table IV describes the other manners with their applicability and summarizes the existing papers on spectrum sensing using these manners.

A. Non-Cooperative Spectrum Sensing

Spectrum sensing to detect holes in a specific spectrum channel depends on the distinguishing between two channel status (busy or idle), as shown in Fig. 4. Usually, PU utilizes the channel and occupy it to carry their signal, in this case the channel contains both noise and signal of PU, so its energy level will be high, and mean busy channel, while the holes result from non-attendance of PUs, which mean that the channel is idle and contains noise only, so it has low level of energy. Thus, when using the most common detection method which is energy detection, the detection algorithms of spectrum sensing can consider only presence and non-presence of PU's signal to detect the holes [21]. In this manner and when SUs adopt Half Duplex (HD) mode, the sensing result may be one of two hypotheses as follows:

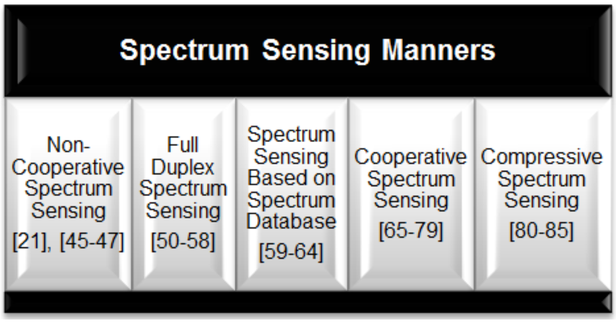

Fig. 3. The spectrum sensing manners.

$$H0: r(t) = n(t) \quad (1)$$

$$H1: r(t) = p(t) + n(t) \quad (2)$$

where $H0$ and $H1$ are the two hypotheses of non-presence and presence of PU respectively. $r(t)$ is the received signal at the SU when sensing the spectrum to detect the presence of PU. $n(t)$ is an Additive White Gaussian Noise (AWGN), and $p(t)$ is PU's signal in a specific spectrum channel.

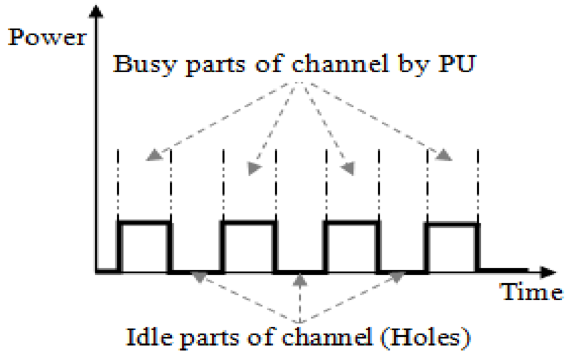

Fig. 4. The channel status diagram (busy or idle).

TABLE III: THE COMMON DETECTION METHODS

Method	Description	Advantages	Disadvantages	Ref.
Energy Detection	Consider only presence and non-presence of PU's signal based on the detected energy level, and does not require beforehand information about PU's signal.	• Easy, without prior knowledge about PU's signal. • Applicable with advanced technologies.	• Inaccuracy when the channel SNR is low. • Cannot distinguish the SU's signal from the signal of PU.	[45], [46]
Matched Filtering Detection	Requires knowledge of PU such as the used modulation type and order, bandwidth, frequency, packet format, and pulse shaping, in order to demodulate PU's signal.	• Short sensing time with a few number of signal's samples.	• Complex computations. • Needs to consume a lot of power.	[21]
Cyclostationary Detection	Requires statistical analysis of signal's parameters to know the behavior of PU with its signals which are modulated and coupled with cyclic prefixes, pulse trains, hopping sequences, or carriers of sine wave.	• Better performance even when the channel SNR is low. • The ability to recognize signals well.	• Complex statistics make it undesired. • Long sensing time.	[47]

The designed algorithms for spectrum sensing which have took into account the transmitter of user, have adopted several detection methods, such as energy detection, matched filtering detection, and cyclostationary detection [21], [45]-[47]. These algorithms have been considered easy, understood, and applicable with advanced technologies, especially energy detection method which is mostly utilized, because it can achieve the sensing without beforehand information about PU [45], [46], while the algorithm of matched filtering detection method requires initial understanding of PU's signal [21]. The algorithm of cyclostationary detection method [47] is built to know the behavior of PU depending on the statistical analysis of signal's parameters which are periodical, and help to recognize signal well, but the required complex statistics for this method make it undesired.

B. Full Duplex Spectrum Sensing

Usually, the SUs adopt Half Duplex (HD) mode when they transmit or receive their signals, by this mode SUs are compelled to sense the select channel before use it for transmission Fig. 5. Adopting HD mode leads to some accompanied disadvantages, such as:

1) Partial loss of channel time, due to the channel sensing.
2) Collision, when the PU needs to use the channel at the time of occupying it by SU, which has not the ability to know PU's activity after the sensing period.
3) Inefficient use of spectrum, when the result of sensing is busy channel, which may become idle after the sensing period directly, once the PU leaves it, then the channel will be unoccupied, because both PUs and SUs are jobless, which lead to non-exploitation of spectrum well.

Since the data demand will be much more in future, efficient use of spectrum is very important to provide large capacity for high data rates to satisfy user's needs, which can achieve by exploitation the all obtainable holes of spectrum, relying on the continuous spectrum sensing process. Full Duplex (FD) mode as illustrated in Fig. 5, enables SU to sense the spectrum and achieving transmission of data by simultaneous way. So, this mode is useful to avoid collision between PUs and SUs as possible, in addition to improve the utilization of spectrum.

Notable, when using energy detection method in this case the sensing result will include SU's signal which represent the self interference shown in Fig. 6. Hence, different from (1) and (2), the two hypotheses $H0$ and $H1$ can be expressed as:

$$H0: r(t) = n(t) + s(t) \quad (3)$$

$$H1: r(t) = p(t) + n(t) + s(t) \quad (4)$$

where $s(t)$ is the SU's signal (self interference).

The FD mode also allows transmitting and receiving signals simultaneously using transceiver, but the self interference especially with this application of FD mode required several solutions to overcome this problem such as using three antennas (two to transmit signals, and one for receiving) with the techniques of digital elimination supported by simulation in [50], to cancel the interference of receiving antenna. For the same objective, [51] suggested FD system using two of antennas with Balun technique which can support wideband and high power systems for cancellation the self interference. Then, OFDM FD system using two of antennas has been introduced as a solution in [52].

Applying FD mode in CRNs, enables the SUs in these opportunistic networks, to perform their functions by one of two modes, either Transmit-and-Receive (TR) simultaneously or Transmit-and-Sense (TS) simultaneously, and each mode refers to the used spectrum sensing technique, which will be Listen-Before-Talk (LBT) for TR mode, and Listen-And-Talk (LAT) for TS mode which has been considered better in [53], when they proposed algorithm for selecting the mode depending on the capability of SUs to cancel the self interference, and their results proved that TS mode makes the PU utilizes spectrum effectively and without delay. In the same context, [54] proposed FD spectrum sensing scheme for multichannel CRNs, to make SUs who use spectrum channels to transmit their signals and meanwhile sense the spectrum and await PU's return, this mean using LAT technique, which also has been suggested by [55] relying on the FD mode.

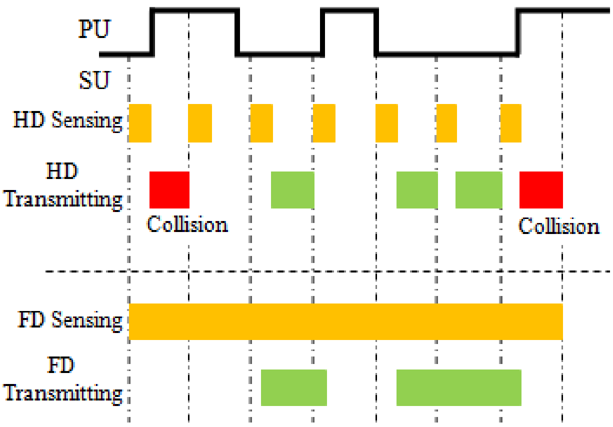

Fig. 5. The difference diagram between HD spectrum sensing and FD spectrum sensing [48].

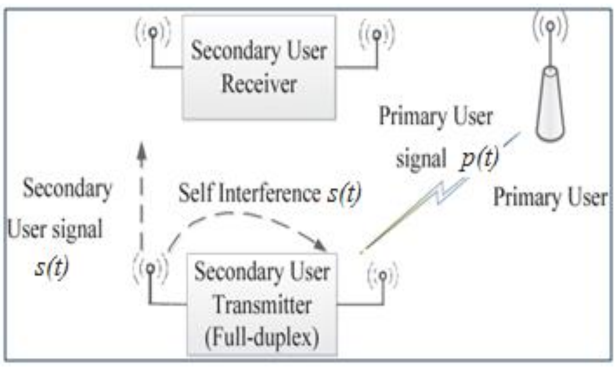

Fig. 6. Self interference problem when adopting FD mode [49].

TABLE IV: THE SUMMARY OF EXISTING PAPERS ON SPECTRUM SENSING MANNERS

Manner	Description	Applicability	Ref.	Algorithm/ Technique
Full Duplex Spectrum Sensing	Enabling SU to sense the spectrum and achieving transmission of data by simultaneous way, relying on continuous spectrum sensing.	Large capacity applications	[50-52]	Self interference cancellation of transceiver.
			[53-55]	Listen-And-Talk (LAT) technique.
			[56]	LAT with the best thresholds to detect holes.
			[57]	LAT with considering samples' weight and the low state of SNR.
			[58]	Adaptive joint (mode/rate), for Wi-Fi which use FD and share unlicensed band with cellular network (LTE-U).
Spectrum Sensing Based on Spectrum Database	Imposes sending the SU's sensing result individually to BS, for comparison with the old stored data in database to make sensing decisions and determine spectrum holes.	Wide coverage applications	[59]	Creating new tables depending on updated data.
			[60]	BS instructs SU according to comparison result for accurate sensing.
			[61]	Exploiting database to reduce interference probability and energy consumption.
			[62]	A framework of the vehicular network topology.
			[63]	Creating geographical location database using many of mobile UEs, for the communication of D2D.
			[64]	Adopting database has the capability to process its data continuously.
Cooperative Spectrum Sensing	Combining many sensing results of different SUs, for more accurate detection.	Low latency applications with high reliability	[65]	Combining different results as a cooperative sensing.
			[66], [67]	Fusion algorithm and a performance metric for diverse fusion algorithms, and performance analysis.
			[68]	Utilizing a directional antenna.
			[69]	Cooperative spectrum sensing based on both belief propagation and quickest detection.
			[70]	Cooperative spectrum sensing based on the threshold of reputation.
			[71]	Subcarrier modulation and fusion method having two levels, for Industrial wireless network (IWN).
			[72]	Decision fusion based on the degree of reliability.
			[73]	Weighting each sensing result to determine its reliability.
			[74]	A model based on the renewal theory in fusion center.
			[75-79]	Facing the malicious interferences.
Compressive Spectrum Sensing	Enabling SU to compress the sparse spectrum as a solution to decrease the sampling rate, for effective sensing and fast detection.	Wideband spectrum sensing applications	[80]	Multiband joint detection technique for several bands.
			[81]	Decentralized algorithm utilizes both cooperative and compressive techniques for wideband multihop CRNs.
			[82]	A scheme adopts both Adaptively Regularized Iterative Reweighted Least Squares for real-time requirements and descent-based decision threshold setting algorithms.
			[83]	Arithmetic-delay BigBand (AD-BigBand) technique.
			[84]	An adaptive algorithm to treat with unknown sparsity in wideband CR system.
			[85]	A sub-Nyquist wideband spectrum sensing algorithm without considering sparsity of signal.

TABLE V: A COMPARISON BETWEEN LBT AND LAT TECHNIQUE

Technique	Feature	Applicable with	Usable for	Advantage	Disadvantage	Reference
LBT	Fixed and predefined sensing periods	Full Duplex (FD) mode	Transmit-and-Receive (TR) mode	Low sensing expenses	SU blind after sensing period	[50-53], [55], [58]
		Half Duplex (HD) mode	Before transmitting			
LAT	Continuous spectrum sensing	Full Duplex (FD) mode	Transmit-and-Sense (TS) mode	Ensure that PU utilizes spectrum without delay	High sensing expenses	[48], [49], [53-58]

In addition to utilize LAT technique, [56] discussed using effective algorithms enable SU to select the best thresholds to detect holes in spectrum sensing process which be more accuracy when the sensing is cooperative, while [57] has took into account the weight of samples and the low state of signal to noise ratio (SNR), to design a scheme has the ability to timely sense PU's status based on energy level, and transmits signal at the same time. Even in unlicensed band, when both Wi-Fi non cellular WLAN and cellular network using LTE-U share the same unlicensed band, the FD mode can be useful for Wi-Fi access point on condition of using the techniques of self interference cancellation, and adopting adaptive joint (mode/rate), to make Wi-Fi able on transmitting and receiving (TR) signals simultaneously, for higher throughput, or transmitting the signal and sensing the cellular network attempts to access unlicensed band (TS) simultaneously, as has been proposed by [58]. Due to the importance of both techniques (LBT and LAT), we present a novel comparison about the differences between them in Table V above.

C. Spectrum Sensing Based on Spectrum Database

One of the important future requirements to achieve the necessary seamless mobility, and high speed service, is continuous wide coverage. In spite of using the advanced spectrum sensing techniques, the expenses of sensing process still high, and worth mentioning, that the algorithm's complexity is according to its ability to detect spectrum holes, and the accurately sensing of PU's status which has the priority and access rights. Hence, some of authorized organizations like Ofcom and FCC have introduced algorithms of spectrum sensing based on spectrum database, which consider a preferable manner for continuous communications in wide coverage area, because the spectrum database can easily serve with low expenses a large number of SUs within its geographical location. The database of spectrum contains old spectrum data, and it can create new tables depending on updated spectrum data [59]. Thus, the spectrum database can make sensing decisions and determine spectrum holes for SUs to achieve the accurate sensing.

The algorithm of spectrum sensing based on spectrum database, imposes sending the SU's sensing result individually to Base Station (BS), the sensing result should include the start time of sensing, period of sensing, the PU's leaving time, and the probability of failing detection due to false alarm, to be ready for the comparison with the old stored data in database existing within the same geographic location, to determine the holes of spectrum. Thus, the BS instructs SU about sensing the spectrum and accessing it according to the comparison result, this procedure leads to accurately sensing [60]. Since SU do not need to sense the spectrum all time, both of interference probability with PUs and the consumption of energy may be lower [61].

On the basis of spectrum database, the vehicular network topology using several of BSs and vehicles, with its data of spectrum has been proposed in [62], due to the spectrum database ability to reduce the environment analysis expenses around vehicle, and improving the sensing results. To create geographical location database, many of mobile UEs have been employed in [63], to sense channels within TV white spaces, for the communication of Device to Device (D2D), the huge obtained sensing results, will utilize by the BS to produce important algorithms for database functions, while [64], proposed using database has the capability to process its data continuously, to find new sensing decisions for SUs, who are utilize these decisions for successful sensing processes as possible and efficient use of energy.

D. Cooperative Spectrum Sensing

In the wireless communications networks, both low latency and reliability represent important requirements among other, for less time delay between the sender and receiver, and more reliable networks for user's benefit, and worth mentioning, that serious efforts offer to achieve ultra-low latency and ultra-reliability for the 5G networks to satisfy the needs of future users. Due to the affect of fading and shadow, the individual sensing result cannot be considered, and it is better relying on many sensing results completed by different users, using algorithms to combine these results as a cooperative sensing [65], for more accurate detection. The first type of combining algorithms makes the shared nodes transmit their sensing results to combine in a center can call it the fusion center for producing new decision, in this case the algorithm is called fusion algorithm as in [66], when they proposed a metric to compare the performance of diverse fusion algorithms, while [67] presented performance analysis based on the relation between detection probability and each of decision threshold or SNR. In the second type, the fusion algorithm makes nodes transmit the sensing results and other data to fusion center, which will process larger amount of data in comparison with the first type, which lead to that this type of algorithms has better performance than the first type. The cooperative sensing techniques often utilize omni-directional antennas. In order to determine the location of PUs and interference reduction, the directional antenna is utilized in [68].

To improve the detection, [69] adopted cooperative spectrum sensing on the basis of integrating both belief propagation and quickest detection, and the performance has been evaluated based on the delay of detection and rate of false alarm. For the security, [70] proposed cooperative spectrum sensing manner based on the threshold of reputation to distinguish between users. The Industrial wireless network (IWN), which adopt CR technology for efficient usage, need quickly sensing scheme with more reliability for better achievement, therefore [71] applied the subcarrier modulation in cooperative spectrum sensing, which allow sending decisions to the fusion center using Orthogonal Frequency Division Multiplex (OFDM), which lead to reduce the delay of making final decision which achieve by the fusion method having two levels, for accurate sensing with minimum error rate, also had considered in the updated reputation to enhance the security, while, [72] introduced a new rule for decision fusion based on the degree of reliability to minimize the interference in industrial networks. The same idea with difference, the sensing result of each user is compared with the previous results and other information, to be weighted to determine its reliability [73]. For vehicular networks, the proposed cooperative sensing system model in [74] for centralized and distributed spectrum, based on the renewal theory in fusion center, to treat with the lack of spectrum, and mobility problem, the results indicated that their model reduces interference.

The CRNs may suffer from malicious interferences which lead to reduce the spectrum sensing performance, to treat with this problem [75] proposed sending the local SINR of each SU to fusion center for producing the proper decision, while the cooperative spectrum sensing scheme for multiband is proposed in [76] to cope the malicious attacks, by making this scheme achieve the comprehensive throughput which surpass comprehensive interferences, to optimize the performance for optimal and accurate cooperative spectrum sensing.

Due to the bad effect of malicious SUs [77] presented two schemes to confront them, the first scheme is non blind CSS, in which SU's reputation is one of three states are: reliable, pending, or discarded, the last state include the SUs who have bad behavior, and the scheme prevents them from cooperating. The second scheme has not state of pending, and according to SU's behavior the scheme authorized to move user from the reliable state to discarded state and not reverse, while in [78] they considered white, gray, and discarded, to determine the reputation of SU, based on the number of serial successful decisions, and the number of errors in detection. Noticeable, that the schemes in [77] and [78] above utilize thresholds, which experimentally tuned to improve the performance. The collaborating in spectrum sensing may produce local attacks which cause the performance degradation, for accurate and secure sensing [79] proposed a mechanism to transfer the reputation, to treat with the problem of loss the reputation due to mobility, also the dynamic game strategy as a motive for SUs to introduce real information.

E. Compressive Spectrum Sensing

The CRNs usually use spectrum sensing techniques to detect the spectrum holes, to be utilized by SUs for better spectrum exploitation, the conventional techniques applied to narrowband spectrum cannot proper for wideband spectrum sensing, because the high rate of sampling leads to huge amount of data which represent real challenge on the Analog-to-Digital Converter (ADC) of these techniques. Due to the spectrum sparsity of wideband, compressive spectrum sensing technique has been proposed to compress the sparse spectrum as a solution to decrease the sampling rate, for effective sensing and fast detection, this technique will be very important and necessary for the future CRNs, especially with the wide spectrum sharing for higher data rates [21].

Spectrum sensing as an essential technique in CRNs has commonly been utilized to sense one channel at a time in the narrowband spectrum, [80] introduced sensing technique named multiband joint detection, to detect together the energy levels in several bands as an efficient way to improve the spectrum usage. So, this reference put the basics to propose many algorithms for wideband spectrum sensing. For wideband multihop CRNs, [81] utilized a cooperative spectrum sensing manner alongside with a compressive spectrum sensing technique to compress the sparse spectrum, thus the existing CRs cooperate to achieve sensing by consensus using decentralized algorithm for better performance.

Applying compressive technique for the wideband spectrum sensing in case of real signals with real-time requirements causes complex and numerous computations, in addition to the errors in reconstruction. To solve these problems, [82] proposed a scheme with two algorithms, the first is Adaptively Regularized Iterative Reweighted Least Squares (AR-IRLS) which is workable with different bandwidths and energy levels, to recover signal at real time, for fast and accurate reconstruction, the second algorithm is a descent-based decision threshold setting, which has been used in the distinction of PU's signal from the noise and errors of reconstruction. The tests and simulations proved that the scheme is applicable with the different sparsity states, and it can achieve well performance.

Instead of the signal's sampling, shifted multiple channels approach is used to sense the sparse wideband spectrum in BigBand technique, which has been improved in [83] to be Arithmetic-delay BigBand (AD-BigBand), to reduce the complexity of computations, for faster processes and lower errors rate in the construction of spectrum. In case of unknown sparsity, an adaptive algorithm for compressed spectrum sensing in wideband CR system was proposed in [84], to decrease the sampling rate by estimation the error of recovering analog signal, and to detect holes for better throughput. Whereas, most wideband spectrum sensing algorithms are designed to treat with the spectrum's sparsity problem, [85] introduced a sub-Nyquist wideband spectrum sensing algorithm, which senses the spectrum without considering sparsity of signal, relying on the theory of sparse fast Fourier transform, the test results confirm that this algorithm proper for the non-sparse and sparse signals, with the less time of running due to no complexity.

IV. Spectrum Allocation

The main concept of cellular communications networks is spectrum reuse, for efficient spectrum utilization due to the resource scarcity. Accordingly, the successful spectrum allocation is necessary, to ensure the minimum co-channel and adjacent channel interference. For CRNs which need dynamic spectrum allocation to exploit the spectrum well by all users, many algorithms have been proposed to solve the allocation problem in these networks.

The latest and effective algorithms which may be applicable for 5G networks are categorized to approaches as in Fig. 7. The summary of existing papers on spectrum allocation approaches is shown in Table VI.

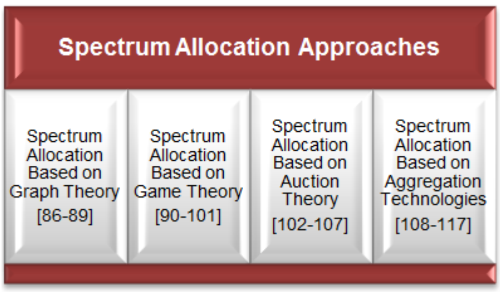

Fig. 7. The approaches of spectrum allocation process.

A. Spectrum Allocation Based on Graph Theory

The graph theory as a mathematical theory with its graph coloring algorithm, has been applied by many of specialists to solve the problem of spectrum allocation in CRNs, in which SUs (CR users) try to obtain the spectrum of PUs (authorized users), when they are jobless, with note that the targeted spectrum is always affected by PUs status, place, and network coverage state. Since the spectrum availability for SUs is different according to their location, graph theory needs to review the goals of spectrum allocation by considering the SUs are equivalent to color numbers, and interferences between them are the equivalent to edges, to transform the competition on available spectrum among SUs to a graph represents CRN, and coloring this graph using graph coloring algorithm is required to build the model of spectrum allocation which can solve the allocation problem in CRN [86]. Usually, when applying the graph theory to allocate spectrum in CRNs, each SU is represented by vertex, and the edge represents interference between any two adjacent vertexes when they use the same spectrum at same time, which is not allowed.

The more important coloring algorithm of spectrum allocation is list coloring algorithm, and specifically the distributed greedy algorithm, which improves the channel usage. In this algorithm all SUs (vertexes or nodes) are arranged according to the degree of user from low to high degree, the available intended channel allocates to the user who has low degree.

When the users having the same degree, the channel should allocate to user who has got the less number of channels, after that the channel randomly allocate to one of users who having the same number of allocated channels. Although the distributed greedy algorithm increased the benefit from channel, but it has been considered unfair in allocation function, because it only emphasized on the interference between SUs.

To mitigate the spectrum scarcity, [87] presented several algorithms to distribute the spectrum for SUs, and focused on the effect of opportunistically available spectrum on SUs which need to utilize the spectrum of PUs temporarily, based on the dynamic of channel availability according to the traffic loads of PUs and their locations. To solve the limitedness problem of spectrum, and to share spectrum which has already been allocated for authorized users, the networks adopted CR technology to utilize channels by SUs at the absence of PUs to avoid collision between them, using spectrum sensing to detect the PU's status. On other hand, because the self coexistence of SUs represent problem need to be solved, [88] proposed fairly channels allocation scheme based on coloring the graph on the basis of non-interference, and fixed QoS, the results proved that the scheme able to allocate channels in multiple sharing network by efficient and fair way.

Due to, the importance of both better utilization and fairness in spectrum allocation process, Color Sensitive Graph Coloring (CSGC) algorithm has been proposed as one of graph coloring algorithms which treat with the allocation problems in terms of utility, fair distribution, and users waiting time. Although this algorithm generally succeeded after using diverse methods of labeling but its solution was not optimal, with instability of its quality. For best optimization, genetic algorithms have been utilized, which could improve the utilization but could not fairly distribute the channels. In [89], they tried to benefit from algorithms above, for the efficient spectrum utilization and fairly channels distribution, by adopting the idea of Ant Colony Optimization (ACO), and changing the setting of pheromone trails and heuristic information instead of changing the method of labeling in CSGC algorithm, their algorithm's results illustrated that this method better than CSGC in all conditions.

TABLE VI: THE SUMMARY OF EXISTING PAPERS ON SPECTRUM ALLOCATION APPROACHES

Approach	Description	Applicability	Ref.	Algorithm
Spectrum Allocation Based on Graph Theory	Using graph theory to transform the competition on available spectrum among SUs to a graph represents CRN and coloring this graph using graph coloring algorithm to build the model of spectrum allocation to solve the allocation problem in CRN.	Numerous connectivity applications	[86]	Abstracting the CRN as a graph, then using coloring algorithm to build an allocation model.
			[87]	Focusing on the effect of opportunistically available spectrum on SUs.
			[88]	Coloring the graph on the basis of non-interference and fixed QoS.
			[89]	Graph coloring algorithm adopting the idea of Ant Colony Optimization (ACO).
Spectrum Allocation Based on Game Theory	All users make their optimal strategies according to their goals. Then, SUs play among them to solve the conflict about the spectrum, while the game among PUs is about the spectrum which can supply.	Low latency applications with high reliability	[90-97]	Important models of non-cooperative game in spectrum allocation.
			[98]	Optimizing performance using game techniques.
			[99]	The effect of game theory dynamics of convergence on the structure of CRNs.
			[100]	A dynamic strategy to share bandwidth between PUs and SUs on an economic basis.
			[101]	A potential spectrum allocation model based on game theory to minimize collision in CRNs.
Spectrum Allocation Based on Auction Theory	Allocating spectrum and solving the problems by organizing the relation between PUs and SUs using the spectrum bid, to protect the PUs rights, in addition to enabling SUs to utilize the PU's spectrum in a right way since they pay before use the spectrum.	Wide coverage applications	[102]	Designing an allocation algorithm for truthful double spectrum auctions.
			[103]	The mechanism of truthful auction to allocate heterogeneous spectrum in term of frequency.
			[104]	Considering SINR in place of the graph of interference, and maximizing the auction organizer's profit.
			[105]	General Greedy algorithm and Enhanced Greedy algorithm to improve total utility.
			[106]	Choosing the lower price in a model consist of two providers.
			[107]	A framework to lease the network infrastructure and TV spectrum as a two separated properties.
Spectrum Allocation Based on Aggregation Technologies	Aggregating five of Component Carriers (CC) in both downlink (DL) and uplink (UL) in order to increase capacity, each carrier no more 20 MHz and up to 100 MHz as a whole bandwidth resulted from aggregation.	Large capacity applications	[108-110]	Carrier Aggregation (CA) features.
			[111]	Adopting diverse scenarios of an inter-band CA and intra-band CA.
			[112]	Channel access scheme in femtocell for unlicensed band using LTE-LAA and CA technology.
			[113]	Role of Wi-Fi hotspots in increasing the capacity.
			[114]	The strategy of delayed offloading to Wi-Fi and re-allocation the resource in multi-RAT networks.
			[115]	Intelligent network selection scheme within Integrated Femto Wi-Fi (IFW) small cell.

[116]	A framework for offloading data based on Software Defined Networking (SDN) for IFW.
[117]	Algorithm of distributed resource allocation for IFW in the software defined 5G networks.

The needed time to complete spectrum allocation process using algorithm based on graph theory is dependent on the numbers of channels contained in the available idle spectrum. Thus, the graph theory algorithms are applicable to the numerous connectivity applications on condition that the spectrum does not change rapidly.

B. Spectrum Allocation Based on Game Theory

The game theory requires knowing the behavior of each user (participant), in which the users make their optimal strategies according to their goals. In the CRNs, game theory with the solution of Nash equilibrium has been applied for the spectrum reuse due to the limitedness of available spectrum. So, the spectrum allocation based on game theory ensures high reliability for users in low latency applications.

When the game theory apply to allocate spectrum in CRNs, the SUs play among them to solve the conflict about the preference of spectrum and bandwidth, while the game among PUs is about the spectrum which can supply, to be selected and utilized by SUs. This game can be either cooperative or non-cooperative according to existence of the compulsion agreement among the users to organize their behavior, or non-existence it, respectively.

Since, getting spectrum is the goal of each SU to achieve their function, the relation among SUs usually competitive, and because providing spectrum by PU may be profitable for this user, often the PUs compete among them to provide spectrum. Thus, in CRNs the non-cooperative way is better for spectrum allocation based on game theory [90]. The important models of non-cooperative game with simple idea for each model are listed and summarized below:

1) Cournot game

This model classifies as one of the complete information static games, in which the output is competition motive among users, and each PU knows the old strategies used by other PUs. The model makes PUs sell more number of spectrums for more benefits [91].

2) Bertrand game

Its model categorized as a static game with complete information, in which the competition is about selling by best price, and each PU knows the old prices of spectrum selling by other PUs. This model increases the price of spectrum sale to raise the benefits of PUs [92].

3) Stackelberg game

The game model has been classified as the dynamic game with complete information, each user aspires to achieve larger amount of product, and because the spectrum sale price is fixed, each PU try to sell more number of spectrums. In this model, the PUs receive strategies in different times, which is useful to increase the amount of sold spectrum by all PUs, as an advantage for both PUs and SUs in term of utility [93].

4) Repeated game

Its model classified as the dynamic game model with complete or incomplete of information, the game consist of several stages have the same form, with the possibility of changing it to be cooperative in some stages. In this model the users may grant spectrum without charge, to build reputation enable them getting benefits for a long time [94].

5) Potential game

In this game every CR user can knows their competitor's strategy by observation, to put their own best strategy which can maximize the benefits when apply it in the processes of next game. By adopting the best strategies and repeating game can achieve Nash equilibrium, for fairly sharing [95].

6) Evolutionary game

It is represent the developed game theory used recently, its idea has been deduced from the evolutional theories, which talk about the need to imitate others, learning, and adaptation according to the changes of environment. When applying this game in CRNs, the PUs rent their spectrum to SUs who compete among them to get spectrum, and at the same time they try to adjust their own strategies as an evolutionary procedure to select the best spectrum. The goal is strategies equilibrium and equilibrium of evolution status, then each SU can get on the same benefits. While, the utility of PUs based on competition about price [96].

7) Auction game

The application of this game in CRNs mean that the SUs ask PUs to lease spectrums, so the PUs will have many requests to rent their spectrums by proper prices. Since the SUs can employ spectrums from different PUs, the PUs bid their spectrums and prices to attract the SUs. In auction game, organizing the bid by PUs bring the utility to them in addition to the amount of spectrum rent, this game makes the spectrum sharing very useful, and lead to efficient utilization of spectrum [97].

In early time, [98] talked about the impact of using CR technology in wireless networks on the performance, and demonstrated how the game theory techniques can be useful to optimize the networks performance. Then in [99], they explained how the game theory dynamics of convergence can affect on the structure of CRNs, also applied these dynamics to previous algorithms to know their influence on the complexity of networks.

After that, [100] introduced a dynamic strategy to share bandwidth between PUs and SUs on an economic basis, this strategy has been examined by simulation the allocation model which has the developed algorithm with a goal of minimization the bandwidth cost ultimately, in addition to improve the utilization of bandwidth. To effectively allocate spectrum with minimum collision in CRNs, based on game theory a potential model has been proposed in [101], which has capability to treat with different results of sensing in terms of accuracy, whether the information of network is complete or incomplete. And according to these conditions, they introduced three algorithms to complete equilibrium in three different cases, are: the algorithm of channel selection based on joint strategy using fictitious play, which achieved a perfect Nash equilibrium in case of accurate results with incomplete information, and evolutionary mechanism of spectrum access to adopt the stability strategy of evolution for best outputs in case of complete information with inaccurate sensing, also the distributed algorithm of learning which has been considered one of the stability strategies of evolution and could complete the non-pure Nash equilibrium, when the information was incomplete.

C. Spectrum Allocation Based on Auction Theory

The main purpose of applying CR technology in wireless networks is spectrum exploitation by SUs (unauthorized users) who cautiously utilize the unused spectrum parts because the spectrum's rights are to PUs (authorized users), so SUs use the spectrum in an opportunistic way without fees, and may cause interference to PUs due to this unfairly use. Hence, auction theory has been adopted to allocate spectrum and solve the problems by organizing the relation between PUs and SUs when they dynamically utilize spectrum. Relying on this theory, the PUs rights are protected in addition to continuance their performance and the SUs can utilize the PU's spectrum in a right way as long as they pay before use the spectrum. Thus, spectrum allocation based on auction theory is serviceable in the applications of wide coverage.

The spectrum allocation algorithm based on auction theory needs to solve three problems at first, the algorithm's ability to treat with the problem of spectrum reuse in CRNs which often requires distinguishing between the buyers according to their interferences using the graph of interference, and establishing one group for the buyers who are without interference to be ready for the spectrum bid, the second problem is how to price the spectrum fairly, and the third problem is about spectrum variety, when the spectrum consist of bands having different frequencies, which lead to difference the distance of interference, and may make each buyer has different interference statuses in different bands, which can affect on their group and classification process.

Previously, most of algorithms either did not consider the reuse of spectrum or became untruthful when considered it, so the challenge was how to achieve a truthfully spectrum reuse by auctions for efficient utilization of spectrum. Reference [102], has proposed the concept of trust which based on using allocation algorithm designed for spectrum reuse, determination the winner user, and the effective mechanism of pricing, to ensure the truthful double spectrum auctions. To treat with different spectrums in term of their frequencies (high or low), [103] introduced the mechanism of truthful auction to allocate heterogeneous spectrum, in which each buyer can request their preferred spectrums, and at the same time several graphs of interference can be built according to spectrum's frequencies, to specify the groups of buyer, their simulation results showed that this mechanism is better comparison with the other mechanisms of homogenous spectrum, because it can satisfy buyers with more income for sellers, which mean improvement the utilization of spectrum. In [104], they considered SINR in place of the graph of interference, to establish groups of SUs according to their SINR, and proposed a new strategy for the pricing in double auction which has been designed competitive, to maximize the auction organizer's profit.

Spectrum allocation using auction algorithms has been considered very important method to allocate spectrum dynamically in CRNs, because this method fair and efficient. In general, auction algorithms adopted four modes to achieve spectrum allocation are: single auction, double auction, combinatorial auction, and combinatorial double auction. In the last mode, PUs as sellers submit their unused spectrums to Primary Operators (POs) who are organize the auctions to get profits, then SUs as a buyers pay to POs for buy required bands of spectrum, at that time the POs give the bought bands to SUs and pay to PUs.

For the ubiquity network, when each PO has heterogeneous spectrum bands and each SU can demand multiple bands of different spectrum types, [105] introduced two schemes for lightweight combinatorial double auction, to allocate spectrum assuming that each SU buy the spectrum from one PO itself. The first scheme was the General Greedy algorithm, which has been designed to maximize the total benefit, while the second scheme was to allocate a group of spectrum with discount as an attraction for SUs to enter the auction and buying spectrum to achieve the maximum total benefit, so it has been named Enhanced Greedy algorithm. Their results proved that both two algorithms could effectively improve the total utility.

In some cases, the operators trade spectrum among themselves, Because each one of them has a fixed part of licensed spectrum, which may leads to that some of operators suffer from congestion more than other. Hence, the operator who has many requests needs to lease spectrum from another operator who hold unused spectrums of PUs. So, the busy operator leases spectrum to satisfy their SUs needs and getting more profits, while the less active operator rent their spectrum to get profits and improve the spectrum utilization.

Reference [106] considered the subject from another point of view, when studied a model of two providers each has fixed part of licensed spectrum, and both of them compete by price between them to utilize the unlicensed spectrum when they need to use it, then assumed that the spectrum's request distributes on providers, and discussed how SUs can choose the lower price among expensive prices to use the spectrum. In order to share unutilized parts of TV spectrum, [107] treated with the infrastructure of network and spectrum as a two separated properties to exploit the TV spectrum well, by introducing a framework to lease each of them from its owner. Thus, the owner of TV spectrum can utilize part of the infrastructure after leasing it to develop services, or can get income by renting part of their unutilized TV spectrum to the infrastructure owner who need it to satisfy their users. The framework enabled both owners to cooperate together and getting benefits, so it has been considered as a green spectrum sharing scheme.

D. Spectrum Allocation Based on Aggregation Technologies

The aggregation technologies have been divided to two types according to the Radio Access Technology (RAT) used by network, whether single or multi-RAT, and as follows:

1) Carrier aggregation for single RAT networks

The technology of Carrier Aggregation (CA) introduced by 3GPP LTE-Advanced (LTE-A) Release 10 has achieved the requirements of large bandwidth to increase the data rates in 4G networks for fulfilling user's demands through aggregation either contiguous carriers or non-contiguous carriers, as a best approach to utilize the unused parts of spectrum. Particularly, Release 10 permitted to aggregate five of Component Carriers (CC) in both downlink (DL) and uplink (UL), and considered that each carrier no more 20 MHz, so it allowed up to 100 MHz as a whole bandwidth resulted from the carrier aggregation, as illustrated in Fig. 8.

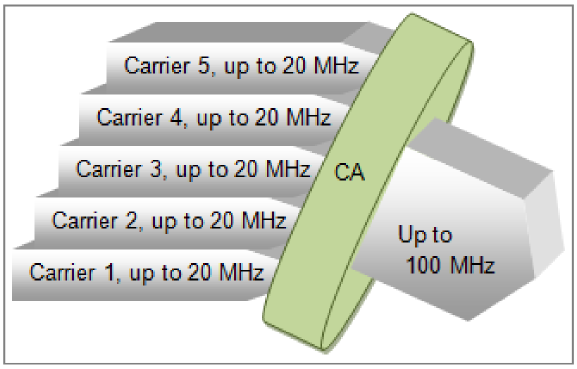

Fig. 8. Aggregating five of Component Carriers (CC) using Carrier Aggregation (CA) technology [108].

The aggregated carriers either from one band itself (intra-band) or from several bands (inter-band) as shown in Fig. 9, and often the band which has large bandwidth is proper for the CA of intra-band, while the band with small bandwidth can be useful for the CA of inter-band.

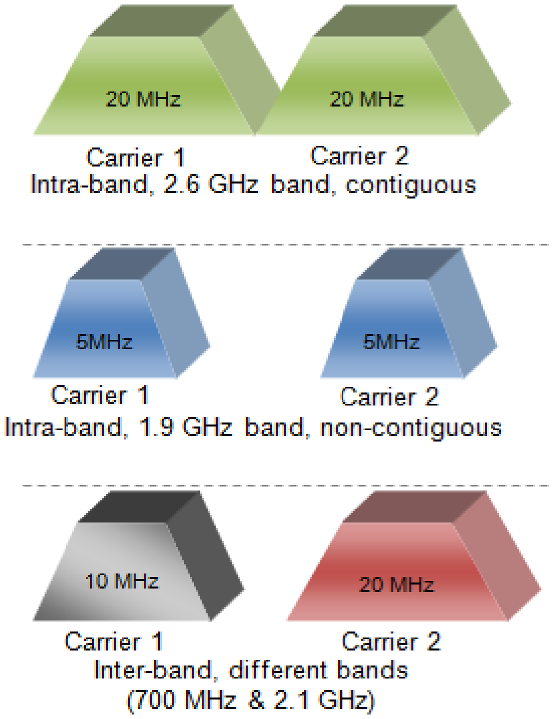

Fig. 9. Illustration for both intra-band and inter-band carrier aggregations [108].

Initially, the CA designed in Release 10 was workable with co-located cells, while the improved CA in Release 11 could also aggregate carriers from non-collocated cells [109]. In addition to above, the CA introduced by Release 12 had the ability to aggregate carriers of different modes represented by both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) [110]. Reference [111], discussed the influence of using carrier aggregation technology on the cellular system performance in both of independent carriers systems and the contiguous carriers systems, then adopted diverse scenarios of an inter-band CA and intra-band CA to study the effect of aggregation in each scenario, and analyzed the results which illustrated that the performance has improved with this technology, especially the performance of inter-band CA with low distances among bands which was equal to the performance of the contiguous carriers in low frequency band, and much better than the performance of the contiguous carriers in high frequency band.

The quickly growing of cellular data traffic due to increasing the data demand, and Limitedness of licensed spectrum have compelled the cellular operators to increase network capacity through offloading macrocell's data traffic to the licensed band of femtocells, and to the unlicensed band of cellular Wi-Fi hotspots, which led to high interferences from femtocells to macrocll, and reduction the system performance when using Wi-Fi hotspots which usually use the spectrum in less efficient way compared with cellular network. Hence, LTE-Unlicensed (LTE-U) has emerged to utilize the idle parts of available unlicensed band and solve the problem of licensed spectrum's scarcity, followed by Licensed-

Assisted Access using LTE (LTE-LAA) which has been standardized by Release 13 to achieve the transmission in unlicensed spectrum, relying on CA technology to aggregate multiple carriers. As an effective method to get more spectrum in femtocell to increase the capacity for better data rates, CA technology has been applied in our earlier study [112] which proposed channel access scheme for unlicensed band using LTE-LAA and CA technology, to utilize both licensed and unlicensed bands in LTE air interface simultaneously as a Dual band Femtocell (DBF), and aggregating carriers from licensed and unlicensed bands, as illustrated in Fig. 9. The scheme also used LBT technique to administrate the relation with other unlicensed band's users, the results illustrated that the proposed scheme could significantly increase throughput compared with the other considered small cells.

2) Link aggregation for multi-RAT networks

In order to increase capacity of cellular networks, cellular operators have built many of cellular Wi-Fi hotspots to offload data traffic from the licensed bands of their networks to unlicensed band in Wi-Fi interface. Although, the spectrum utilization efficiency when using Wi-Fi hotspots is lower in comparison with the cellular network of single RAT (LTE only), but the deployment of these Wi-Fi hotspots has effectively increased the capacity of network [113]. For further benefits from Wi-Fi hotspots, [114] has proposed the strategy of delayed offloading to Wi-Fi and re-allocation the resource in multi-RAT networks for better energy efficiency, the strategy included algorithm could accumulate the users who having lower QoS, and considered them users of Wi-Fi, and because the delay of offloading creates unused spectrum in cellular network, the re-allocation process of spectrum has been adopted, results showed the advantages of proposed strategy.

The importance of cellular Wi-Fi hotspots mentioned above opened the door to the cellular operators to apply the technology of link aggregation to benefit from both Wi-Fi and LTE technologies, which led to thinking of combination femto BS and cellular Wi-Fi AP together, especially with the existence of non-cellular WLANs almost everywhere, with noted that each WLAN AP needs leverage it to be able to use 2.4 and 5 GHz unlicensed spectrum for the purposes of combination. Thus, Integrated Femto Wi-Fi (IFW) has been proposed relying on link aggregation technology in context of the convergence between 3GPP standards and IEEE 802.11 standard, and to get the advantages of both networks (LTE and Wi-Fi).

Reference [115] discussed the role of IFW small cell in offloading mobile data traffic using licensed band of cellular network and unlicensed band through Wi-Fi interface, and introduced the intelligent network selection scheme according to preference of UE, also proved that the scheme has increased network capacity, reduced energy consumption, and was fair among users, while [116] presented a framework for offloading data based on Software Defined Networking (SDN) for IFW, then explained the distribution of data traffic between cellular network and Wi-Fi network, and how the framework enabled UE to select interface based on the traffic information obtained from server.

For the software defined 5G networks, [117] proposed the algorithm of distributed resource allocation for IFW, which took into account maximizing the utility by full distribution to improve resource allocation and maintaining the low interference with macrocell users, smart and Wi-Fi devices are considered into the simulations, and numerical results showed that the introduced algorithm has increased the average of both throughput and utility of all system's devices. Finally, the aggregation technologies effectively contribute in increasing the networks capacity, so these technologies are suitable for the applications which require large capacity for higher data rates.

V. SPECTRUM ACCESS

As in Fig. 10, the spectrum access process includes two procedures are: sharing the spectrum with PUs to exploit it, and organizing the relation among SUs themselves according to priority. The summary of existing papers on spectrum access procedures is shown in Table VII.

A. Dynamic Spectrum Access (DSA)

The available bands of licensed spectrum with their constrained current policy are accessible by PUs who having rights as authorized users. Thus, the spectrum utilization is insufficient to treat with the spectrum scarcity problem. Hence, the DSA technique has been adopted to enable SUs accessing the spectrum for better spectrum exploitation [118]. The main transmission modes of DSA technique are summarized below:

1) Overlay mode

In which the SUs utilize holes of spectrum in opportunistic way and immediately leave when PUs return to the spectrum, which mean that SUs can only use the spectrum during the absence period of PUs.

2) Underlay mode

It permits to SUs accessing the spectrum and using it by simultaneous way with PUs on condition of reducing the used power in their transmissions, to avoid the bad effect of SUs’ interference on the PUs performance, with noted that the SU must continuously observe their interference degree and adjusting it by modifying the power of transmissions to be acceptable to PU.

3) Hybrid mode

This mode allows getting the benefits from both overlay and underlay modes by switching between them, and according to PU's status the SU chooses either overlay or underlay mode, to use it as a best mode.

For CR femtocell networks, [119] designed the mechanism of spectrum access using hybrid mode (overlay/underlay) to be used by the users of femtocell as allied users, and compared the performance of introduced algorithm with other algorithms which adopted overlay or underlay mode, simulation results illustrated that the proposed hybrid mechanism improved throughput of all users 72% compared with the overlay mode algorithm, and 35% compared with the underlay mode algorithm.

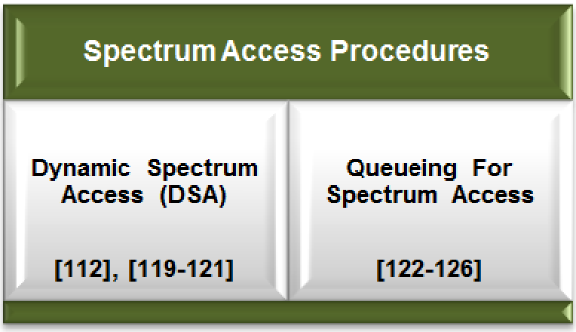

Fig. 10. The procedures of spectrum access process.

TABLE VII: THE SUMMARY OF EXISTING PAPERS ON SPECTRUM ACCESS PROCEDURES

Procedure	Description	Purpose	Ref.	Scheme/ Method
Dynamic Spectrum Access (DSA)	Enables SUs accessing the spectrum and achieving their transmissions using the spectrum holes in opportunistic way by overlay mode, or utilizing the spectrum with PUs simultaneously by underlay mode. SUs can choose either overlay or underlay when adopting hybrid mode.	Spectrum exploitation	[119]	A mechanism of spectrum access using hybrid mode (overlay/underlay) for the allied femtocell users.
			[120]	Fixed number of SUs use underlay mode, while overlay mode for additional SU.
			[121]	Selecting between two modes in only DL based on the users throughput and energy consumption by BS.
			[112]	Applying DSA technique to femtocell network to exploit the unlicensed band of non-cellular Wi-Fi using LTE air interface.
Queuing For Spectrum Access	Organizing the relation among SUs themselves according to priority when they wait PU, or sometimes waiting another SU who using the spectrum at that time, and explaining the latency reasons of SUs.	Organizing SUs and protecting PUs' rights	[122]	Developing methods to determine forming queue or not depending on PU's status.
			[123]	Presenting a distributed precedence queuing scheme in CRNs, and categorizing the channels to periodic and non-periodic.
			[124]	Queue model include different service capacities for SUs who need channels as servers.
			[125]	A coupled queues model, and the penalty to reduce collision's rate.
			[126]	Active Queue Management (AQM) algorithm based on QoE metric, to reduce Bufferbloat.

From another point of view and to improve system's throughput, [120] presented hybrid method to access the spectrum, by assuming that fixed number of SUs can access using underlay mode, whereas overlay mode is adopted by the additional SU to access the channel, results proved that the proposed method has effectively improved the throughput. For dynamically selection between overlay and underlay mode in CR small cells, when their users usually utilize the same licensed band used by macrocell's users due to spectrum's scarcity, and because the transmission efficiency of small cell's users change according to the macrocell users activities in overlay mode, and the low efficiency when using underlay mode which require low power, [121] introduced a scheme can select between two modes in only downlink based on the throughput of small cell's users and the consumption of energy by the small cell BS, and showed that the scheme could improve small cell's performance through increasing throughput and decreasing energy consumption. The DSA technique is also applicable to unlicensed bands to get more spectrum, [112] assumed that femto BS coexist with WLAN AP, and applied DSA technique to femtocell network to exploit the unlicensed band of non-cellular Wi-Fi using LTE air interface, for better spectrum efficiency and to increase cellular capacity of the DBF users, also maintaining the interference to macrocell's users below the known thresholds.

B. Queuing for Spectrum Access

The limitedness of available spectrum and the need to use it make SU mostly waits the PU to utilize their spectrum, or sometimes waiting another SU who using the spectrum at that time. Thus, the waiting time which may be long depending on the activity of PU affect on SU's performance, and even when SU access the licensed spectrum channel, the return of PU who has priority compels SU to leave the utilized channel immediately, and switching to the unoccupied channel, or waiting the same channel until PU leaves it. Usually, the queue of SUs is explained by queuing theory to understand the relation between PU's activity and SU's performance, which mean understanding the latency reasons of SUs in spectrum access process.

Reference [122] investigated in a process of making the spectrum access decision of SUs in CRNs, and developed methods for the game of queuing which determine forming queue in case of PU's absence or not forming it at the PU presence, also discussed the best pricing strategy from the providers' perspective. For better spectrum efficiency, the DSA techniques adopt a queue based on precedence among SUs to access the holes of PU's licensed spectrum. In order to improve the utilization of channel and realize spectrum reuse, [123] presented a distributed precedence queuing scheme in CRNs, which categorized the channels to periodic and non-periodic according to PU's activity and evaluated the cost of allocation for each channel based on its characteristics. In [124], a queuing theory is adopted to occupy spectrum using queue model include different service capacities for SUs who need channels which have been considered servers to achieve their transmissions, and failing the server mean that PU using the channel, then the performance of network has been evaluated based on its capacity and number of SUs in the proposed queue. In CRNs, the channel sensing process used by SUs to detect the holes may be inaccurate and cause collision when the traffic of SU hinders PU's traffic. In [125], the penalty has been imposed as a protection for PU and their traffic through the compensation for each collision in order to reduce collision's rate, also a coupled queues model was proposed to save the QoS of PU's traffic, in addition to solve the delay problem caused by collision and the data traffic quantity of both PUs and SUs. In order to reduce Bufferbloat and keep the performance in a reasonable levels, [126] proposed Active Queue Management (AQM) algorithm which use Quality of Experience (QoE) as a metric.

VI. SPECTRUM HANDOFF

There are three different mechanisms to achieve the spectrum handoff process, according to followed approach by SU and the initiating time of spectrum handoff, and are summarized as follows:

A. Passive Handoff

The SU suddenly starts spectrum handoff due to the PU return, or when the quality of communication becomes low.

B. Active Handoff

In this mechanism, SU analyzes and understands the behavior of PUs to estimate the coming PUs state and PU's return on the used channel in advance, so SU takes the decision of spectrum handoff and leaves the channel before the PUs appearance.

C. Hybrid Handoff

It adopts the two approaches used by both mechanisms (active and passive), to get the advantages from both of them, when the prediction of active mechanism provide list of the jobless channels to SU before PU's return which will be sensed using the passive mechanism, which mean reducing the delay.

Due to the priority of PUs as authorized users, SUs cannot keep the channels which they use it for a long time, and for continuing their transmissions they need to switch and use other unoccupied channels. Another reason push SUs to leave their used channels is the low quality of communication. Thus, spectrum handoff usually depends on the PU's status quo, or SU's mobility which may sometimes cause the Ping-pong effect when SU’s movement is between boundaries of adjacent cells which lead to unnecessary spectrum handoffs. Reference [127], suggested a fuzzy logic for the system has the ability to make proper decisions in order to reduce the ping-pong effect occurrence.

The switching to other channel requires adopting effective processes for signal modulation, coding the allocated channel to SU and reduction SU's performance during switching period to ensure the QoS of SU. The spectrum handoff process and switching to other jobless channel or waiting to utilize the same channel is illustrated in Fig. 11. The summary of existing papers on spectrum handoff process is shown in Table VIII.

To reduce the time of switching which accompany spectrum handoff process and increase transmission rate, [129] introduced a strategy of adaptive weights adjustment to select channel according to the transmission power of SU, signal fading and required bandwidth, also used the dynamic weights in algorithm of multi-attribute simple additive weight to choose the proper channel after channels analysis. For multi-channel CRN which adopt overlay mode when access the channels, [130] proposed an optimal channel sensing sequence length as a design uses dynamic program to treat with its problems, in order to complete the spectrum handoff with higher throughput or lower consumption of energy. Due to, the restrictions of both preemptive and non-preemptive queuing models, [131] introduced a hybrid queuing model as part of the proposed optimal scheme for spectrum handoff in CRN, to explain the priority of SUs for spectrum access, and to estimate the needed time to switch and use other channel in spectrum handoff process, while the another part of scheme talked about the multi-teacher concept, when the adaptable SUs to spectrum share their experiences with SU who has no experience, for the accurate spectrum handoff.

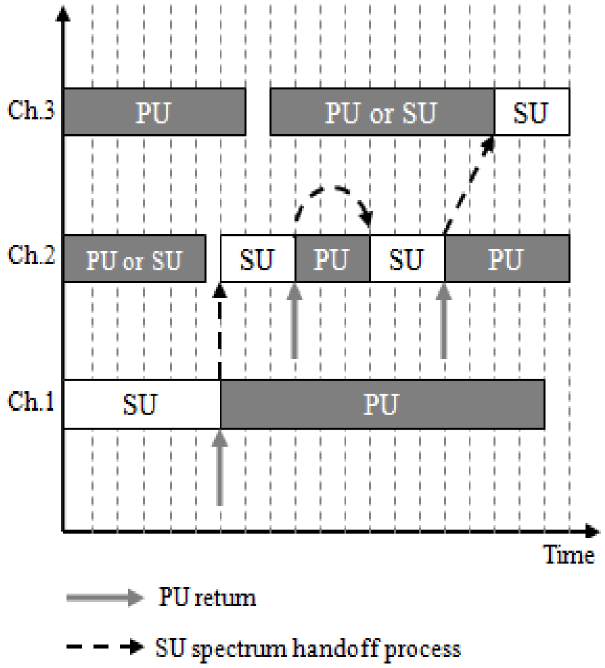

Fig. 11. Illustration for the spectrum handoff process adopted by SU [128].

TABLE VIII: THE SUMMARY OF EXISTING PAPERS ON SPECTRUM HANDOFF PROCESS

Process	Description	Purpose	Ref.	Strategy/ Scheme
Spectrum handoff	SU must leave the used channel when the PU return or when the quality of communication becomes low, then switching to other jobless channel or waiting the same channel to complete their transmissions.	Protecting PUs' rights	[127]	A fuzzy logic for the system to make proper decisions for spectrum handoffs.
			[128]	A framework to evaluate the effects of multiple spectrum handoffs.
			[129]	A strategy of adaptive weights adjustment, and dynamic weights in multi-attribute simple additive weight algorithm.
			[130]	Designing an optimal channel sensing sequence length with dynamic program.
			[131]	An optimal scheme for spectrum handoff in CRN with hybrid queuing model, and multi-teacher concept.

VII. POTENTIAL CHALLENGES AND OPEN ISSUES

The spectrum sharing techniques discussed in the preceding sections have the capability to be useful in 5G networks. Yet, a number of potential challenges provide an open issues need more research and development by researchers, for the better performance of these techniques for wide spectrum sharing in the future 5G networks.

The spectrum sharing in small cells is being studied in term of DSA in licensed and unlicensed bands. Both DBF and IFW as methods to share 5GHz band with other unlicensed band devices must be studied carefully. Each method need to create a scheme can exactly determine the access opportunities, accurately sense the unlicensed band, and align with LTE frame structure for the transmission. By looking into these requirements, several open research issues such as fairly coexisting with WLAN AP and its devices in case of DBF, tightly integrating with cellular infrastructure, control plane interworking between LTE and Wi-Fi, and the minimum backhaul in cellular BS due to use both LTE and Wi-Fi air interfaces in case of IFW.

5G networks will be more heterogeneous with multi-RAT (LTE and Wi-Fi) and may utilize higher frequency bands (millimeter-wave) which can provide large bandwidths. IFW small cell may be the acceptable solution for 5G networks. Nevertheless, number of challenges can be addressed as follows:

- The current sensing techniques and existing algorithms may be unable to detect the channel's holes in higher frequency bands. Even though that compressive spectrum sensing technique may be applicable, but more research and investigation are needed.
- The successful spectrum allocation to distribute spectrum according to the need of SU as possible still a critical open issue and must be paid attention to.
- The current aggregation technologies allow to aggregate five of Component Carriers (CCs) and up to 100 MHz, in both DL and UL. In 5G, it is expected that the higher frequency bands may provide carrier bandwidth of 100 MHz which is big challenge. Thus, aggregation technologies need more investigation and development work.
- When applying sleep modes in BS to save energy the waking time related with increasing the load must be specified very well, to avoid the unnecessary loss of energy during turn on/off.

In addition to above, with the ultra dense small cells deployments in 5G networks, DBF small cells will utilize the unlicensed bands via cellular air interfaces. The spectacle will be like reuse unlicensed band. This may reduce the performance of cellular transmission in unlicensed bands. Such this challenge need further research about the resource allocation in 5G network and its architectures.

In 5G networks, when the BS adopt FD mode or specifically in-band full-duplex (IBFD) mode to transmit-receive signals on higher frequency bands (millimeter-wave), the self-interference may has new features. Hence, the new circuits/algorithms designs may be required to treat with self-interference cancellation issue. Currently, the necessary circuits to cancel self-interference have large sizes. Therefore, the mobile UE cannot adopt IBFD mode now, and further development will be needed in the future. Spectrum sharing can effectively increase network capacity, as discussed, looking into the numerous connectivity in 5G networks as expected can envisaging so many CR nodes in these networks. The spectrum resources may become much more needed. Then the PUs who have the rights may not desire to share their bands with SUs, especially if SUs are managed by different MNOs. Such this issue needs more investigation and efficient algorithm of spectrum allocation based on auction theory to lease the required spectrum. Consequently, a number of potential challenges must be defeated to achieve wide spectrum sharing in the future CRNs.

VIII. Conclusion

The paper has reviewed the procedure and type of provided support which is different according to the adopted manner, algorithm, mode, or mechanism, of each technique, to determine and understand the applicability to particular application, which help to recognize the preferable techniques for 5G networks by considering the technique which can serve particular application requirements. Consequently, the optimal spectrum utilization by exploitation the obtainable holes in all spectrum resources using a successful spectrum sharing scheme which must include the proper and accurate techniques can get much more spectrums to increase networks capacity which effectively contribute in achievement all requirements of 5G networks and satisfy users' demands.

For the future, a studies are required to highlight on the current developments related with aggregation technologies purposeful to increase the number of aggregated component carriers, for the perfect and more capable aggregation, and further experimental investigation is necessary to solve the problems of detection the channel's holes in higher frequency bands by developing the current sensing techniques specially the compressive spectrum sensing technique, also the seeking to find more accurate techniques to allocate spectrum according to the need of SU as possible. In addition to above, all efforts must take into account the lower energy consumption requirements, for the extended future networks which will connect almost everything.

Our ongoing work to increase networks capacity, investigates into both DBF and IFW small cells as methods to simultaneously access the channels in licensed and unlicensed bands. We plan to design algorithm for each method consider the optimal power control in the licensed band, and the optimal control of channel's time usage in the unlicensed band, for fair spectrum sharing.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The first author collected the data, conducted the research, and wrote the paper under the second author supervision. The authors contributed together to analyze the data. All authors had approved the final version.

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