Spectrum Sensing in Cognitive Radio: Components and Methodologies

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***Abstract*— Scarcity of available spectrum and the inefficient usage of the same motivated the researchers to look for solutions in Dynamic Spectrum Access (DSA). Cognitive Radio (CR) is the enabling technology for dynamic spectrum access. Cognitive devices are intelligent systems which can sense the idle license bands and can use these vacant spaces (called holes) to transmit the data. However, they are sensitive enough to detect the presence of licensed user. In this case they swiftly move to next optimum spectrum space. This paper describes the various dimensions of radio spectrum space, the hardware challenges associated and the various concerns associated with the domain. Cooperative sensing overcomes the problem of shadowing, fading, noise uncertainty and hidden primary user problem. Also, a detailed discussion and comparison of various spectrum sensing techniques is presented. These techniques can be categorized as blind detection methods and methods having prior knowledge.**

***Keywords:* Cognitive Radio (CR, Dynamic Spectrum Access, Fusion Centre, Primary User (PU), Primary User Emulation Attack (PUEA), Secondary User (SU), Spectrum Holes.**

I. INTRODUCTION

The proliferation of wireless devices have led to increased demand in spectrum utilization. Radio spectrum is a valuable but a scarce resource. According to fixed spectrum allocation policy [1], the systems were bound to operate within assigned frequency band. As a result there was spectrum inefficiency. This is attributed to the fact that when a system is not transmitting then the band goes unutilized. For instance, the channel-bands allotted to TV channels stay under-utilized at night time. In has been studied in [2] that based on temporal and geographical variations, the utilization of the fixed spectrum assignment is nearly 15-85%.

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Cognitive Radio (CR) is the enabling technology for Dynamic Spectrum Access (DSA) [3] [4]. The idea of cognitive radio was first conceived by Joseph Mitola III. The latin word 'Cognoscere' forms the root of term 'Cognition'. It means 'to know' [5]. The Federal Communications Commission (FCC) adopted the definition for cognitive radios as "Cognitive Radio: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets" [6]. CRs have the capability to sense the radio environment. They can choose the portion of spectrum that is unused. These portions are referred to as Spectrum Holes or White Spaces. Thereafter, the data can be transmitted on this chosen band without interference with the licensed user.

Primary Users (PU) are users having access rights to licensed spectrum band. On the other hand, Secondary Users (SU), have cognitive radio capabilities. They have the ability to sense the surroundings for availability of unused band. They request the PU to make use of this unused spectrum for wireless communication. PUs have higher priority over SUs. SUs exploit the spectrum in such a way so as to ensure that they do not cause interference to PUs.

The mechanism followed by Cognitive cycle is shown in figure 1. The various terminologies used in the figure are: *Spectrum Sensing:* Spectrum sensing is one of an important building block of cognitive radio. It involves the task of sensing the radio environment for the presence of spectrum holes and detection of PUs. *Spectrum decision:* Spectrum decision makes the optimum selection of spectrum hole to transmit the data. *Spectrum Sharing:* As there are several CR users sharing the same spectrum, there is a need for a mechanism which coordinates the network access to all specified CR users. *Spectrum Mobility:* If any primary licensed user is detected, then the CR should seamlessly switch over to some other suitable spectrum hole for further transmission [7].

The rest of the paper is divided into following sections. The components of spectrum sensing are presented in Section II. It describes the various dimensions of radio spectrum space, the hardware challenges associated and the various concerns that need to be addressed. Section III discusses in detail the different techniques for spectrum sensing. These include traditional techniques of blind detection and the techniques having prior knowledge. In addition some new techniques are also reviewed. Also, a comparison of these techniques is done in this section. Finally the paper is concluded in Section IV. References are appended at the end.

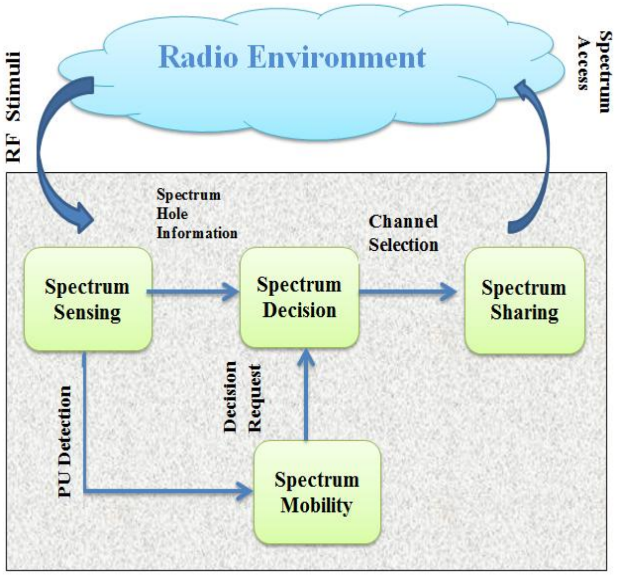

Fig. 1. Cognitive Cycle

II. COMPONENTS OF SPECTRUM SENSING

Spectrum sensing comprises of the dimension space, the hardware challenges, methodologies of spectrum sensing and concept of cooperative sensing. This is depicted in figure 2.

A. Radio Spectrum Space

It is *n* dimension space and spectrum holes are searched with in each one of them so that the secondary user can transmit the data over the unused spectrum. Different methodologies for radio spectrum space are given as [8]:

Frequency domain utilization: The frequency division multiple access (FDMA) utilization in cellular communication provides opportunity for unused small chunks of bands.

Time domain utilization: The use of time division multiple access (TDMA) in cellular communication offers unused spectrum for small chunk of time duration as an opportunity for SU usage.

Spatial domain utilization: In space dimension, the location (longitude, latitude and elevation) and the distance of PU are sensed, which allows unused spectrum in the area not filled by spectrum.

Code dimension: The sensing parameters in this dimension are: (i) Spreading code (ii) Frequency Hopping (FH) (iii) Time Hopping (TH). The data can be transmitted simultaneously on the orthogonal code to the code used by primary user without causing interference with the PU.

Angle dimensions: The sensing parameters of angle dimension are (i) beam directions of PU i.e azimuth angle and elevation angle (ii) location of PU. Here, spectrum space is created as per the fact that if PU is transmitting in some particular direction then SU can transmit in other direction, thus avoiding interference.

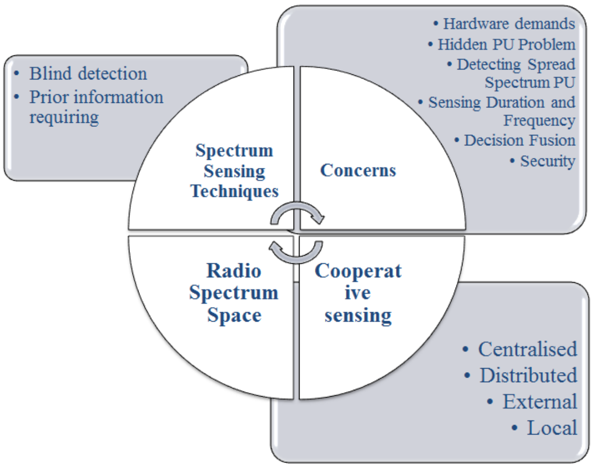

Fig. 2. Components of Spectrum Sensing

B. Challenges in Spectrum Sensing

Hardware Requirements: The implementation of CR users requires high resolution Analog to Digital Converters (ADCs), and high speed signal processors which increases the overall cost of the system.

Hidden Primary User Problem: The hidden primary user problem in CR is similar to hidden node problem in CSMA. The primary user transmitter and cognitive radio are out of range of each other. Each is communicating with the primary user. As CR and PU transmitter are out of range, they might transmit simultaneously. This causes interference at PU. The hidden PU problem can be solved by using cooperative sensing.

Detecting Spread Spectrum PU: It is difficult to detect primary users and specifically those that are using spread spectrum techniques as in this case, the power of PU is distributed over the large frequency range.

Sensing Duration and Transition Period: It is required that as soon as the unused spectrum is detected, the band should be vacated for SU. The real time implementation poses challenges that there is need for less sensing duration and transition period. The sensing period of 30sec is chosen by IEEE802.22 draft [8].

Security: Primary User Emulation Attack (PUEA) is one of the most common security threat. In PUEA, some malicious user tries to imitate like PU and clogs the idle frequency bands from being used by CR [9] [10].

C. Cooperative Spectrum Sensing

If multiple secondary users are present and are distributed at different locations, then it becomes essential for these secondary users to work in cooperative manner in order to achieve high reliability of spectrum sensing. CR users cooperate to share their sensing information for making a combined decision which is usually more accurate than individual decision. This scheme of cooperation has been suggested by researchers as an answer to issues like fading, shadowing and noise uncertainty. It reduces the probability

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of false alarm and mis-detection. Moreover, it solves the hidden primary user problem and reduces the sensing time [11]. The raw or processed data from each user is sent to a *data fusion center*. It processes this collected data and finally makes a decision. The implementation of cooperative sensing can be classified as centralized, distributed, external and relay assisted sensing [12] [13].

Centralized Sensing: In centralized sensing, there is a central unit called Fusion Center (FC) surrounded by many CRs. CRs performs the local sensing while FC acts as a base station and collects the sensing information from several CR devices. The final decision is made by FC [14].

Distributed Sensing: In distributed sensing, the CR devices share the information with each other. However, the decision is made independently about presence and absence of PU. The basic concept in this sensing technique is that the user closer to a primary transmitter enjoys better chance of its detection than the far-off users. Hence the closer user can share information with distant user [15].

External Sensing: In this sensing technique, an external device instead of CR performs the task of sensing. It then broadcasts the channel occupancy information to neighboring CRs. The issue of hidden primary user problem is conquered in this scheme. Also, the uncertainty due to fading and shadowing is reduced. Moreover, spectrum efficiency is enhanced as sensing time is now reduced.
Relay Assisted Spectrum Sensing: The process is similar to multi-hop sensing. Some CRs observe weak reporting channel but strong PU detection whereas other CRs sense strong reporting channel but weak PU detection.

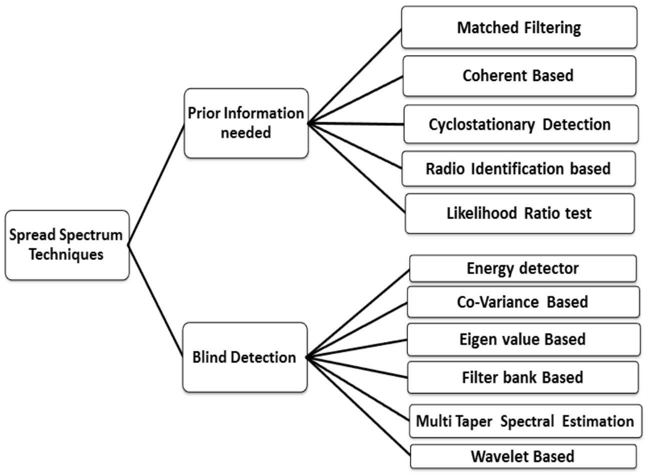

Fig. 3. Classification of Spectrum Sensing Techniques

Hence, CRs detecting strong PU send the information to those CRs which have strong reporting channel. Then these CRs send data to FC. This scheme offers benefits of higher probability of hidden user detection, lesser sensing time, prevention of shadowing effect and avoiding hidden user problem. However, there are few limitations like higher complexity and traffic overhead [16] [12].

III. SPECTRUM SENSING METHODOLOGIES

The main objective of sensing methods is to detect the spectrum holes so that the SU can use these vacant bands to transmit the data. The methods for spectrum sensing are classified in figure 3 and the description of each is given in the following sub-section. These methods are classified as 'Prior Information Needing' and 'Blind Detection' methods. In prior information needing, prior knowledge of various essential parameters of signal, channel and noise is needed whereas blind detection is free from such prior knowledge.

A. *Prior Information Needing*

1) Matched Filtering (MF)

In this methodology, the concept of matched filter detection technique is applied. Here an unknown signal $x(t)$ is convolved with filter impulse signal $h(t)$. Prior knowledge of bandwidth requirement, operating frequency, frame format, pulse shaping and modulation types etc. is needed [17].

The advantage offered by Matched filtering technique is that it offers high probability of detection in less sensing time. It is considered as the best method in this category. Even with less signal samples detection is good. It is robust to noise uncertainty. Moreover, it offers good detection even at low SNR. On the other hand, the implementation is quite complex and involves large power consumption. In addition, there is a need for precise information about certain waveform patterns of PU [18].

2) Cyclostationary Detection (CSD)

This method utilizes the cyclostationary features like operating frequency, required bandwidth, frame format and modulation types from received signal of PU statistics like mean, cyclic correlation and autocorrelation; or periodicity in the signal causes cyclostationary features [19]. The robustness to uncertainty in noise power and propagation channel makes it attractive. However, there is need for high sampling rate. Need for large samples adds to the complexity. Also, the sensing time is high [20].

3) Coherent detection

In coherent detection, preambles, mid-ambles and pilot patterns are regularly transmitted. A preamble is a sequence (known already) which is sent before each slot. The sequence which is transmitted in the middle of the slot is known as mid-amble. When the information of these known patterns is available, received signal is correlated with its own known copy. Thus it assists in signal detection [21].When there is long known primary signal pattern, the accuracy gets better. The stumbling block of this method is that huge amount of information is needed for the signal patterns of the primary user to witness high performance.

4) Radio Identification Based Detection

The main concept used in this technique is to identify the presence of some known technology and to achieve communication using this technology. If the technology used by primary user for transmission is known, then good knowledge can be derived about the spectrum characteristics. In addition it imparts higher accuracy. Eg: if the primary user is using bluetooth, then the CR can use this

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information to gain some knowledge in space dimension. Here, it uses the knowledge that bluetooth operates in the range of 10m. Then CR device may use bluetooth to communicate for some applications in the range supported by bluetooth. The detection process is highly accurate, has average sensing time. Also, it is robust to SNR. Never-the-less, high power consumption due high complexity makes it unattractive [22].

A. *Blind Detection*

1) Energy Detector

Energy detector is the most commonly used method commercially. The decision is made by comparing the output of signal detector with a fixed threshold value which helps in deciding the presence or absence of PU [22]. The attractive feature of this methodology is that it is simple and easy to implement. It consumes low sensing time and has low power consumption. But the noise uncertainty leads to increase in probability of false alarm. It is very unreliable in low SNR regime. Also it is unable to distinguish between PU from other signal source. This technique has low accuracy as compared to other techniques [23] [24] [25]. An energy detector is ineffective in detecting spread spectrum signals [26].

2) Co-variance Based Sensing:

The spectrum sensing using co-variance technique works on the concept of comparison between covariance of the detected signal with the covariance of noise [27] . The probability to differentiate between signal and noise is too high even at low values of SNR. The power consumed is low though increased complexity and increased computational overhead are the weakness of this methodology. Moreover, it has low detection performance and proves inefficient in case of spread spectrum signal [28].

Table 1 gives a comparison of above discussed techniques in terms of several essential parameters. This comparison can prove useful in selecting a technique for a particular application.

B. *Other Sensing Techniques*

1) Wavelet Based Sensing

Wavelets are used to detect the edges in the Power Spectral Density (PSD) of a wideband channel [29]. Edges correspond to transitions from empty band to occupied band and vice versa. When these edges are detected, the powers between two edges can be estimated. Thus with the help of this information and knowing the edge positions, it can be known whether the band is occupied or fallow in a binary fashion. The article in [30] extends the idea of wavelet based detection by employing sub-Nyquist sampling. If the signal spectrum is sparse then a coarse spectrum can be obtained with sub-Nyquist sampling.

TABLE 1: COMPARISON OF SPECTRUM SENSING TECHNIQUES

	Prior Information needed				Blind Sensing	
	CD	MF	CF	RB	ED	Co
Prior information needing	Yes	Yes	Yes	Yes	No	No
Sensing Time	***	***	***	**	*	**
Robustness against SNR	***	***	***	**	*	**
Detection Performance	**	***	*	**	*	*
Complexity	**	***	**	**	*	**
Accuracy	***	***	*	**	*	**
Power Consumption	**	***	***	***	*	*
*** High ** Medium *Low						
CD-Coherent Detection; MF-Matched Filter; CF-Cyclostationary Feature detection; RB- Radio Identification Based ED- Energy Detector; Co- CoVariance Based						

2) Eigenvalue Based Sensing: The two major eigen-value based sensing are:

- Maximum-Minimum Eigenvalue Detection (MME): It uses the concept similar to energy detection. It does not require any prior knowledge of the signal and the channel. This eliminates the issue of synchronization as no synchronization is required. The ratio of maximum eigenvalue to the minimum value is utilized to detect the signal. For this Random matrix theories (RMT) are employed. The ratio is quantized to find the threshold value [31].

- Energy with Minimum Eigenvalue (EME) Based Detection: In EME, the detection process is carried out using the ratio of the signal energy to the minimum eigen-value [27]. Now the question arises that how is ED different form EME. ED compares the signal power to the noise power. This noise power needs to be evaluated in advance. However, EME compares signal energy with the minimum eigen-values of the sample covariance matrix, which is computed from the received signal only.

Both the eigen-value techniques use the received signal samples for detection. They do not need information about the transmitted signal and channel. The advantage offered by EME over ED is that latter requires noise power for detection while former is free from this requirement.

3) Multi Taper Spectral Estimation (MTSE)

It is an approximation of maximum likelihood PSD estimator with an advantage that it has lower complexity. It is nearly optimal for wideband signals [1].

4) Random Hough Transform

Random Hough transform of received signal is proposed in [32]. It is used to detect the radar pulses in the operating

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channels of WLAN systems. This algorithm can be used to observe any type of signal with a periodic pattern.

5) Filter Bank Based Spectrum Sensing (FBSE)

FBSE is considered as simplified version of MTSE. It uses only one prototype filter for each band. It has been proposed for multi-carrier modulation based CR networks. A pair of matched Nyquist filters is used for this purpose. It uses the concept that maximum energy is concentrated in the bandwidth fc -W to fc +W. CR users explore this information to identify if the spectrum is occupied or not. FBSE performs better for large number of samples as compared to MTSE which requires small number of samples for its operation [33].

IV. CONCLUSION

The swelling demand for wireless communication has led to scarcity of radio resources. Some of the bands are over utilized, whereas some are under-utilized. In an endeavor to efficiently tap these under-utilized bands, the researchers are relentlessly studying this field of great importance. Dynamic spectrum access provides the answer to this issue and cognitive radios is the enabling technology for the same.

This paper presents the components and aspects of spectrum sensing. The dimensions of radio spectrum space and the hardware challenges like hidden primary user problem, security attacks, sensing duration are described in detail. The issue of shadowing, fading, noise uncertainty and hidden primary user problem can be overcome by employing cooperative spectrum sensing. In cooperative spectrum sensing the CR users cooperate to share their sensing information for making a combined decision which is usually more accurate than individual decision. The final decision is made at the fusion centre. Centralized sensing, distributed sensing, external sensing and relay assisted sensing are some of the types of cooperative spectrum sensing techniques. Further, different techniques of spectrum sensing are explored and compared. These techniques can be categorized as blind detection methods and methods having prior knowledge. Energy detection, a blind detection method is the most commonly used technique attributed to its simplicity of implementation and good sensing time. Matched filtering technique employs the concept of matched filter. A reversed time delayed signal is convolved with the impulse response. In addition to traditional spectrum sensing technique, some new methodologies are also outlined.

The future research direction points towards optimum selection of threshold value for detection of PU. Also, there is a need to find a balance between two opposing attributes like sensing time and throughput. Various machine learning techniques can be used to sense the licensed user.

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