Spectrum Sensing Techniques and Challenging Issues in Cognitive Radio

Samriti Kalia

Abstract

Cognitive radio is the most promising and reliable emerging technology which can utilize the scarce radio spectrum efficiently. In this technology the secondary (unlicensed) users need to find idle channels by spectrum sensing for their transmission. Spectrum sensing may be single user or cooperative. However cooperative spectrum sensing is considered better. In this paper simple overview on different spectrum sensing techniques in cognitive radio is given. Apart from that the various challenging issues in spectrum sensing are outlined.

Keywords - *cognitive radio, dynamic spectrum access, primary user, secondary user, spectrum sensing.*

I. INTRODUCTION

Wireless communication has been the fastest growing segment of the communication industry in the last decade. With the incredible growth in the number of wireless systems and services the availability of high quality wireless spectrum has become severely limited. However the spectrum is not scarce but the inefficient ways of utilizing has made it limited. This inefficiency results from the rigid regulations of spectrum allocation methods by government regulatory bodies. The fixed spectrum allocations give rise to inefficient use of spectrum. Since most of the channels actively transmit the information only for a short duration while the certain portion of the spectrum remains idle when the licensed or primary user (PU) are not transmitting. In order to change this scenario and to improve spectrum efficiency Cognitive Radio technology is the most optimum solution [1], [2].

This term was first defined by Joseph Mitola in 2002. Cognitive Radio(CR) is an intelligent wireless communication technology in which the secondary(unlicensed) users utilize the unused frequency bands owned by primary(licensed) users when they are idle without causing interference to licensed users. The unused licensed spectrum is called white space or spectrum hole. This opportunistic access of spectrum hole is
called dynamic spectrum access. In cognitive radio network(CRN), SU's should sense the spectrum before utilization in order to prevent interfering with the primary user. This is called spectrum sensing in CR. As soon as primary user (PU) becomes active for spectrum usage, the cognitive user switches to a different spectrum hole or may stay in the same band but alters the power level and modulation method for avoiding interference to the existing licensed users in that band [3]. Spectrum opportunities may be in time, space, frequency or angle domains depending on the context and systems. Secondary users (SU) are essentially invisible to PU in CR systems, hence possibly no changes are needed for licensed devices.

CR has four main functions: i) spectrum sensing ii) spectrum management iii) spectrum sharing iv) spectrum mobility.

Spectrum sensing aims to determine spectrum availability and the presence of the PU. Spectrum management is to predict how long the spectrum holes are likely to remain available for use to the SU or CR users. Spectrum sharing is to distribute the spectrum holes fairly among the SU's. Spectrum mobility is to maintain seamless communication requirements during the transition to better spectrum.

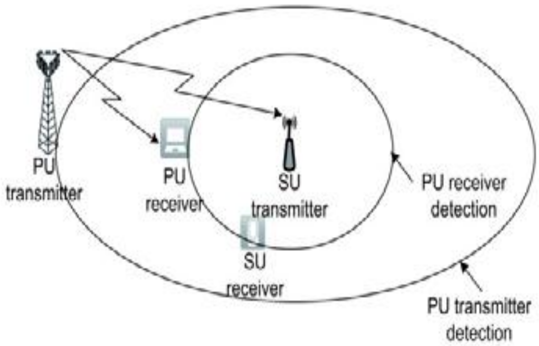

Fig. 1 Principle of Spectrum Sensing

Among all these functions spectrum sensing is the most challenging task to establish CRNs. Spectrum sensing estimation can be divided into direct and indirect methods. The direct method is recognized as frequency domain approach where the estimation is carried out directly from signal. Indirect method is called time domain approach where the estimation is performed using autocorrelation of the signal. Another way of classification depends on the need of spectrum sensing as stated below[4].

A. Primary Transmitter Detection

Detection of primary users is performed based on the received signal at CR user receiver. This method includes energy based detection, matched filter (MF) based detection, covariance based detection, waveform based detection, cyclostationary based detection, radio identification based detection and random Hough Transform based detection.

B. Primary Receiver Detection

In this method, spectrum opportunities are detected based on primary user- receiver's local oscillator leakage power.

C. Cooperative Detection

In this approach the primary user signal for spectrum opportunities are detected reliably by interacting or cooperating with other users and the method can be implemented as either centralized access to spectrum coordinated by a spectrum server or distributed approach implied by the spectrum load.

D. Interference Temperature Management

In this approach, CR system works as in the ultra wideband technology where the secondary users coexist with primary users and are allowed to transmit with low power and are restricted by the interference temperature level so as not to cause harmful interference to primary users[5]-[7].

II. VARIOUS SPECTRUM SENSING TECHNIQUES

A. Primary Transmitter Detection

1) Energy Detection

It is a non coherent detection method that detects the primary signal based on the sensed energy. Due to its simplicity and no requirement on a prior knowledge of primary user signal, energy detection (ED) is the most popular sensing technique in cooperative sensing.

The block diagram for the energy detection technique is shown in the Figure 2. In this method, signal is passed through band pass filter of the bandwidth W and is integrated over time interval. The output from the integrator block is then compared to a predefined threshold. This comparison is used to discover the existence or absence of the primary user. The threshold value can set to be fixed or variable based on the channel conditions.

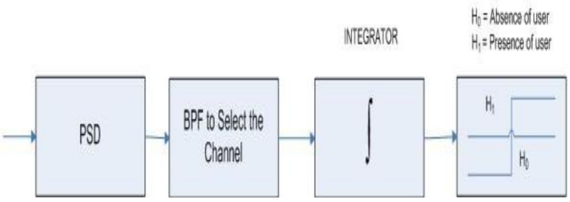

Fig. 2 Energy Detector Block Diagram

The ED is said to be the Blind signal detector because it ignores the structure of the signal. It estimates the presence of the signal by comparing the energy received with a known threshold derived from the statistics of the noise. Analytically, signal detection can be reduced to a simple identification problem, formalized as a hypothesis test

$Y(k)=n(k)$..................................H_0

$Y(k)=h * s(k)+n(k)$..................H_1

Where $y(k)$ is the sample to be analyzed at each instant k and $n(k)$ is the noise of variance σ^2, h is the channel gain between primary transmitter to CR receiver, $s(k)$ is the primary user's signal (to be detected). Let $y(k)$ be a sequence of received samples $k\epsilon\{1,2.....N\}$ at the signal detector, then a decision rule can be stated as,

H_0 .... if $\epsilon < v$
H_1 .... if $\epsilon > v$

Where $\epsilon = E|y(k)|^2$ the estimated energy of the received signal and v is the noise variance σ^2

This approach has some disadvantages. The poor choice of threshold value, poor performance under low signal to noise ratio (SNR) value and inability to differentiate between interference from licensed users and noise are major factors to limit the performance of this approach. In addition this approach cannot detect spread spectrum signals (e.g CDMA)

2) Matched Filter Detection

A matched filter (MF) is a linear filter designed to maximize the output signal to noise ratio for a given input signal. When secondary user has a prior knowledge of primary user signal, matched filter detection is applied. Matched filter operation is equivalent to correlation in which the unknown signal is convolved with the filter whose impulse response is the mirror and time shifted version of a reference signal. The operation of matched filter detection is expressed as:

$$Y[n] = \sum_{k=-\infty}^{\infty} h[n-k]\,x[k]$$

where 'x' is the unknown signal (vector) and is convolved with 'h', the impulse response of matched filter that is matched to the reference signal for maximizing the SNR.

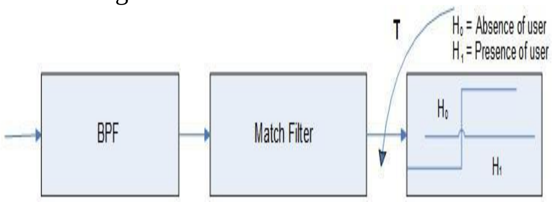

Fig. 3 Block Diagram of Matched Filter

However matched filtering has more disadvantages than its advantages: First it requires perfect knowledge of the primary user signalling features(such as modulation type, operating frequency etc). Second, implementation complexity of detector unit is very high because CR system needs receivers for all signal types of wide band regime. Lastly large power will be consumed to execute such several detection processes. Thus this approach is not a good choice for CR system due to its above mentioned disadvantages.

3) Cyclostationary Feature Detection

In this detection technique, CR can distinguish between noise and user signal by analyzing its periodicity. The cyclostationarity based signal detection takes advantage of cyclostationarity properties of the received signals to detect primary user transmissions. Generally the transmitted signals are stationary random process however the cyclostationary features are induced because of modulation of signals with sinusoidal carriers, cyclic prefix in OFDM, code sequence in CDMA. Whereas the noise is wide sense stationary with no correlation. Therefore , this method can differentiate primary users signals from noise. The filter is used to measure the energy around the related band and then FFT is computed. Correlation block will correlate the signal and feature. Thus cyclostationary feature detection is robust to noise uncertainties and perform better than energy detection in low SNR regions. This method has its own shortcomings due to its high computational complexity and long sensing time.

The comparison of different transmitter detection techniques for spectrum sensing and the spectrum opportunities is shown in figure 5. As it is evident from the figure, that matched filter based detection is complex to implement in CR's but has highest accuracy. Similarly, the energy based detection is least complex to implement in CR system and least accurate compared to other approaches. And other approaches are in the middle of these two.

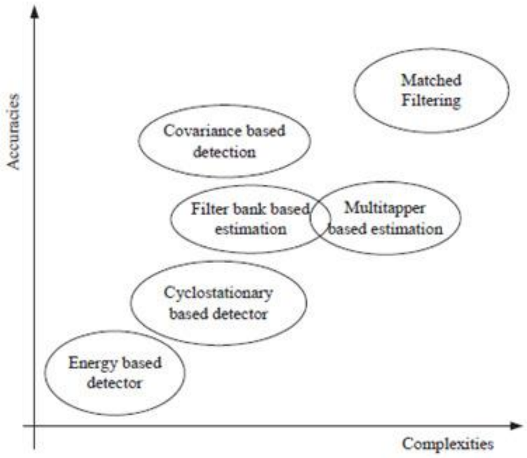

Fig.4 Sensing Accuracy and Complexity of Various Sensing Methods.

B. Cooperative Techniques

In cooperative detection, the spectrum estimation can be done by interacting or collaborating with other wireless users in order to get reliable and accurate information regarding spectrum opportunities. A single user may not detect the spectrum reliably when it is a hidden terminal or PU suffers from multipath fading and shadowing. Hence cooperative spectrum sensing get around with all these problems and is considered the best method of spectrum sensing. Cooperative sensing can be classified into three types according to their level of cooperation.

1.1.1) Centralized Coordinated Techniques: In such networks, an infrastructure deployment is assumed for the CR users. One CR that detects the presence of a primary transmitter or receiver, informs a CR controller which can be a wired immobile device or another CR user. The CR controller notifies all the CR users in its range by means of a broadcast control message.

1.1.2) *Decentralized Coordinated Techniques:* This type of coordination implies building up a network of cognitive radios without having the need of a controller. Various algorithms have been proposed for the decentralized techniques among which are the gossiping algorithms or clustering schemes, where cognitive users gather to clusters, auto coordinating themselves. The cooperative spectrum sensing raises the need for a control channel, which can be implemented as a dedicated frequency channel or as an underlay UWB channel.

1.1.3) Decentralized Uncoordinated Techniques: The cognitive users in the network don't have any kind of cooperation which means that each CR user will independently detect the channel, and if a CR user detects the primary user it would vacate the channel without informing the other users. Uncoordinated techniques are fallible in comparison with coordinated techniques. Therefore, CR users that experience bad channel realizations detect the channel incorrectly thereby causing interference at the primary receiver.

The main benefits of Cooperation are: i) It reduces the probability of miss-detection and false alarms. ii)This method can solve the hidden terminal (primary user) problem. iii) Reduces sensitivity requirements upto -25dBm and also reduces detection time[5], [7],[8].

C. Primary Receiver Detection

The other way to detect idle bands of licensed system is to detect primary user-receivers which are within the communication range of CR system users. In general, primary receiver emits the local oscillator (LO) leakage power from its RF front-end while receiving the data from primary transmitter. Using that leakage power, one can detect the primary signal. This approach does not introduce any modification to primary user devices however the CR system need to be equipped with sensor and communication capability to detect the primary receiver LO leakage power, and report to the CR transmitter. Using received information from sensors, the CR transmitters will identify the spectrum opportunities for given time and location to transmit their data.

D. Interference Temperature Management

Unlike the primary receiver detection, the basic idea behind the interference temperature management is to set up an upper interference limit for given frequency band in specific geographic location such that the CR users are not allowed to cause harmful interference while using the specific band in specific area. Typically, CR user transmitters control their interference by regulating their transmission power (their out of band emissions) based on their locations with respect to primary users.

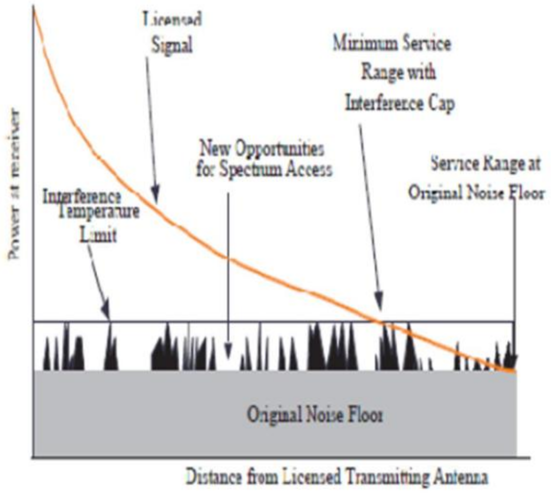

Fig.5 Interference Temperature Model

This method basically concentrates on measuring interference at the receiver. The operating principle of this method is like an UWB technology where the CR users are allowed to coexist and transmit simultaneously with PU's using low transmit power that is restricted by the interference temperature level so as not to cause harmful interference to the PU's. In this approach, CR users do not have to sense and wait for spectrum opportunities.[9]-[10] However the CR users can not transmit their data with higher power (when the licensed system is completely idle) because of imposed low transmit power and interference temperature limit.

E. Other Methods

1) Multi Taper Spectrum Sensing/Estimation

In Multi Taper Spectrum Sensing Estimation(MTSE) the last N received samples are collected in a vector form and represented it as set of Slepian base vectors. The main idea of this method is that the Fourier transforms of Slepian vectors have the maximal energy concentration in the bandwidth fc-W to fc+W under finite sample size constraints. By exploiting this feature, CR user can easily identify the spectrum opportunities in given band.

2) Filter Bank Based Spectrum Sensing

Filter bank based spectrum estimation (FBSE) is regarded as the simplified version of MTSE which uses only one prototype filter for each band and has been proposed for multi-carrier modulation based CR systems by using a pair of matched root Nyquist filter. FBSE uses the same concept of maximal energy concentration in the bandwidth fc-W to fc+W. By exploiting this information, CR user identifies the spectrum occupancy and hence the spectrum opportunities. MTSE is better for small samples whereas FBSE is better for large number of samples.

3) Wavelet based Detection

It is widely used technique in image processing for edge detection applications. In this approach, wavelets are used for detecting edges in the power spectral density (PSD) of a wideband channel. The edges in power spectral density are the boundary between spectrum holes and occupied bands and hence it helps to find vacant bands. Based on this information CR can identify the spectrum opportunities[11].

III. CHALLENEGES IN SPECTRUM SENSING

A. Channel Uncertainty

Channel fading or shadowing may cause higher interference. If the primary signal is experiencing a deep fade or being heavily shadowed by obstacles then secondary user may wrongly interpret that the primary user is located out of its interference range. Therefore, cognitive radios have to be more sensitive to distinguish a faded or shadowed primary signal from a white space. This issue may be handled by having a group of cognitive radios (cooperative Sensing) since a single cognitive radio will be unable to achieve this increased sensitivity.

B. Sensing Interference Limit

The net major challenge lies in the interference measurement at the licensed receiver caused by transmissions from unlicensed users. First, an unlicensed user may not know exactly the location of the licensed receiver which is required to compute interference caused due to its transmission. Second, if a licensed receiver is a passive device, the transmitter may not be aware of the receiver. So these factors need attention while calculating the sensing interference limit[12].

C. Noise Uncertainty

The detection sensitivity can be defined as the minimum SNR at which the primary signal can be accurately (e.g. with a probability of 0.99) detected by the cognitive radio and is given by

$$\gamma_{min} = \frac{PL(D+R)}{N}$$

Where N is the noise power, P is transmitted power of the primary user, D is the interference range of the secondary user, and R is maximum distance between primary transmitter and its corresponding receiver.

[13]The above equation suggests that in order to calculate the required detection sensitivity, the noise power has to be known, which is not available in practice, and needs to be estimated by the receiver.

However the noise power estimation is limited by calibration errors as well as changes in thermal noise caused by temperature variations. Since a cognitive radio may not satisfy the sensitivity requirement due to an underestimate of N, γ_{min} should be calculated with the worst case noise assumption, thereby necessitating a more sensitive detector.

D. Spectrum Mobility Issues

The spectrum mobility in cognitive radio allows the secondary user to change its operating spectrum dynamically based on the spectrum conditions. Spectrum mobility gives rise to a new type of handoff in CR networks, *spectrum handoff*. Protocols for different layers of the network stack must adapt to the channel parameters of the operating frequency. Moreover, they should be transparent to spectrum handoff and the associated latency. Each time a CR user changes its frequency of operation, the network protocols may require modifications to the operation parameters. The purpose of the spectrum mobility management in CR networks is to ensure smooth and fast transition leading to minimum performance degradation during a spectrum handoff. An important requirement of mobility management protocols is information about the duration of a spectrum handoff. This information can be provided by the sensing algorithm. After the latency information is available, the ongoing communications can be preserved with only minimum performance degradation[14].

IV. CONCLUSION

By exploiting the existing spectrum opportunistically cognitive radio technology is definitely going to shift the paradigm in wireless communication. In this paper various spectrum sensing techniques along with their advantages and disadvantages is presented and some spectrum sensing challenges are also mentioned. Cooperative spectrum sensing is better than classical spectrum sensing as it overcomes the hidden primary user problem, reduces false alarm and gives more accurate signal detection. However, to ensure efficient spectrum aware communication, more research is still required on the lines of above mentioned challenges.

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