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Cognitive Radio Networks: A Survey

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***Abstract*— Cognitive Radio (CR) technology is developed to overcome the spectrum scarcity due to rapid development in wireless networks. Both licensed and unlicensed users can utilize the spectrum using this technology. Spectrum is allocated dynamically in cognitive radio networks thus it increases the spectrum utilization. The unlicensed users can transmit in the vacant spectrum already assigned to licensed users with minimum level of interference. It senses the spectrum to find the vacant spectrum and choose the best spectrum which meets the required QoS of the unlicensed users. The unlicensed users leave the spectrum whenever the licensed users return. This paper tries to give a comprehensive description of cognitive radio and its functions such as spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility.**

***Index Terms*—Cognitive radio, spectrum sensing, spectrum decision, spectrum sharing, spectrum mobility.**

I. INTRODUCTION

With the rapid development in communication applications the spectrum becomes more congested and also the need for data rate increased. Radio spectrum is a limited resource and the service is allocated by fixed spectrum assignment. So some frequencies are heavily used and other bands are weakly used. The number of devices utilizing the unlicensed spectrum is growing, which indicates the increase in spectrum demand. So spectrum scarcity is a major issue faced by wireless networks. In order to overcome this issue Dynamic spectrum access (DSA) is introduced, which improves the spectrum efficiency. In DSA the unlicensed systems are allowed to use the licensed bands without interfering the existing user. So the weakly used spectrum can be used by other users. Cognitive Radio (CR) uses dynamics spectrum allocation which provides higher bandwidth and efficient spectrum usage. CR enables to reuse the licensed spectrum in unlicensed manner i.e., it open the licensed bands to unlicensed users to use them without causing any interference to the licensed user. Radio sensing, self-adaptation and dynamic spectrum sharing are the abilities of CR. Spectrum underutilization and spectrum scarcity can be mitigated by an efficient spectrum usage of CR.

CR network contains two types of users: primary user (PU) and secondary user (SU). Licensed users are PU. They have the higher priority to access the channel. SU are unlicensed user. They can access the spectrum only in the absence of the PU. The SU can use the channel without causing any interference to the PU. SU wants to leave the channel when the PU reappears. SU is also called as Cognitive Radio (CR) user. CR users choose the vacant portion of the spectrum which can meet its QoS.

Paper is organized as follows: background concepts and functions of cognitive radio are overviewed in section II. In section III, various spectrum sensing techniques are explained and compared. Spectrum decision is briefed in section IV. Spectrum sharing classifications are described in section V and in section VI various spectrum mobility strategies are compared. Finally, the paper is concluded.

II.COGNITIVE RADIO

Cognitive radio is a radio which alters its transmission parameters according to the environment in which it operates. Cognitive radio is dynamic in nature. The main objective of CR is to choose the best spectrum. The CR user senses the spectrum in order to find the vacant one. The vacant spectrum is called as the spectrum holes or white space. CR user continues its transmission until the PU reappears otherwise it leaves the spectrum as illustrated in Fig. 1 [8]. The CR user should be aware about the interference level with the PU. For seamless transmission it moves to new vacant spectrum.

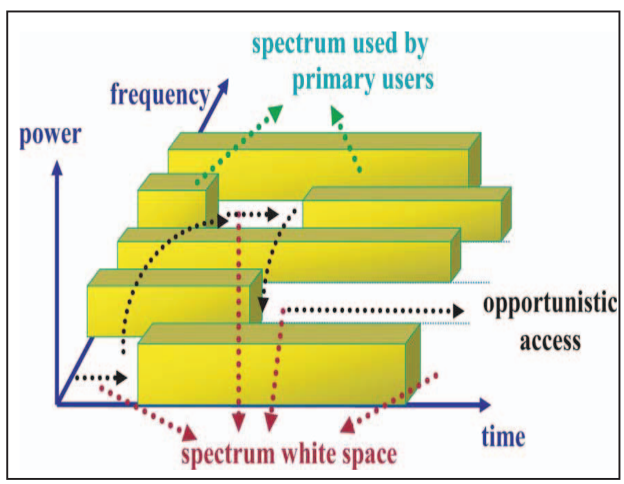

Fig.1. Spectrum hole concept

The CR transceiver contains a Radio Frequency (RF) unit, analog to digital converter and baseband processing unit. RF and analog to digital converter together called as the RF front end. General CR transceiver is shows in Fig. 2 [2]. The RF front end amplifies the received signal and it converted to digital signal. Then the signal is modulated/demodulated and encoded /decoded at the base processing unit.

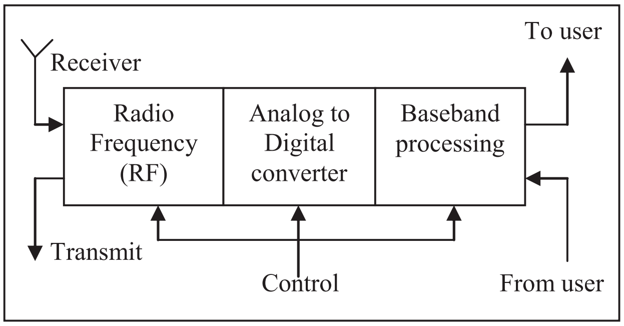

Fig.2. Cognitive radio transceiver

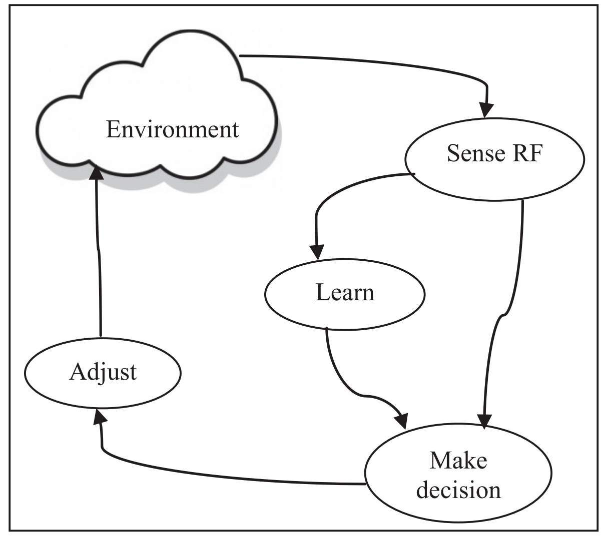

Fig.3. Cognitive cycle

The main characteristics of cognitive radio are:

- Cognitive capability: It refers to the ability of CR node to sense and gather the information such as transmission frequency, bandwidth, power, modulation, etc from its environment. By appropriate sensing the SU can choose the best spectrum by adjusting the parameters.
- Reconfigurability: It adjusts the parameters such as operating frequency, modulation, transmission power, etc. based on the gathered information without any modification in hardware components [13].

The main functions of CR are illustrated in Fig. 3. The CR senses the environment and collects the information. Based on this it make a decision and adjust the parameters. These functions are named as spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility.

- Spectrum sensing: CR senses the spectrum and determines the spectrum holes. Also it captures their information.
- Spectrum decision: Out of the sensed spectrum the CR selects the best spectrum and determines the transmission parameters.
- Spectrum sharing: It coordinates the spectrum access with other users.
- Spectrum mobility: SU vacate the channel when the licensed user reappears. For continuous transmission the CR user moves to another spectrum hole.

III. SPECTRUM SENSING

Channel selection and spectrum hole detection are the main functions of spectrum sensing. CR should be aware of the surroundings. Normally, CR senses the spectrum in order to find the presence of PU. More the sensing time, the gathered information will be more accurate. But it decreases the transmission time. In cooperative sensing, the sensing time can be decreased due to the cooperation between the users. Spectrum sensing can be classified into:

A. Primary transmitter detection

Primary transmitter detection detects the weak signal from primary transmitter [11]. It is also called as non-cooperative detection. The CR user configures itself based on the information sensed. Different non-cooperative sensing techniques are:

- Energy detection: *CR* user sense the presence of PU by analyzing the energy of the received signal. If the energy of the signal is greater than the threshold then PU is present otherwise PU is absent [14]. Threshold value is calculated based on the channel condition.
- Matched filter detection: It gives optimal detection in AWGN channel and maximizes the SNR. Prior knowledge of signal is required in matched filter feature detection. The received signals are compared with the primary user signals. Main advantage of matched filter is it needs less time to attain high processing gain [9]. If the prior knowledge such as modulation type, pulse shape, packet format are incorrect then it performs poorly.
- Cyclostationary feature detection: In cyclostationary detection, the PU transmissions can be detected by analyzing the cyclostationary features of received signals [3]. The cyclostationary features can be periodicity in signal, mean, autocorrelation. It has the ability to differentiate the noise from PU signal. If the autocorrelation of the received signal is calculated as

zero indicates the absence of PU i.e. there is only noise. Cyclostationary detection is a complex method. Comparison of primary transmitter detection techniques are given in Table I.

TABLE I. COMPARISON OF PRIMARY TRANSMITTER DETECTION

Spectrum sensing techniques	**Advantages**	**Disadvantages**
Energy detection	Does not require any prior knowledge about the PU signal so it is easy to implement.	Difficult to differentiate the signal types.
Matched filter detection	Short time is required to achieve probability of false alarm and high gain.	Require prior knowledge about the user and it consumes more power.
Cyclostationary feature detection	It can easily differentiate the signal types and the hidden PU problem can be minimized by high probability of detection	Require partial information about the primary user and high implementation cost.

B. Primary receiver detection

In primary receiver detection, it detects the primary users that are receiving data within the communication range of CR user [5]. Sensing time can be reduced due to the cooperative sensing, so the transmission period is large. Thus the throughput can be increased in cooperative sensing. Hidden terminal is a problem faced by CR network. Due to fading and shadowing CR become unable to sense the presence of the PU. It decreases the overall performance of the network. It can be overcome by cooperative sensing or primary receiver detection.

C. Interference temperature management

The interference to the PU must be controlled by limiting the transmitting power of CR user. The transmitting power of the CR user should be below the interference limit and then it can transmit through the channel without any interference to PU [1].

D. Issues in spectrum sensing

- Interference temperature measurements: In most of the works CR user is unaware about the current location of PU due to the lack of communication between PU and CR network. It causes interference with the PU. So a better technique is required to measure the interference level.
- Spectrum efficient sensing: CR user cannot do sensing while transmitting. In order to sense the channels, the CR user wants to stop the transmission. It delays the transmission and also it affects the spectrum efficiency.

IV. SPECTRUM DECISION

Out of the sensed spectrum, the CR network should decide the best spectrum to meet the QoS. Spectrum decision is affected by the activities of CR user. Spectrum decision includes spectrum characterization, spectrum selection and reconfiguration. Initially the spectrum is characterized based on the sensed information and the spectrum which meets the required QoS is selected. Then, the bandwidth (parameters) for the transmission is reconfigured. Spectrum can be characterized by interference, path loss and link layer delay.

A. Interference

CR node can calculate its power based on the amount of interference at the PU. Proper power allocation decreases the interference as well as increases the channel capacity.

B. Path loss

Path loss depends upon the distance and frequency. If the operating frequency increases, the path loss also increases but it decreases the transmission range. In order to reduce the path loss, the transmission power can be increased but it increases the interference to other users [7].

C. Link layer delay

Different types of link layer protocols are needed to represent the interference, path loss which results in different link layer delays [11].

D. *Issues in spectrum decision*

- PU activity modelling: Several characteristics of primary networks cannot be modelled using simple ON-OFF model. Inaccurate model adversely affect the spectrum sensing. Practical models are to be developed which considering the access technology and traffic types.
- Joint spectrum decision and reconfiguration: Once an appropriate spectrum is selected by considering the QoS, the spectrum characters may change with time. So it should be reconfigured with time. Optimal combination of spectrum decision and reconfiguration are to be considered according to the applications.

V. SPECTRUM SHARING

Spectrum sharing is the distribution of spectrum among the CR users according to the usage. It coordinates the channel access to maintain the QoS of the CR users without causing

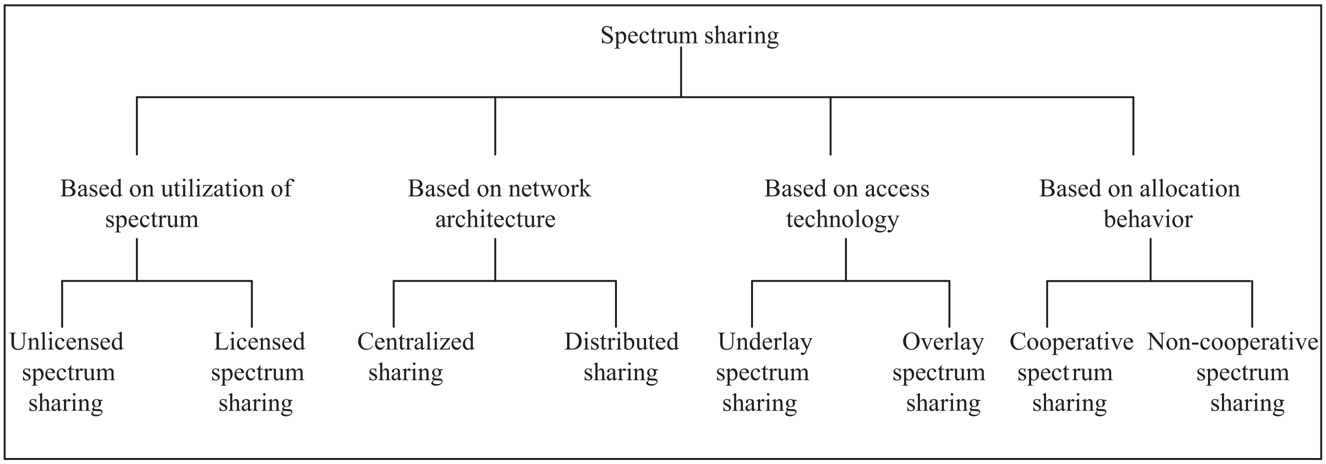

Fig.4. Spectrum sharing classification

interference to the PU. Spectrum sharing shares some features of spectrum sensing. Sharing techniques include sharing among multiple CR networks and sharing inside the CR network. Classification of spectrum sharing has been showed in Fig.4.

A. *Based on utilization of spectrum:*

- Unlicensed spectrum sharing: In unlicensed spectrum sharing, all the users have same priority. SU can access only the unlicensed spectrum. If the spectrum is free then the user can access the spectrum.
- Licensed spectrum sharing: Channel access is based on the priority. PU has the higher priority to access the channel. SU can access the channel only in the absence of PU.

B. Based on network architecture:

- Centralized sharing: In centralized spectrum sharing, a central entity controls the spectrum access and allocation. Each user in a network forwards their requirements and information to the central entity. Based on this the central entity constructs the spectrum allocation map.
- Distributed sharing: Distributed spectrum sharing is used where infrastructure construction is impossible. Each node is responsible for the spectrum access and the allocation.

C. Based on access technology

- Underlay spectrum sharing: CR users are allowed to transmit along with the PU without causing any interference to PU in underlay spectrum sharing. Usually spread spectrum techniques are used to fully utilize the spectrum by SU [8].The CR user need to control their power below the threshold value to minimize the interference to PU.
- Overlay spectrum sharing: In overlay spectrum sharing, the CR user uses the spectrum only in the absence of PU. So it minimizes the interference with PU and utilization of spectrum [12].

D. Based on allocation behavior:

- Cooperative spectrum sharing: It is also called as collaborative spectrum sharing. It considers the effect of each node communication on other nodes [2]. The interference measurements of each node are shared among other nodes. Cooperative sharing have better throughput compared to non- cooperative sharing.
- Non-cooperative spectrum sharing: It is also called as non-collaborative spectrum sharing. In non cooperative spectrum sharing, the nodes never exchange their interference measurements to other nodes.

E. Issues in spectrum sharing:

- Location information: SU can calculate the interference level by knowing the location and transmit power of PU. The information about the location and transmit power of PU may not be valid always.
- Distributed power allocation: In distributed sharing scheme, the transmission power f node is calculated in distribute manner without any central entity. So a network should select power control methods adaptive to the environment [6].
- Topology discovery: Usage of non-uniform channel by different CR users causes difficulty in finding the topology. Those CR users can't send periodic signals to other CR nodes within the range.

TABLE II. COMPARISON OF SPECTRUM SHARING TECHNIQUES

Spectrum sharing		**Advantages**	**Disadvantages**
Based on utilization of spectrum	Unlicensed spectrum sharing	Free to use	Only unlicensed spectrum can use
	Licensed spectrum sharing	Spectrum utilization increases	Cause interference to PU
Based on network architecture	Centralized sharing	It is easier to develop	High computational expense and information overhead
	Distributed sharing	It is flexible	High information interaction between nodes
Based on access technology	Underlay spectrum sharing	Increase the spectrum utilization	Improper power allocation will cause interference to PU
	Overlay spectrum sharing	Interference to PU is minimum	Spectrum utilization is minimum
Based on allocation behavior	Cooperative spectrum sharing	Increase throughput	Accurate information is needed for proper sharing
	Non-cooperative spectrum sharing	It is suited for small network	High interference

VI. SPECTRUM MOBILITY

The CR user wants to vacate the spectrum whenever the PU arrives to a specific spectrum. In order to continue the communication the PU moves to another vacant spectrum. This is spectrum mobility. Main function of spectrum mobility is spectrum handoff. In order to provide seamless communication the CR user moves to vacant spectrum which can maintain the QoS requirements. Spectrum mobility can occur due to link failure, PU reappearance, and CR user mobility. Different handoff strategies are:

A. Non-handoff strategy

In non-handoff strategy, the CR user remains idle until the channel becomes free i.e. the CR user takes the current channel as its next target channel. Its main disadvantage is wastage of CR user time. The CR user can transmit the data when the channel becomes free. Next disadvantage is high waiting latency.

B. Pure reactive handoff strategy

In pure reactive handoff strategy, the CR user switches the spectrum only after detecting the link failure i.e. CR applies reactive spectrum sensing and reactive handoff action. Delay in spectrum sensing is the major disadvantage in this handoff.

C. Pure proactive handoff strategy

In pure proactive handoff strategy, CR user switches the spectrum before the detection of link failure because the CR user has the ability to predict the future i.e. CR applies proactive spectrum sensing and proactive handoff [10]. CR users perform the spectrum sensing to provide a backup channel before the handoff triggering occurs. Advantage is it has low handoff latency. It can plan everything in advance. Overall spectrum mobility performance can be degraded by poor spectrum sensing.

D. Hybrid handoff strategy

Hybrid handoff combines pure reactive and pure proactive strategy. CR user prepares the target channel but it transmits to new channel only after the handoff triggering occurs. Faster spectrum handoff time can be achieved. Comparison of handoff strategies are given in Table III.

E. Issues in spectrum mobility

- Spectrum mobility in time domain: CR user selects the available spectrum for current transmission. The available spectrum changes as time goes. So enabling QoS requirements for entire transmission is a challenge.
- Spectrum mobility in space: As the user moves from one place to another, the available spectrum also changes. So the continuous spectrum allocation is a challenge.
- Energy efficiency: Spectrum mobility methods depend on the spectrum information update and spectrum sensing. Limited resources of CR node are a major factor of energy efficiency of network.
- Adaptive spectrum handoff strategy: Based on the PU traffic pattern the secondary user should apply the most suitable handoff strategy. Whenever the PU traffic patterns changes the SU adapt the handoff strategy accordingly.
- Switching delay: While moving from one spectrum to another, the switching time should be minimized. Otherwise the data transmission discontinued.

TABLE III. COMPARISON OF HANDOFF STRATEGIES

Handoff strategy	**Advantages**	**Disadvantages**	**Application**
Non-handoff strategy	Low PU interference	Unpredictable handoff latency	Applicable for short data transmission
Pure reactive handoff strategy	Accurate channel selection	Slow response	Well suited for short sensing time data
Pure proactive handoff strategy	Move faster to another channel	Poor sensing leads to performance degradation	Well suited for large sensing time data
Hybrid handoff strategy	Move faster to another channel	Moves only after the occurrence of interference	Applicable in general PU network

VII. CONCLUSION

In this survey, the fundamental concepts of cognitive radio, its functions and issues are presented. Spectrum is a valuable resource for wireless communication. CR sense and adapt their transmission parameters based on the environment. So, it solves the scarcity problem in wireless communication and also it increases the spectrum utilization. Sensing is the most important function of CR. Accuracy in sensing increase the performance of network. CR technology can be used in future wireless device to provide additional bandwidth, reliable broadband communications and versatility for rapid growing data applications.

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