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Cognitive Radio for Dynamic Spectrum Management

Lector Materials

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Lessons content

Key Topics

Week	Topic description
7.	Cognitive Radio for Dynamic Spectrum Management
8.	Spectrum Sensing Theories and Methods
9.	Concurrent Spectrum Access
10.	Blockchain for Dynamic Spectrum Management
11.	Artificial Intelligence for Dynamic Spectrum Management
12.	ML for Spectrum Sharing, ML for Signal Classification, Deep Reinforcement Learning for Dynamic Spectrum Access
13.	

Week 7. Lector Content

This chapter covers the following content:

- Radio Spectrum Overview
- Dynamic Spectrum Management
  - Opportunistic spectrum access
  - Concurrent spectrum access
- Cognitive Radio for Dynamic Spectrum Management
- Artificial Intelligence for Dynamic Spectrum Management

1.1 Radio Spectrum

- 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, when 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.

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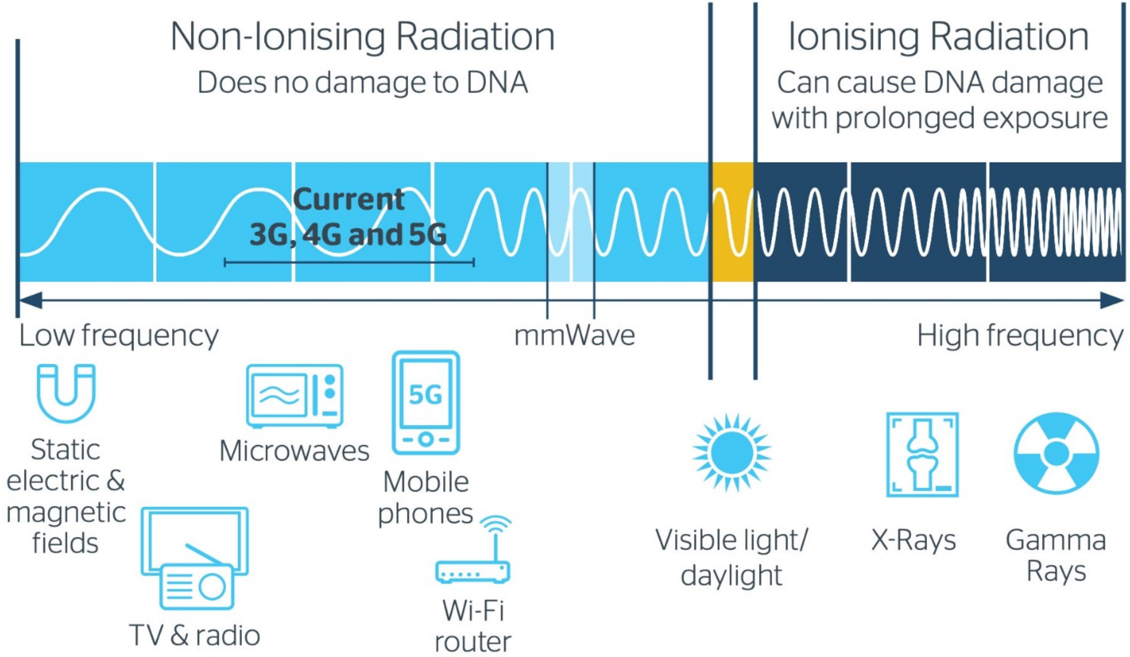
Radio Spectrum
As a Resource

Radio spectrum is a natural but limited resource that enables wireless communications



New wireless services:

- heavy traffic,
- massive connections
- various quality-of-services (QoS) requirements

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Radio Spectrum

Distribution

- Regulation of government agencies (FCC, Ofcom, Úrad pre reguláciu elektronických komunikácií a poštových služieb …):
  - GSM-800: 790 – 862 MHz
  - GSM-1800: 1805 – 1880 MHz
  - GSM-2600: 2500 – 2690 MHz
- 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.
- Only the authorized users, also known as licensed users, have the right to utilize the assigned spectrum
- FSA can successfully avoid interference among different applications and services

5G	700
5G	900
5G	1800
5G	3400-3800
5G	24,25-27,50GHz 31,80-33,40GHz 40,50-43,50GHz

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Radio Spectrum

Fully Allocated but Underutilized

- 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%.
- In Singapore, the average occupancy over 80–5850 MHz band is less than 5%, Chicago 0–3 GHz - 17,4% and Virginia low as 1%.
- 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.

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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

Dynamic Spectrum Management

- In DSM, the users without license (unlicensed users), also known as secondary users (SUs), can access the spectrum of authorized users
- authorized users also known as primary users (PUs)
- if the primary spectrum is idle, then PUs 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

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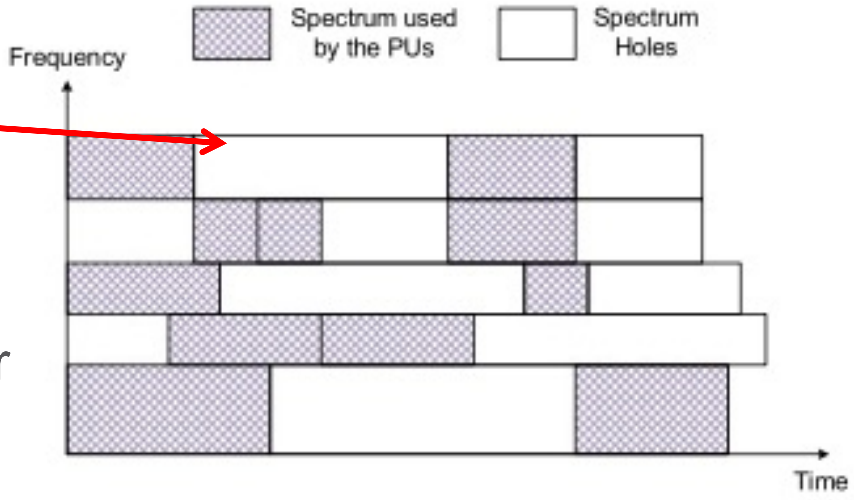
Dynamic Spectrum Access

- 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:
  - the opportunistic spectrum access (OSA) model and
  - the concurrent spectrum access (CSA) model.

Opportunistic Spectrum Access

- A spectrum usage in the OSA model is illustrated like:
- 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.



Opportunistic Spectrum Access

- To enable the operation of the OSA, 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
  - 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:
  - Geolocation database
  - Spectrum sensing

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

Spectrum Sensing

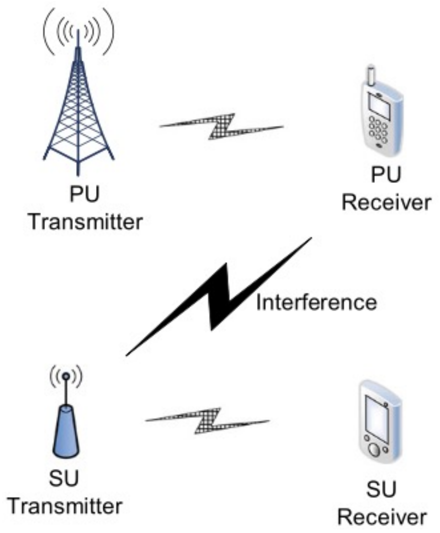
- Without a geolocation database, an SU can carry out spectrum sensing periodically or consistently to monitor the primary spectrum and detect the spectrum holes
- When there are multiple SUs, cooperative spectrum sensing can be applied to improve the sensing accuracy
- Different from the previous method 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*

Spectrum Sensing

- To measure the performance of spectrum sensing, two main metrics, i.e., the probability of detection and the probability of false alarm, are used
- probability of detection - probability of detecting the PU as being present when the PU is active indeed
- probability of false alarm - probability of detecting the PU as being present when the PU is actually inactive
- a good design of spectrum sensing should have a high probability of detection but low probability of false alarm
- current standards developed such as IEEE 802.22 and ECMA 392 still use a combination of geolocation database and spectrum sensing

Concurrent Spectrum Access

- A spectrum usage in the CSA model is illustrated like:
- 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



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Concurrent Spectrum Access

- for example, a user in a 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
- 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

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

- a hybrid spectrum access model combines the benefits of OSA and CSA, which gains higher spectrum utilization

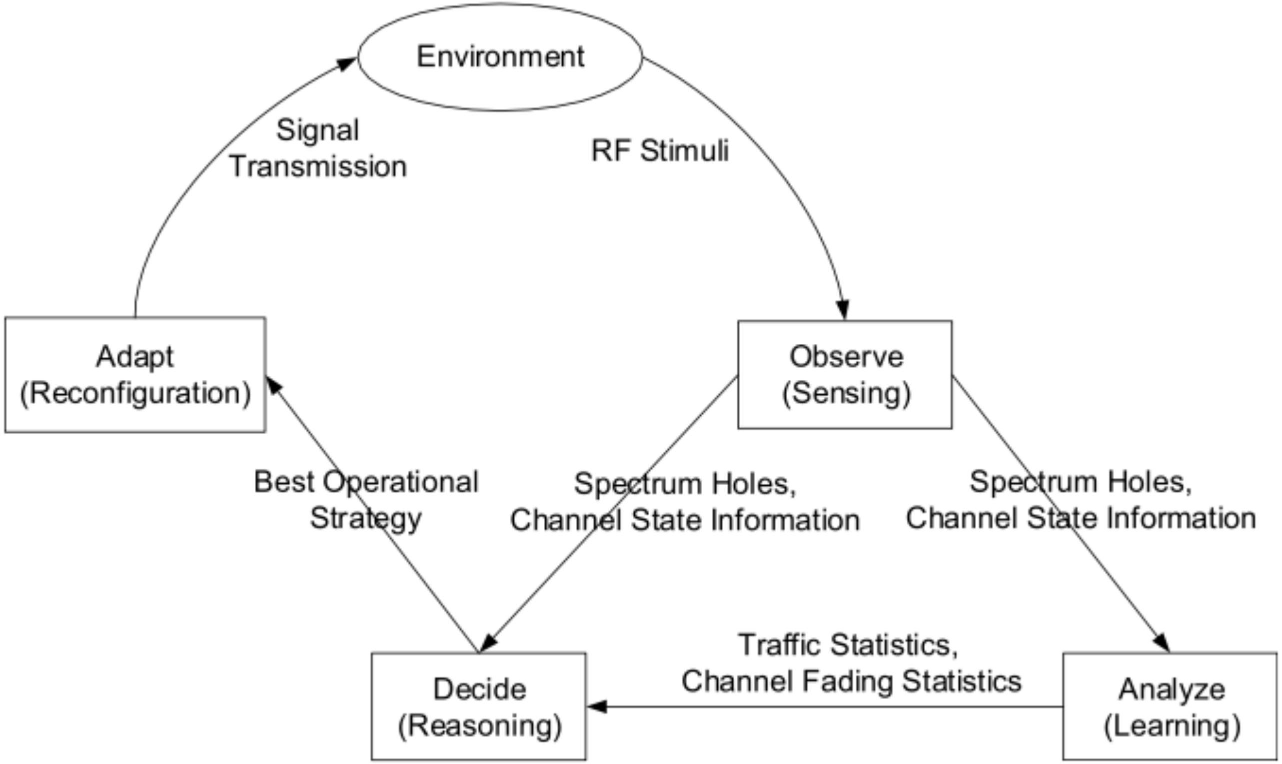
1.3 Cognitive Radio for Dynamic Spectrum Management

- 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 inter-action 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.

Cognitive Radio Overview

- 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 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)

Cognitive Cycle



Cognitive Cycle

- 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.

Open the Spectrum

- 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
- 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
- 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

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CR standards

- 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
- the standard specifies an air interface (both PHY and 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 first international CR standard on the use of personal/portable devices over TV White Spaces is ECMA 392

Other Standards

- the first edition of the standard was finalized by ECMA International based on the draft specification contributed from cognitive networking alliance (CogNeA)
- it specifies an air interface as well as a MUX sublayer for higher layer protocols, which is targeted for in-home, in-building and neighborhood-area applications in urban areas
- 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 5GHz unlicensed bands for the operation of LTE

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1.4 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]
- 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
- nowadays, AI has become one of the hottest topic both in the academia and in the industry

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AI in CR

- 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
- 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

Machine Learning techniques

- Generally, there are three branches of the ML techniques:
  - **Statistical Machine Learning** using statistical models (SVM, K-nearest neighbor (KNN), K- means and Gaussian mixture model (GMM))
  - **Deep Learning** based on approximate functions (CNN) for image data and recurrent neural network (RNN) for temporal data
  - **Deep Reinforcement Learning** (deep Q-network (DQN), double deep Q-network (DDQN), asynchronous advantage actor-critic (A3C) and deep deterministic policy gradient (DDPG))

Machine Learning techniques

- Many research organizations have been investigating on the applications of AI techniques to the dynamic spectrum management
- 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
- 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

AI benefits

- Using the machine learning and AI techniques, the model-based schemes in the traditional DSM can be transformed into data-driven ones and 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.

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AI benefits

- **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.

AI benefits

- **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.

- it is believed that the DSM would be achieved in a more efficient, robust, flexible way by applying AI and machine learning techniques

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Next lessons content

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