Chapter 1
Introduction

Abstract Facing the increasing demand of radio spectrum to support the emerging wireless services with heavy traffic, massive connections and various quality-of-services (QoS) requirements, the management of spectrum becomes unprecedentedly challenging nowadays. Given that the traditional fixed spectrum allocation policy leads to an inefficient usage of spectrum, the dynamic spectrum management (DSM) is proposed as a promising way to mitigate the spectrum scarcity problem. This chapter provides an introduction of DSM by firstly discussing its background, then presenting the two popular models: the opportunistic spectrum access (OSA) model and the concurrent spectrum access (CSA) model. Three main enabling techniques for DSM, including the cognitive radio (CR), the blockchain and the artificial intelligence (AI) are briefly introduced.

1.1 Background

Radio spectrum is a natural but limited resource that enables wireless communications. The access to the radio spectrum is under the regulation of government agencies, such as the Federal Communications Commission (FCC) in the United States (US), the Office of Communications (Ofcom) in the United Kingdom (UK), and the Infocomm Development Authority (IDA) in Singapore. Conventionally, the regulatory authorities adopt the *fixed spectrum access* (FSA) policy to allocate different parts of the radio spectrum with certain bandwidth to different services. In Singapore, for example, the 1805–1880 MHz band is allocated to GSM-1800, and it cannot be accessed by other services at any time. With such static and exclusive spectrum allocation policy, only the authorized users, also known as licensed users, have the right to utilize the assigned spectrum, and the other users are forbidden from accessing the spectrum, no matter whether the assigned spectrum is busy or not. Although the FSA can successfully avoid interference among different applications and services, it quickly exhausts the radio resource with the proliferation of new services and networks, resulting in the spectrum scarcity problem.

The statistics of spectrum allocation around the world show that the radio spectrum has been almost fully allocated, and the available spectrum for deploying new

Y.-C. Liang, *Dynamic Spectrum Management*, Signals and Communication Technology, https://doi.org/10.1007/978-981-15-0776-2_1

services is quite limited. The emerging of massive connections of internet-of-things (IoT) devices accelerates the crisis of spectrum scarcity. According to the study in [1], around 76 GHz spectrum resource is needed for accommodating billions of end devices by exclusive occupying the spectrum. Nevertheless, extensive measurements conducted worldwide such as US [2], Singapore [3], Germany [4], New Zealand [5] and China [6], have revealed that large portions of the allocated radio spectrum are underutilized. For instance, in US, the average occupancy over 0–3 GHz radio spectrum at Chicago is 17.4%. This number is even as low as approximately 1% at West Virginia. In Singapore, the average occupancy over 80–5850 MHz band is less than 5%. These findings reveal that the inflexible spectrum allocation policy leads to an inefficient utilization of radio spectrum, and strongly contributes to the spectrum scarcity problem even more than the physical shortage of the radio spectrum.

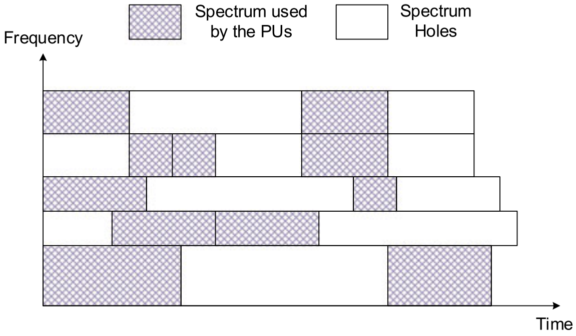
1.2 Dynamic Spectrum Management

The contradiction between the scarcity of the available spectrum and the underutilization of the allocated spectrum necessitates a paradigm shift from the inefficient FSA to the flexible and high-efficient spectrum access. In this context, *dynamic spectrum management* (DSM) has been proposed and recognized as an effective approach to mitigate the spectrum scarcity problem. It has been foreseen that by using DSM, the spectrum requirement for deploying the billions of internet-of-things (IoT) devices can be sharply reduced from 76 to 19 GHz [7]. In DSM, the users without license, also known as secondary users (SUs), can access the spectrum of authorized users, also known as primary users (PUs), if the primary spectrum is idle, or can even share the primary spectrum provided that the services of the PUs can be properly protected. By doing so, the SUs are able to gain transmission opportunity without requiring dedicated spectrum. This spectrum access policy is known as *dynamic spectrum access* (DSA). According to the way of coexistence between PUs and SUs, there are two basic DSA models: (1) The *opportunistic spectrum access* (OSA) model and (2) the *concurrent spectrum access* (CSA) model.

1.2.1 Opportunistic Spectrum Access

A spectrum usage in the OSA model is illustrated in Fig. 1.1. Due to the sporadic nature of the PU transmission, there are time slots, frequency bands or spatial directions at which the PU is inactive. The frequency bands on which the PUs are inactive are referred to as *spectrum holes*. Once one or multiple spectrum holes are detected, the SUs can temporarily access the primary spectrum without interfering the PUs by configuring their carrier frequency, bandwidth and modulation scheme to transmit on the spectrum holes. When the PUs become active, the SUs have to cease their transmission and vacate from the current spectrum. To enable the operation of the OSA,

Fig. 1.1 An illustration of spectrum usage in the OSA model



the SU needs to obtain the accurate information of spectrum holes, so that the quality of services (QoS) of the PUs can be protected. Two factors determine the method that the SU can adopt to detect the spectrum holes. One factor is the predictability of the PU's presence and absence, and the other factor is whether the primary system can actively provide the information of the spectrum usage. Accordingly, there are basically two methods which can be adopted by SUs to detect spectrum holes.

(1) *Geolocation Database*

If the PU's activity is regular and highly predictable, the geographical and temporal usage of spectrum can be recorded in a geolocation database to provide the accurate status of the primary spectrum. For accessing the primary spectrum without interfering the PUs, an SU firstly obtains its own geographic coordinates by its available positioning system, and then checks the geolocation database for a list of bands on which the PUs are inactive in the SU's location. The geolocation database approach is suitable for the case when the PUs' presence and absence are highly predictable, and the spectrum usage information can be publicized for achieving a highly efficient utilization of spectrum [8–10]. For example, in the final rules set by the FCC for unlicensed access over TV bands, the geolocation database is the only approach that is adopted by unlicensed devices for protecting the incumbent TV broadcasting services [11]. Nevertheless, for other services, such as cellular communications, the activities of users are difficult to be predicted and there is lack of incentive for the PUs to provide their spectrum usage, especially when the primary and secondary services belong to different operators. In this case, the geolocation database is inapplicable.

(2) *Spectrum Sensing*

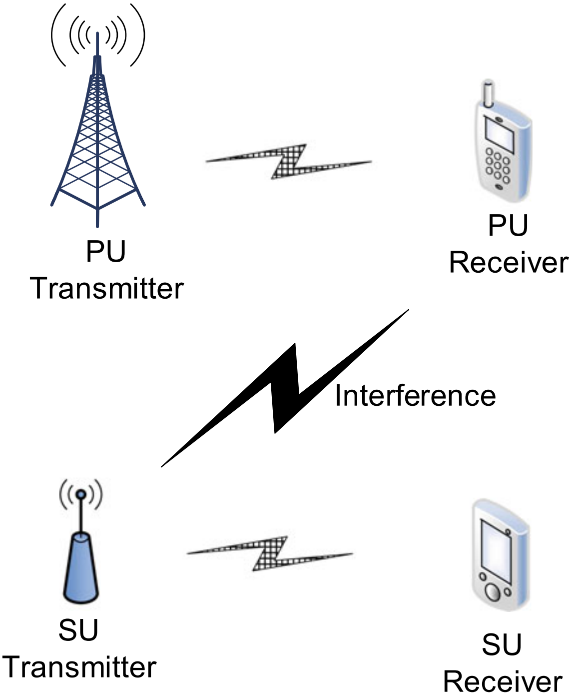
Without a geolocation database, an SU can carry out *spectrum sensing* periodically or consistently to monitor the primary spectrum and detect the spectrum holes. When there are multiple SUs, cooperative spectrum sensing can be applied to improve the sensing accuracy [12–17]. Different from the previous method where the accurate spectrum usage information is recorded in the geolocation database, the spectrum sensing is essentially a signal detection technique, which could be imperfect due to the presence of noise and channel impairment, such as small-scale fading and large-scale shadowing [18]. To measure the performance of spectrum sensing, two main metrics, i.e., the probability of detection and the probability of false alarm, are used. The former one is the probability of detecting the PU as being present when the PU is active indeed. Thus, it describes the degree of protection to the PUs, i.e., a higher probability of detection provides a better protection to the PUs. The latter one is the probability of detecting the PU as being present when the PU is actually inactive. Therefore, it can be regarded as an indication of exploration to the spectrum access potential. A lower probability of false alarm indicates more transmission opportunities can be utilized by the SUs, and thus better SU performance, such as throughput, can be achieved. To this end, a good design of spectrum sensing should have a high probability of detection but low probability of false alarm. However, these two metrics are generally conflicting with each other. Given a spectrum sensing scheme, the improvement of probability of detection is achieved at the expense of increasing probability of false alarm, which leads to less spectrum access opportunities for the SUs. In another word, a better protection to the PUs is at the expense of the degradation of the SU's performance. To improve the performance of spectrum sensing, there has been a lot of work on designing different detection schemes or allowing multiple SUs to cooperatively perform spectrum sensing [12–17].

It is worth noting that the spectrum sensing is an essential tool for enabling DSA and deserves continued development from the research communities. Although spectrum sensing is not mandatory for the unlicensed access over TV white space, the current standards developed such as IEEE 802.22 and ECMA 392 still use a combination of geolocation database and spectrum sensing [19–21]. In some literatures, the OSA model is also referred to as spectrum overlay [22], or interweave paradigm [23].

1.2.2 Concurrent Spectrum Access

A typical CSA model is shown in Fig. 1.2, where the SU and the PU are transmitting on the same primary spectrum concurrently. In this type of DSA, the secondary transmitter (SU-Tx) inevitably produces interference to the primary receiver (PU-Rx). Thus, to enable the operation of the CSA, the SU-Tx needs to predict the interference level at the PU-Rx caused by its own transmission, and limit the interference to an acceptable level for the purpose of protecting the PU service. In practice, a communication system is usually designed to be able to tolerate a certain amount of interference. For example, a user in a code-division multiple access (CDMA) based third-generation (3G) cellular network can tolerate interference from other users and compensate the degradation of signal-to-interference-plus-noise ratio (SINR) via the embedded inner-loop power control. Such level of tolerable interference is known as *interference temperature*, which is also referred to, in some literatures, as interference margin. The concurrent transmission of SU-Tx is allowed only when the interference received by the PU-Tx is no larger than the interference temperature. Therefore, different from the OSA model where the geolocation database or spectrum sensing is used for detecting spectrum holes, interference control is critical for CSA to protect the PU services.

Fig. 1.2 An illustration of the spectrum sharing model



The protection of the PU is mathematically formulated as an interference power constraint. A basic interference power constraint indicates that the instantaneous interference power received by PU-Rx is no larger than the interference temperature. Such a formulation requires that the SU-Tx has the information of the interference temperature provided by PU-Rx and the channel state information (CSI) from SU-Tx to PU-Rx, also known as cross channel state information (C-CSI), to quantify the actual interference received by the PU-Rx. Variants of the basic interference power constraint result in different performance of the secondary system. For example, the average interference power constraint gives better secondary throughput than the peak interference power constraint [24, 25]. This is because that the former constraint is less stringent, and in some fading states it allows the interference exceed the interference temperature. Furthermore, if there are multiple SUs, the secondary system can exploit the multiuser diversity (MUD) to improve secondary capacity by choosing the SU with best receive quality and least interference to the PU-Rx to be active for transmitting or receiving. The MUD of sharing a single frequency band was carefully studied in [26–29]. To benefit from the interference diversity or MUD, the CSI from SU-Tx to SU-Rx and SU-Tx to PU-Rx should be known by the SU-Tx.

Exploiting the primary system information can offer more sharing opportunities. In [30], rate loss constraint was proposed to restrict the performance degradation of the PU due to the secondary transmission. To formulate this constraint, not only the C-CSI, but also the CSI from PU-Tx to PU-Rx and the transmit power of PU-Tx are required [31]. Without direct cooperation between the primary and secondary systems, the SU-Tx can trigger the power adaptation of primary system by intentionally sending the probing signal with a high power [32, 33]. To tackle the strong interference, PU-Tx will increase its transmit power which can be heard by the SU-Rx. Then, the secondary system deduces the interference temperature provided by the primary system and estimates the C-CSI, which is the critical information for secondary system to successfully share the primary spectrum.

It is worth noting that, similar to OSA, the protection to the primary system and the secondary throughput are contradictory with each other. A stringent protection requirement of the primary system leads to a low secondary throughput. Therefore, making good use of the interference temperature is the way to optimize the performance of the secondary system in the CSA model. In some literatures, the CSA model is also referred to as spectrum underlay [33].

The comparison of OSA and CSA is summarized in Table 1.1. It can be seen that when the PU is off, the SU can transmit with its maximum power based on OSA model. However, when the PU is on, the SU can still transmit by regulating its transmit power based on the CSA model, rather than keep silent according to the OSA model. Such a hybrid spectrum access model combines the benefits of OSA and CSA, which gains higher spectrum utilization. Moreover, in the aforementioned OSA and CSA models, the PUs have higher priority than the SUs, and thus should be protected. Such a DSA is also known as hierarchical access model, since the priorities of accessing the spectrum are different based on whether the users are licensed or not. In the hierarchical access model, since the PUs are usually legacy users, the cooperation between the primary and secondary systems are unavailable, and only the SUs are responsible to carry out spectrum detection or interference control. In some cases, the primary system is willing to lease its temporarily unused spectrum to the SUs by receiving the leasing fee, which is an incentive for the PUs to provide certain form of cooperation. In the literatures, the DSA model in which all of the users have equal priorities to access the spectrum has also received lots of attention, such as license-shared access (LSA) and spectrum sharing in unlicensed band [34–36]. Although there is no cap of interference introduced to the others, in this DSA model, each user has to take the responsibility to protect the others or keep fairness in accessing the spectrum.

Table 1.1 Comparison of OSA and CSA

	OSA	CSA
Whether SU is always on?	No	Yes
How to learn the environment?	Spectrum sensing, geolocation database	Channel estimation, interference prediction
Techniques to protect PU	No transmission when PU is on	Interference control
Measurement of PU protection	Detection probability	Interference temperature, performance loss margin

1.3 Cognitive Radio for Dynamic Spectrum Management

Cognitive radio (CR) has been widely recognized as the key technology to enable DSA. A CR refers to an intelligent radio system that can dynamically and autonomously adapt its transmission strategies, including carrier frequency, bandwidth, transmit power, antenna beam or modulation scheme, etc., based on the interaction with the surrounding environment and its awareness of its internal states (e.g., hardware and software architectures, spectrum use policy, user needs, etc.) to achieve the best performance. Such reconfiguration capability is realized by software-defined radio (SDR) processor with which the transmission strategies is adjusted by computer software. Moreover, CR is also built with cognition which allows it to observe the environment through sensing, to analyse and process the observed information through learning, and to decide the best transmission strategy through reasoning. Although most of the existing CR researches to date have been focusing on the exploration and realization of cognitive capability to facilitate the DSA, the very recent research has been done to explore more potential inherent in the CR technology by artificial intelligence (AI).

A typical cognitive cycle for a CR is shown in Fig. 1.3. An SU with CR capability is required to periodically or consistently observe the environment to obtain the information such as spectrum holes in OSA or interference temperature and C-CSI in CSA. Based on the collected information, it determines the best operational parameters to optimize its own performance subject to the protection to the PUs and then reconfigures its system accordingly. The information collected over time can also be used to analyse the radio environment, such as the traffic statistics and channel fading statistics, so that the CR device can learn to perform better in future dynamic adaptation.

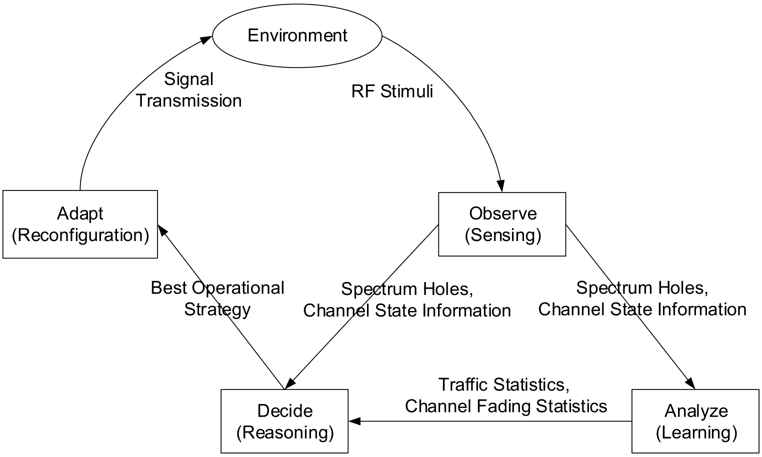


Fig. 1.3 The cognitive cycle for CR

Although enabling DSA with CR is a technical issue which involves multidisciplinary efforts from various research communities, such as signal processing, information theory, communications, computer networking, and machine learning [37], its realization also largely depends on the willingness of regulators to open the spectrum for unlicensed access. Fortunately, over the past decades, we have seen worldwide efforts from regulatory bodies on eliminating regulatory barriers to facilitate DSA. For example, in the US, the FCC set forth a few proposals for removing unnecessary regulations that inhibit the development of secondary spectrum markets in November, 2000 [38]. Later, in December 2003, the FCC recognized the importance of CR and promoted the use of it for improving spectrum utilization [39]. In May 2004, the FCC issued a notice of proposed rulemaking (NPRM) that proposes to allow the unlicensed devices (both fixed and personal/portable) to reuse the temporarily unused spectrum of TV channels, i.e., TV white space [40], and the rules for such unlicensed use were finalized in September 2010 [11]. In the national broadband plan released in March 2010, the FCC also indicated its intention to enable more flexible access of spectrum for unlicensed and opportunistic uses [41]. The TV white space is considered to be very promising for a wide range of potential applications due to its favorable propagation characteristics [11], and hence it has also drawn attention from other regulators worldwide. For example, in the UK, the Ofcom proposed to allow licence-exempt CR devices to operate over the spectrum freed up due to analog to digital TV switchover in the statement of the Digital Dividend Review Project released in December, 2007 [42]. In Singapore, the IDA has also recognized the potential of TV white space technology and conducted trials for testing the feasibility and developing regulatory framework to facilitate it [43].

Besides regulators' efforts on spectrum "deregulation", various standardization communities have also been actively working on developing industrial standards that expedite the commercialization of CR-based applications. Following the FCC's NPRM in May 2004, the IEEE 802.22 working group was formed in November 2004 that aims to develop the first international standard that utilizes TV white space based on CR [44, 45]. The standard specifies an air interface (both physical (PHY) layer and medium access control (MAC) layer) for a wireless regional area network (WRAN), which is designed to provide wireless broadband access for rural or suburban areas for licensed-exempt fixed devices through secondary opportunistic access over the VHF/UHF TV broadcast bands between 54 and 862 MHz. The finalized version has been published in July, 2011 [20]. The first international CR standard on the use of personal/portable devices over TV White Spaces is ECMA 392 [46]. The first edition of the standard was finalized in December, 2009 by ECMA International based on the draft specification contributed from cognitive networking alliance (CogNeA) [46]. It specifies an air interface as well as a MUX sublayer for higher layer protocols [21], which is targeted for in-home, in-building and neighborhood-area applications in urban areas [46]. Other standards based on CR include IEEE 802.11af, IEEE 802.19, IEEE SCC 41 (previously known as IEEE 1900), as well as the Third Generation Partnership Project (3GPP) LTE Release 13 which introduces the licensed assisted access (LAA) to utilize the 5 GHz unlicensed bands for the operation of LTE [9, 47–49].

1.4 Blockchain for Dynamic Spectrum Management

The past decade has witnessed the burst of blockchain, which is essentially an open and distributed ledger. Cryptocurrency, notably represented by bitcoin [50], is one of the most successful applications of blockchain. The price for one bitcoin started at $0.30 in the beginning of 2011 and reached to the peak at $19,783.06 on 17 December 2017, which reveals the optimism of the financial industry in it. Facebook, one of the world biggest technology company, announced its own cryptocurrency project Libra in June 2019. Besides the cryptocurrency, with its salient characteristics, blockchain has many uses including financial services, smart contracts, and IoT. According to a report from Tractica, a market intelligence firm, enterprise blockchain revenue will reach $19.9 Billion by 2025 [51]. Moreover, blockchain is believed to bring new opportunities to improve the efficiency and to reduce the cost in the dynamic spectrum management.

Blockchain is essentially an open and distributed ledger, in which transactions are securely recorded in blocks. In the current block, a unique pointer determined by transactions in the previous block is recorded. In this way, blocks are chained chronologically and tamper-evident, i.e., tampering any transaction stored in a previous block can be detected efficiently. The transactions initiated by one node are broadcast to other nodes, and a consensus algorithm is used to decide which node is authorized to validate the new block by appending it to the blockchain. With the decentralized validation and record mechanism, blockchain becomes transparent, verifiable and robust against single point of failures. Based on the level of decentralization, blockchain can be categorized into public blockchain, private blockchain and consortium blockchain. A public blockchain can be verified and accessed by all nodes in the network, while a private blockchain or a consortium blockchain can only be maintained by the permissioned nodes.

A smart contract, supported by the blockchain technology, is a self-executable contract with its clauses being transformed to programming scripts and stored in a transaction. When such a transaction is stored in the blockchain, the smart contract is allocated with a unique address, through which nodes in the network can access and interact with it. A smart contract can be triggered when the pre-defined conditions are satisfied or when nodes send transactions to its address. Once triggered, the smart contract will be executed in a prescribed and deterministic manner. Specifically, the same input, i.e., the transaction sent to the smart contract, will derive the same output. Using a smart contract, dispute between the nodes about transactions is eliminated since that node can identify its execution outcome of the smart contract by accessing it.

Blockchain has been investigated to support various applications of IoT. As a decentralization ledger, blockchain can help integrate the heterogeneous IoT devices and securely store the massive data produced by them. For instance, with data such as how, where and when the different processes of production are completed being immutably recorded in a blockchain and traceable to consumers, the quality of products can be guaranteed. Other uses of blockchain in IoT include smart manufacturing, smart grid and healthcare [52]. Moreover, blockchain is also applied to manage the mobile edge computing resources to support the IoT devices with limited computation capacity [53].

Recently, telecommunication regulator bodies have paid much attention to apply blockchain technology to improve the quality of services, such as telephone number management and spectrum management. In the UK, Ofcom initiated a project to explore how blockchain can be used to manage telephone numbers [54]. Specifically, a decentralized database could be established using the blockchain technology, to improve the customer experience when moving a number between the service providers, to reduce the regulatory costs and to prevent the nuisance calls and fraud. On the other hand, blockchain is also believed to bring new opportunities to spectrum management. According to a recent speech by FCC commissioner Jessica Rosenworcel, blockchain might be used to monitor and manage the spectrum resources to reduce the administration cost and speed the process of spectrum auction [55]. It is also stated that with the transparency of blockchain, the real-time spectrum usage recorded in it can be accessible by any interested user. Thus, the spectrum utilization efficiency can be further improved by dynamically allocating the spectrum bands according to the dynamic demands submitted by users using blockchain.

Researchers have been investigating the application of blockchain in spectrum management. In [56], applications of blockchain to spectrum management are discussed by pairing different modes of spectrum sharing with different types of blockchains. In [57], authors provide the benefits of applying blockchain to the Citizens Broadband Radio Service (CBRS) spectrum sharing scheme. In [58], dynamic spectrum access enabled by spectrum auctions is secured by the use of blockchain. In [59], smart contract supported by blockchain is used to intermediate the spectrum sensing service, provided by sensors, to the secondary users for opportunistic spectrum access. In [60], dynamic spectrum access is enabled by the combination of cryptocurrency which is supported by blockchain, and auction mechanism, to provide an effective incentive mechanism for cooperative sensing and a fair method to allocate the collaboratively obtained spectrum access opportunity.

Essentially, there is a need to derive some basic principles to investigate why and how applying blockchain to the dynamic spectrum management can be beneficial. Specifically, we can use blockchain (1) as a secure database; (2) to establish a self-organized spectrum market. Moreover, the challenges such as how to deploy the blockchain network over the cognitive radio network should be also addressed.

- *Blockchain as A Secure Database*: The conventional geolocation database for the usage of spectrum bands, such as TV white spaces, can be achieved by the blockchain with increased security, decentralization and transparency. Moreover, other information such as historical sensing results, outcomes of spectrum auctions and access records can also be stored in the blockchain.
- *Self-organized Spectrum Market*: A self-organized spectrum market is desired with its improved efficiency and reduced cost in administration compared to relying on a centralized authority to manage the spectrum resources. With the combination of smart contract, cryptocurrency, and the cryptographic algorithms for identity and

transaction verification, blockchain can be used to establish a self-organized spectrum market. For example, traditional spectrum auctions usually need a trusted authority to verify the authentication of the users, decide the winning user and settle the payment process. With blockchain, specifically, with the smart contract, spectrum auctions can be held in a secure, automatic and uncontroversial way. Moreover, with the security provided by blockchain, transactions can be made between users without any trust in each other. Thus, the high bar to obtain the spectrum resources can be reduced. Besides the spectrum access right, other property/services related to the spectrum management, such as the spectrum sensing, can also be traded between users by smart contracts.

- *Deployment of Blockchain*: The consensus algorithm, such as Proof of Work (PoW), through which a new block containing transactions can be added to the blockchain, is usually computationally intensive. Thus, it is needed to consider the limited computation capacity and battery of mobile users when deploying the blockchain over the traditional cognitive radio network. Based on this, we will provide three ways, including (1) enabling users to directly maintain a blockchain, (2) using a dedicated blockchain maintained by a third-party authority, and (3) allow users to simply offload the computation task to edge computing service providers (ECSPs) while keeping the verification and validation authority to themselves.

In summary, the blockchain technologies have been believed to bring new opportunities to the dynamic spectrum management, to hopefully improve the decentralization, security and autonomy, and reduce the administration cost. While challenges such as the energy consumption, the deployment and design of blockchain network over the traditional cognitive radio network should also be investigated. With a detailed and systematic investigation on blockchain technologies to dynamic spectrum management, which will be given in Chap. 5, we believe the directions will be more clear for the readers interested in the relevant researches.

1.5 Artificial Intelligence for Dynamic Spectrum Management

AI, which is a discipline to construct intelligent machine agents, has received increasing attention. AlphaGo, the most famous AI agent, has beaten many professional human players in Go games since 2015 [61]. In 2017, AlphaGo Master, the successor of Alpha Go, even defeated Ke Jie, who was the world No.1 Go player at the time. The concept of AI was proposed by John McCarthy in 1956, and its primary goal is to enable the machine agent to perform complex tasks by learning from the environment [62]. Nowadays, AI has become one of the hottest topic both in the academia and in the industry, and it is even believed to lead the development in the information age [63]. Specifically, the AI techniques have been successfully applied to many fields such as face and speech recognition. Moreover, AI techniques have shown potentials in the dynamic spectrum management, to improve the utilization of the increasingly congested spectrum.

Machine learning (ML), as the core technique of AI, has been greatly developed both in theories and applications [64]. Generally, there are three branches of the ML techniques.

- *Statistical Machine Learning*: With the training data obtained and the task known, statistical machine learning (SML) first constructs a statistical model, and then trains the parameters in the model. After that, when new data arrives, the agent is able to perform the task based on the learnt model. The commonly used SML methods include support vector machine (SVM), K-nearest neighbor (KNN), K-means and Gaussian mixture model (GMM).
- *Deep Learning*: Based on the artificial neural network (ANN), which has a strong ability to approximate functions, deep learning (DL) is normally used in the classification tasks. Compared with the traditional ANN, DL is distinctive with its deeper architecture. Moreover, its performance is improved by designing and adopting ad-hoc neural networks for data of different types, such as convolutional neural network (CNN) for image data and recurrent neural network (RNN) for temporal data.
- *Deep Reinforcement Learning*: Aiming to solve the sequential decision-making tasks, deep reinforcement learning (DRL) allows the agent to maximize its long-term profit by continuously interacting with the environments. The commonly used DRL methods are deep Q-network (DQN), double deep Q-network (DDQN), asynchronous advantage actor-critic (A3C) and deep deterministic policy gradient (DDPG).

The application of the AI techniques especially the above ML techniques to the next-generation communications networks has attracted a significant amount of attention of the telecommunication regulators. In the U.S., the FCC hosted a forum on AI and machine learning for 5G on Nov 30, 2018. In this forum, the panelists concluded that the AI techniques could improve network operations and would become a critical component in the next-generation wireless networks [65]. It is stated by A. Pai, the chairman of the FCC, that AI has the potentials to construct smarter communications networks and to improve the efficiency of the spectrum utilization [66]. In the UK, Ofcom also recognized AI and machine learning as powerful technologies to support 5G application scenarios such as ultra-reliable low-latency communications (URLLCs) [67].

Motivated by the superiority of AI, many research organizations have been investigating on the applications of AI techniques to the dynamic spectrum management [68]. The defense advanced research projects agency (DARPA) in the U.S. has held a 3-year grand competition called “spectrum collaboration challenge” (SC2) since 2017 [69]. The main objective of the SC2 is to imbue wireless communications with AI and machine learning so that intelligent strategies can be developed to optimize the usage of wireless spectrum resource in real time. Recent works from national institute of standards and technology (NIST) in the U.S. show that the AI-based method greatly outperforms the traditional methods on spectrum sensing [70].

Using the machine learning and AI techniques, the model-based schemes in the traditional DSM can be transformed into data-driven ones. In this way, DSM becomes more flexible and efficient. Specifically, we summarize the benefits of applying AI techniques to the DSM as follows.

- *Autonomous Feature Extraction*: Without pre-designing and extracting the expert features as in the traditional schemes, AI-based schemes can automatically extract the features from data. In this way, the agent can achieve its objective without any prior knowledge or assumptions of the wireless network environments.
- *Robustness to the Dynamic Environment*: With periodic re-training, the performance of the data-driven approaches would not be significantly affected by the change of the radio environment, resulting in the robustness to the environment.
- *Decentralized Implementation*: With the help of AI techniques, the spectrum management mechanisms can be achieved in a decentralized manner. This means that the central controller is no longer needed and each device can independently and adaptively obtain its required spectrum resource. Moreover, in the distributed implementation, each device is allowed to only use its local observations of the radio environment to make decisions. Thus, massive message exchange and signaling overheads to acquire the global observations can be avoided.
- *Reduced Complexity*: In most AI-based schemes, management policies can be directly obtained and repeatedly used after the convergence. In this way, the repeated computation for obtaining the policies in the traditional schemes is avoided. Additionally, the direct use of raw environmental data in AI-based approaches eliminates the complexity of designing expert features and can even achieve better performance.

However, there exist some challenges to achieve the AI-based DSM schemes. For example, it is needed for an AI-based scheme to differentiate the importance of data of different types in the radio environment. On that basis, the AI-based scheme is more likely to extract features useful for its objective. Moreover, since there exist huge computation overheads in the training of the existing AI techniques, how to accelerate computation to reduce the latency and the expense is also a matter of concern.

In summary, it is believed that the DSM would be achieved in a more efficient, robust, flexible way by applying AI and machine learning techniques. However, challenges in the implementations of AI-based DSM schemes should also be addressed. A detailed and systematic investigation on machine learning technologies and their applications to the DSM will be presented in Chap. 6.

1.6 Outline of the Book

DSM has been recognized as an effective way to improve the efficiency of spectrum utilization. In this book, three enabling techniques to DSM are introduced, including CR, blockchain and AI.

Chapters 2–4 discuss the CR techniques. Specifically, the Chap. 2 focuses on the CR for OSA. We start with a brief introduction on the OSA model and the functionality of sensing-access design at PHY and MAC layers. Then three classic sensing-access design problems are introduced, namely, sensing-throughput tradeoff, spectrum sensing scheduling, and sequential spectrum sensing. Furthermore, existing works on sensing-access design are reviewed. Finally, the application of the OSA to operating LTE in unlicensed band (LTE-U) is discussed.

Chapter 3 is especially used for discussing the spectrum sensing, which is the critical technique for OSA. We first provide the fundamental theories on spectrum sensing from the optimal likelihood ratio test perspective. Then, we review the classical spectrum sensing methods including Bayesian method, robust hypothesis test, energy detection, matched filtering detection, and cyclostationary detection. After that, we discuss the robustness of the classical methods and review techniques that can enhance the sensing reliability under hostile environment. Finally, we discuss the cooperative sensing that uses data fusion or decision fusion from multiple senors to enhance the sensing performance.

Chapter 4 focuses on the CR for CSA. We start with an introduction on the challenges existing in the CSA model. Then, the basic single-antenna CSA is presented and the optimal transmit power design under different types of power constraints is discussed. Furthermore, the multi-antenna CSA is presented and the channel information acquisition and transceiver beamforming are discussed. After that, the transmit and receive design for CR multiple access channel and broadcasting channel are presented, which is followed by the discussion of the robust design for the multi-antenna CSA. Finally, the application of CSA to operating LTE in the legacy licensed band, as known as spectrum refarming, is provided.

Chapter 5 presents the applications of blockchain techniques to support DSM. Generally, the use of the blockchain technologies can achieve the improvement of the decentralization and security, as well as the reduction in the administration cost. We investigate the basic principles of applying the blockchain technologies to spectrum management and practical implementation of blockchain over the CR network. Moreover, the recent literatures are reviewed, and the challenges and the future directions are also discussed.

Chapter 6 presents the applications of AI techniques to support DSM. With the help of AI techniques, the spectrum management would be achieved in a more flexible and efficient way, meanwhile obtaining performance improvement. This chapter starts with the basic principle of AI. Then, a review of ML techniques, including the statistical ML, deep learning and reinforcement learning is presented. After that, the recent applications of AI techniques in spectrum sensing, signal classification and dynamic spectrum access are discussed.

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