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Introductory Chapter: Primary and Secondary Users in Cognitive Radio-Based Wireless Communication Systems

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1. Wireless communications and the necessity of cognitive radio

Wireless communication systems play a special role in human life, facilitate the life, and change the world much more in the future. The diversity of applications and services of wireless communications indicates the widespread use of wireless systems and equipment in the future. Since the first radio link by Marconi in 1896, it has been more than 120 years, and several wireless communication systems have been introduced up to now. Meanwhile, the advancement of cellular wireless communications, whose idea came back to 1947 and their first generation in 1978 (namely advanced mobile phone service), has been well adopted and has grown dramatically, so that the researchers and operators are focused on standardization and design of 5G and 6G wireless communication systems [1].

From the beginning, one of the main problems in wireless communications is the scarcity of radio resources (frequency, time, and power). In recent years, the lack of frequency spectrum and the necessity of frequency reuse at different times and places and reduction of the consumed power are of great importance. Looking at the following laws:

- Moore's law: The number of transistors that can be cheaply placed on a microchip doubles and the computer power exponentially increases approximately every 2 years [2]
- Cooper's law: The number of voice calls or data that can be sent over the usable radio spectrum doubles every 30 months [2]

It is clear that, in spite of the rapid technological changes, the number of requests for accessing the wireless systems and the achievable data rate is sharply increasing. In order to achieve the ultimate goal of communications, “Communications at anytime, anywhere, with anything (human, machine and object), at a low cost, low power consumption, high quality and reliability, with high speed and low latency,” extensive research, design, and implementation of new techniques and technologies are required. Hence, it is necessary to anticipate the future trend in designing, upgrading, improving, and deploying wireless communication systems because it is essential to know the following:

- What are the users’ requests and operators’ plans?
- What are the limitations and drawbacks of current techniques and technologies?
- What is the current technology trend and what changes are needed in the future?
- What is the strategy?

In order to achieve the intended goals, the following are crucial and critical aspects [3]:

- Reusing the available radio spectrum in both time and space and use of new spectrum
- Eliminating the technological and technical constraints to achieve higher capacity
- Reducing the cost of designing, configuring, and installing a wireless network
- Decreasing the time needed to operate and deploy the system
- Reducing the hardware changes and making the ability of more software processing
- Standards, instructions, and recommendations.

One of the most important issues in wireless communications that require accurate recognition and modeling is the transmission channel. The high diversity of wireless communication channels and their time and frequency variant nature make the issue more relevant. The various types of channels in modeling, simulation, and measurements depend on the following categories and classifications:

- Indoor or outdoor/line of sight (LOS) or non-LOS (NLOS)
- Sparse or dense, based on the density of users or base stations (servers)
- The location of the users and servers to each other
- Single, double, or multilayer, in terms of coverage and the type of cells
- Homogeneity or heterogeneity of the network
- Type of control, signaling, measurement, and decision
- Noise-dominant or interference-dominant

This diversity reflects the differences and variations in the models and analyses. Therefore, it requires comprehensive research, because necessarily the model of each channel is not applicable or cannot be extended to the other channels. Hence, the dynamic cognition of the environment and the adjustment and adaptation of system parameters are the main goals.

The static spectrum allocation has over the years led to many successful applications, but it has also resulted in a situation where almost all the available frequency spectrum has been assigned to specific applications and there is no space for emerging services. On the other hand, it is shown that the spectrum is actually underutilized in time or space.

The spectrum scarcity problem has led researchers and operators to use the licensed spectrum efficiently and reuse it by considering the resource reuse techniques and introduce new frequency ranges. Briefly, we can see the main solutions for spectrum allocation:

- Array processing and signal improvement
- Multi-input multi-output (MIMO) technology
- Non-orthogonal multiple access (NOMA)
- Waveforms with high spectral efficiency, low inter-symbol interference (ISI), and a controlled peak-to-average power ratio (PAPR)
- Adaptive coding and modulation based on the signal and channel quality
- New frequency bands in the range of millimeter wavelengths and terahertz frequencies

It is suggested that new devices use the underutilized spectrum in an opportunistic manner, which is the core idea behind the cognitive radio (CR). Cognitive radio is a radio that is aware of the environment and can adapt the transmissions according to noise, interference, and channel variations. CR is based on software-defined radio (SDR). It means that a CR system at least needs “flexibility and agility”, “sensing”, and “learning and adaptability”.

2. Cognitive radio

Cognitive radio was first introduced by Mitola [4], which is aware of the surrounding environment and is able to change its parameters to improve user performance. Measurements and research studies show that some parts of the spectrum are not used in time and space. These parts, which are named white spaces (as shown in **Figure 1**), have no active primary users. Secondary users in these parts of the spectrum will be able to detect and communicate with each other freely. This method is called the overlay manner, which is considered in many radio systems [6]. Also, in the other parts of the spectrum, the power level is very low. By using the capabilities of the cognitive radio, this part of the spectrum can be used in the underlay manner, if the transmit power of the secondary users be controlled below a pre-defined threshold level, and it does not make any harmful impact on the primary users [7]. Herein, we mention the coexistence of CR-based systems as follows:

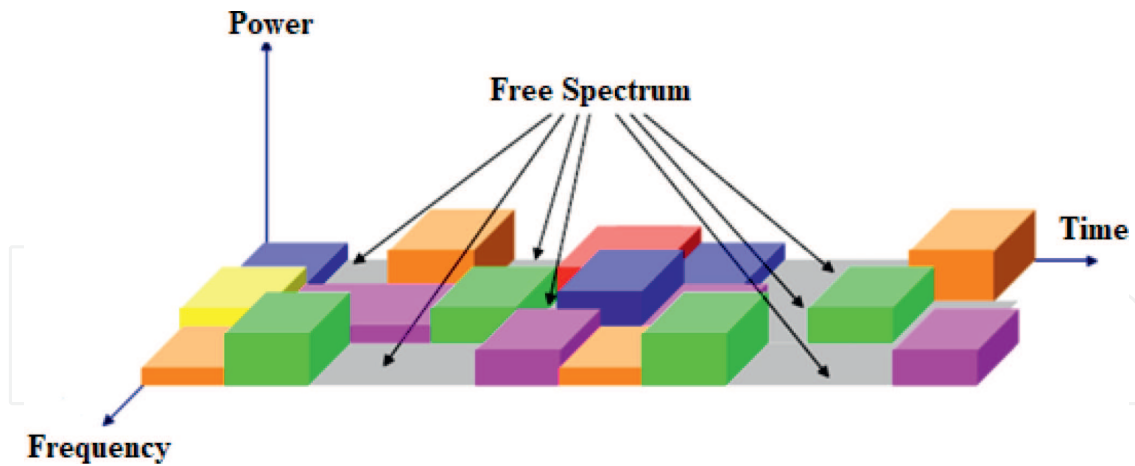


Figure 1. The free and occupied spectrums [5].

- Low-power spread spectrum communications along with existing narrowband systems
- Low-power technologies such as ultra-wide-band (UWB) and near-field communications (NFC)
- Unicast and multicast device-to-device (D2D) communications
- Multilayer heterogeneous structures based on macrocell, femtocell, nanocell, picocell, and attocell, and underlaying or overlaying conventional cellular systems.

Three important characteristics of the cognitive radio system are awareness, cognition, and adaptability [8]. Awareness means that the system has the ability to measure and sense the environment if the spectrum is free or occupied, location of the radio source, user profiles, and even the traffic and propagation characteristics of the network. Cognition, in fact, shows the ability to process information received from the environment, which should be used for making an optimal system performance. The third concept is the ability to set the parameters of the system without making any modification in the system hardware using SDR. According to these CR characteristics, it is actually a completely dynamic system in which its parameters such as frequency, transmit power, antenna pattern, transmission protocol, modulation type, coding rate, and communication technology are reconfigurable [9]. Therefore, dynamic access to the spectrum, as the main part of a cognitive radio, can help to overcome the spectrum scarcity and reuse the unused spectrum [10].

In addition to dynamic access to the spectrum, other applications are also noteworthy. For example, localization, radio frequency energy harvesting (RF-EH), D2D communications, navigation of vehicles such as a CR-based unmanned autonomous vehicle (UAV), vehicle-to-vehicle (V2V) communications, and machine-to-machine (M2M) communications.

3. Spectrum sharing in cognitive radio

Spectrum sharing, as the main part of a cognitive radio, has five important parts [11–15]:

1. Spectrum sensing dependent on the following items:

- Wireless channel: Quality of channel (path loss and noise), temporal and spatial variations of channel (multipath fading and shadowing), and type of link (LOS or NLOS)
- Network: Homogeneous or non-homogeneous
- User: Personal, social, and physical characteristics
- Other aspects: Complexity, power consumption, type of management,...

2. Spectrum allocation

3. Spectrum access

4. Handshake between transmitter and receiver

5. Spectrum mobility

Spectrum sharing classifications are based on:

1. Frequency band

- Horizontal (open) such as industrial, scientific, and medical (ISM) band
 - Coexistence
 - Spectrum sharing games
 - Centralized spectrum coordination
- Vertical (hierarchical)
 - Reuse of TV bands
 - Spectrum pooling and common control
 - Operator-assisted
 - Spectrum load smoothing

2. Access to the spectrum

- Underlay, such as orthogonal frequency division multiplexing (OFDM), UWB, and spread spectrum
- Overlay (opportunistic)

3. Network structure and control scenario such as centralized, decentralized, and distributed

4. Type of cooperation of secondary users such as cooperative, non-cooperative (selfish), coexistence, spectrum sharing games, and centralized spectrum coordination

4. Primary and secondary users in cognitive radio-based systems

By defining the priority in the usage of the assigned radio frequency spectrum, two types of users, namely primary users (PUs) and secondary users (SUs), can coexist under a specific policy. Usually, the SUs are allowed to use the spectrum in such a way that they do not cause any harmful interference on the PUs, overlay or underlay. One of the important functions of a CR system in the overlay manner is spectrum sensing. It is the ability to detect the existence of the PUs in the frequency band. Many attempts have been done to develop the applicable approaches in the spectrum sensing process. Some of the centralized and distributed scenarios for narrowband and wideband signals have been introduced [16]. Complexity, signaling and overhead, presence of multiple SUs, small and large-scale fading phenomena and shadowing, and power consumption are the main aspects of designing efficient spectrum sensing algorithms. In this area, several spectrum sensing techniques such as energy detection (ED), cooperative detection, wavelet detection, and covariance detection have been proposed and investigated [17]. Spectrum sensing approaches can be categorized into blind, semi-blind, and non-blind classes. Though some methods can acquire channel state information by minimizing the variance of channel or noise uncertainty, they are not complexity-efficient for some applications such as wireless sensor networks (WSNs) [18, 19], OFDM-based cognitive radio [20], ultra-dense networks (UDNs), D2D communications, and cognitive radio heterogeneous networks (CR-HetNets). In the following, two examples of CR-based systems including primary and secondary users are presented.

4.1. CR-based HetNets

In recent years, several new technologies have been envisioned to fulfill the increasing demands of future wireless networks and meet the requirements of the fifth generation (5G) mobile standard. The main goal of these technologies is to improve the network performance in terms of the quality of service, the number of users, coverage, data rate, spectral efficiency, and end-to-end latency. A heterogeneous network (HetNet) is an important emerging technology that has been proposed for next-generation cellular networks, where multiple network tiers, from macrocells to small cells, coexist in the same coverage area [21]. Recently, CR technology has been proposed to be combined with HetNets to further improve the spectral efficiency of these networks [22]. Employing the CR technology in HetNet (namely CR-HetNet) has introduced the concept of vertical spectrum sharing in which low-priority users in a macrocell, which are referred to as cognitive secondary users (CSUs), are handed over to small cells, and they try to access the spectrum of the primary users in that cell [23, 24]. This spectrum sharing can be performed in an underlay or an overlay manner [25]. In the underlay spectrum sharing method, the CSUs can access the spectrum by only complying with the PU's stringent requirements, such as interference avoidance rules and maximum allowable transmission power. In the overlay spectrum sharing, the CSUs can utilize a portion of the frequency band left completely idle by the PUs. In a CR-HetNet, both the PUs and CSUs can be served by either the macro base station (MBS) or femto base stations (FBSs). However, as the CSU may move out of the coverage area of the MBS or the MBS may require offloading, the CSU needs to perform vertical handover (VHO) from the MBS to the FBS. In this case, the CSUs must sense

the underutilized spectrum of the FBS to find an appropriate channel and then perform VHO on that channel. Once a PU requests the same channel, the CSU should leave that channel, perform spectrum handover (SHO), and switch to another appropriate free channel [26]. A management strategy is then necessary to control the number of SHOs, decrease the number of unnecessary handovers, and minimize the effect of multiple interruptions [27–30].

The CR-HetNet technology has shown great potential to meet the demands of both users and networks in the future wireless networks [31]. Hot topics in this field of research are:

- Resource allocation
- Offloading and handover due to traffic load or propagation conditions [32, 33] in the form of VHO, horizontal handover (HHO), and SHO
- Clustering to speed up the resource allocation and power control
- Power control, interference alignment, and energy harvesting

4.2. D2D communications

One of the main strategies for reusing radio resources is D2D communications between two adjacent users. D2D pairs, directly or through a relay, overlay, or underlay or in-band or out-band, transmit and receive the signal [34, 35]. By using D2D communications, the delay and the traffic load of the main network decrease, the spectral efficiency increases, and the consumed energy and cost reduce [36]. In order to do the optimum resource allocation in D2D communications, we have two approaches. In the first one, regarding the signal quality, minimizing the outage probability and in the second one, in view of the traffic and the desired throughput, maximizing the throughput can be achieved. In an in-band underlay manner, in addition to considering the noise effects and multi-path fading phenomenon, it is necessary to add the effect of interference arising from the reused radio resources [37, 38]. With the help of fixed or mobile relay nodes, the distance between the transmitter and receiver nodes of a D2D pair increases and the quality of service (QoS) improves. In the field of the D2D communications underlaying cellular network, first the communication mode should be selected between conventional cellular, relay-assisted cellular, direct D2D, and relay-assisted (or relay-aided) D2D modes. The relay has a limited coverage area much lower than a BTS, but it can handle the signals between two distant D2D users, which improves the total achievable throughput especially for the users near to the cell boundary. Several relaying strategies have been proposed, including amplify-and-forward (AF) and decode-and-forward (DF). Joint resource allocation and power control of direct/relay-aided D2D communications underlaying/overlaying cellular network is an NP-hard problem. In addition to optimum mode selection, resource allocation, and power control, finding the proper power splitting (PS) factor of relay nodes in an energy-harvested D2D communication is a goal. Achieving low-complexity closed-form expressions for the outage probability and throughput helps us to do the optimization problem in an acceptable processing time [39]. **Table 1** summarizes the advantages and disadvantages of different underlay and overlay scenarios in D2D communications, in view of interference, collision, outage probability, reuse factor, and achievable throughput.

No.	Scheme	Advantages	Disadvantages
1	Underlay (non-orthogonal)	<ul style="list-style-type: none">• Activating D2D pairs with active licensed resources• No spectrum sensing needed	<ul style="list-style-type: none">• Interference• No use of idle licensed resources
2	Overlay (orthogonal)	<ul style="list-style-type: none">• Activating D2D pairs by idle licensed resources• No interference• Moderate spectrum efficiency	<ul style="list-style-type: none">• Collision
3	Underlay/overlay	<ul style="list-style-type: none">• Activating D2D pairs by both idle/active licensed resources• High spectrum efficiency	<ul style="list-style-type: none">• Interference• Collision
4	Random access k-reuse underlay/overlay	<ul style="list-style-type: none">• High spectrum efficiency• Higher reuse factor to 3• Higher throughput to 3	<ul style="list-style-type: none">• Interference• Collision• Higher outage to 3
5	Overlapped access k-reuse underlay/Overlay	<ul style="list-style-type: none">• High spectrum efficiency• Higher reuse factor to 3• Higher throughput to 4• Lower outage to 4	<ul style="list-style-type: none">• Interference• Collision

Table 1. Comparison of different resources reused in D2D communications [40].

Sometimes in a network, a number of nearby users may request a file (for example, a movie). In such cases, we can put those users who need the same information in a group by clustering. In the multicast D2D communications, D2D users are assigned to different clusters, each one including one cluster head and multiple cluster members. In this model, the main problem is the interference between the co-channel D2D and cellular users, which can be controlled by an efficient clustering and resource allocation. The user who can support more files will be chosen as the transmitter that multicasts the required information to the other users in that cluster. A multicast scenario combines the benefits of both a fixed cellular infrastructure and the flexibility of an ad-hoc network. In order to choose the proper cluster head and cluster the devices, it is necessary to consider some of the social and physical features. For example, social trust is a good standard for family members, friends and colleagues, and mutual trust is a good metric for beneficial collaboration among unknown users. The greater the social association of the users equals the higher chance of the nodes being in a similar group. Moreover, users close to each other need less energy for direct D2D communications, and those who have more neighbors have a higher priority for clustering. The weight of each criterion depends on the purpose of clustering [41, 42]. Hence, minimizing the outage probability and maximizing the throughput, are the main goals for resource allocation.

Hot topics in the field of unicast and multicast D2D communications are:

- Modeling based on the stochastic geometry, game theory, and graph theory
- Solving the optimization problems through fast tools and problem solvers

- Selection between direct/relay-based cellular and direct/relay-based D2D modes
- Selection between overlay or underlay scenarios
- Sharing between in-band or out-band frequencies
- Resource allocation and clustering
- Power control and energy efficiency
- Energy harvesting and energy saving

5. Future studies

New research topics that have been taken in recent years as strategies for the optimal use of radio resources, the further development of cognitive radio, and the improvement of the efficiency of wireless communication systems include:

- Massive-MIMO and ultra-dense networks
- Non-orthogonal multiple access techniques
- Power control based on beamforming or on-off techniques
- Green communications to save the resources and decrease the biological effects
- RF energy harvesting based on the time switching and NOMA techniques
- Energy-efficient algorithms for mode selection, resource allocation, and power control
- New services in 5G and 6G communications such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), massive machine type communications (mMTC), opportunistic Internet of Things (IoT) network, and software defined network (SDN) [43].

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