International Journal of Research in Advent Technology, Vol.4, No.7, July 2016
E-ISSN: 2321-9637
Available online at www.ijrat.org

A Review of Cognitive Radio Spectrum Sensing Technologies and Associated Challenges

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Abstract- Spectrum under-utilization has become a focus area with emergence of data intensive wireless applications. Increased demand for spectrum has made it imperative to look for potential solutions to use the spectrum in a more efficient way. Cognitive Radio utilizes dynamic spectrum management and iswidely recognized as a promising solution to this problem. In this paper we have reviewed the Cognitive Radio with dynamic spectrum allocation technique and its components. In particular, Spectrum Sensing techniques have been reviewed in detail including brief mathematical modeling. Newer approaches to solve problems associated with traditional techniques have been discussed. Also, challenges associated with cognitive radio in general, have been investigated, identifying the potential future research areas to mitigate current implementation problems.

Keywords: Cognitive Radio, Spectrum Sensing, Energy Detection, Matched Filter, cyclostationary detection, Likelihood Ratio Test (LRT), cooperative based sensing, waveform based detection, spectral-correlation density (SCD), Software Defined Radio(SDR), Spectrum – Hole, Dynamic Spectrum Management.

1. INTRODUCTION

With increase in connected devices and consequent demands for higher data transmission rates, there is an ever growing interest in utilizing the available frequency spectrum in a more efficient way. The U.S. Federal Communications Commission (FCC) recognized severe under-utilization of radio spectrum more than a decade ago [1]. This led to research in various techniques to exploit un-utilized but available spectrum for wireless communications.

One of the proposed solutions is use of Cognitive Radios. Concept of Cognitive Radio was first introduced as extension of Software Defined Radio (SDR) by Joseph Mitola in 1999[2]. "Full Cognitive Radio" as envisaged by Mittola et al[2] is a highly "*reconfigurable*" SDR capable of having an "*intelligent conversation*" with its radio environment to deliver services to users who may or may not know how to obtain those services. However, for the purpose of this paper, we will adopt the FCC definition of Cognitive Radio:

"*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.*" [1].

From this definition we can deduce three primary cognitive radio tasks:

1) Spectrum Sensing (*senses its operational electromagnetic environment)*
2) Channel Identification (to *maximize throughput)*
3) Transmit power control & Dynamic spectrum management (*dynamically and autonomously adjust its radio operating parameters to modify system operation, mitigate interference, facilitate interoperability)*

This definition also suggests that Cognitive Radio are self-configurable radios that sense the spectral environment, autonomously & dynamically detect and interpret the changes occurring and facilitate coherent, reliable wireless communication without causing interference with existing licensed users. Exploitation of spectrum needs efficient spectrum management that comprises of both static and dynamic processes. Static allocation technique is fixed by regulatory mechanisms (i.e. static in temporal and spatial dimensions) while newer approach works with dynamic spectrum management for dynamic allocation in wireless communication system.

Basic methodology of cognitive radio based on dynamic spectrum management, for accessing the spectrum opportunistically is divided into four phases:-

Spectrum Sensing involves "spectrum hole" detection for efficient usage of dynamic allocation technique. *Spectrum Hole* is the potential opportunity to use the spectrum by a secondary user without interfering with licensed user. However definition of "Spectrum Hole" in time and frequency domain may be more nuanced [3].

Spectrum allocation follows spectrum sensing and refers to interpreting the frequency band to use. In case of multiple users, sharing of spectrum can occurs. In spectrum allocation, bandwidth sensing is necessary to distinguish between the margins of bandwidth for proper detection of signals.

SpectrumConfigurationis adaption and estimation of the parameter required for transmission. Cognitive Radio may potentially reconfigure itself according to required modulation scheme, carrier frequency, transmit power etc. and this reconfiguration must occur very quickly.

Spectrumtransmission is the phase where system identifies the transmission of other units with primary user. It must be able to detect any interference accurately to minimize the number of false detections. After reliable identification of the available spectrum holes, the cognitive radio system needs to estimate the transmission parameters such as spectrum bandwidth, power levels, Power control, bit rate control, etc.

Cognitive Radio Components

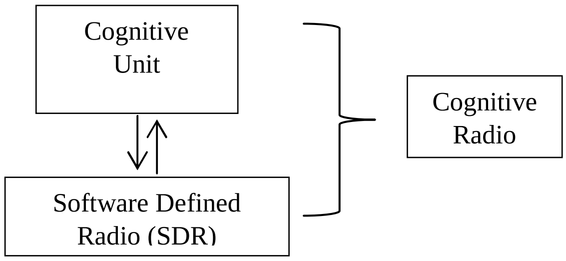

Fig 1. Cognitive Radio as sophisticated SDR

Prime advantages offered by Cognitive Radio are

1) Improved efficiency by allowing unlicensed users to exploit spectrum whenever it will not cause interference to licensed users.
2) Highly Reliable communication as and when required.

Accurate Spectrum sensing is one of the major challenges in Cognitive Radios. We review Cognitive Radio basic model in Section 1 & 2. The rest of the paper is organized as follows: We review various spectrum sensing methodologies and their strengths and shortcomings in Section 3. Section 4 discusses challenges/issues in cognitive radio systems. Section 5 provide small introduction of dynamic spectrum management (DSM). Finally, Section 6 concludes the paper and outlines potential future research areas.

2. COGNITIVE RADIO – BASIC MODEL

Both licensed and unlicensed frequency bands are available for opportunistic exploitation by Cognitive Radios. However, in the licensed band, detection of existing legacy users - also known as primary users - is of prime importance to avoid interference with cognitive radio transmission, by continuously hopping to next vacant frequency band [4]. From cognitive radio perspective, primary users are generally defined as the users who have license to use a given frequency spectrum in a given time window. Similarly, Secondary Users (SUs), are unlicensed users having no legacy rights to the spectrum and thus having low priority as compared to PUs. To establish reliable communication, SUs need to opportunistically exploit this spectrum without causing interference to primary users [5,6,7].

Mathematical model

The objective of the spectrum sensing is to decide between the two hypotheses, namely [8,9],

$$x(t) = \begin{cases} n(t)H_0 \\ hs(t) + n(t)H_1 \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where *x(t)* is the complex signal received by the cognitive radio, *s(t)* is the transmitted signal of the primary user, *n(t)* is the additive white Gaussian noise (AWGN) and *h* is the complex amplitude gain of the ideal channel or propagation channel coefficient. H_0 is the null hypothesis, which states that no licensed user is present in a certain spectrum band. H_1 is the alternative hypothesis which indicates that some primary user signal exists.

The performance of a spectrum sensing algorithm is measured on three metrics:

Probability of detection, P_d indicating, hypothesis H_1 being true, the probability of the algorithm correctly detecting the presence of the primary user;

Probability of false alarm, P_{fa} indicating, hypothesis H_0 being true, the probability of the algorithm falsely detecting the presence of the primary user;

Probability of Missing, P_m indicating, hypothesis H_1 being true, the probability that the algorithm missed detection of a primary user.

A sensing algorithm can be adjudged '*optimal*', if it maximizes the ratio P_d/P_{fa} for a given sample of primary users [10]. However, practically, other factors like noise, fading, shadowing etc. influence the detection of primary users. Hence, other statistical methods may be required for performance evaluation of sensing algorithms [11].

3.SPECTRUM SENSING TECHNIQUES

3.1. *Spectrum Sensing – An Overview*

Accurate spectrum sensing has remained the fundamental problem in Cognitive Radio. It is so important because reliability of transmission without any interference to PUs depends squarely on accurately detecting the presence of any PUs. Presence or absence of PUs will facilitate identification of spectrum holes which can be exploited by SUs.

In cognitive radio, process of sensing of spectrum has three main objectives:

- *Continuous radio channel monitoring to sense the temporal spectrum occupancy by a PU at a given time without interference.*
- *Continuous sensing for spectrum holes to dynamically allocate spectrum as and when needed.*
- *Estimation of transmission parameters like power levels, interference temperature, and conditions required for dynamic spectrum management.*

A number of solutions have been proposed over the years to facilitate accurate spectrum sensing [12]. (See Fig-2)

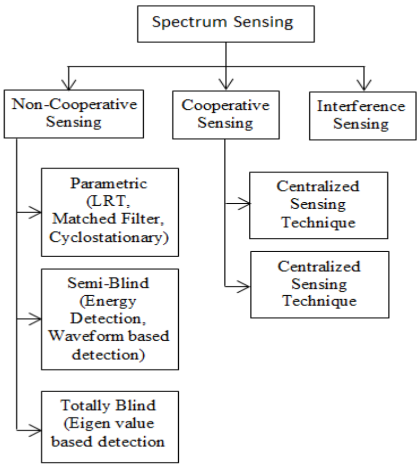

Fig 2. Spectrum Sensing Methods in Cognitive Radio

From *implementation* point of view, Spectrum sensing can be classified on the basis of hardware architecture which makes use of various spectrum sensing methodologies [13, 14, 15]. There are two architectures under consideration:

Single Radio architecture where a single cognitive radio is used for both spectrum sensing and transmission. It is simple and low cost but less accurate.

Dual Radio architecture utilizes two radios making it complex and costly as compared to Single Radio Architecture but is more accurate [5].

For the purpose of this paper however, we shall focus on the *Cooperative* and *Non-Cooperative* spectrum sensing techniques as depicted in Fig-2.

3.2. *Non-Cooperating Sensing*

As the name suggests, this type of spectrum sensing depends on ability of a cognitive radio to sense individually the presence of primary users, estimate channel characteristics and make transmission decisions based on individual local observations. Traditional non-cooperating techniques can be classified as [16, 17, 18]:

1. Sensing methods where channel information, primary user information and noise distribution is known to secondary user ***(Parametric approach, a-priori information)***

1) Likelihood Ratio Test (LRT)

As per Neyman-Pearson theorem [6, 7, 8], for a given probability of false alarm, the test statistic that maximizes the probability of detection is the likelihood ratio test (LRT) defined as

$$T_{LRT}(x) = \frac{p(x/H_0)}{p(x/H_1)} \ldots\ldots\ldots (2)$$

Where p(·) denotes the probability density function (PDF), and x denotes the received signal vector that is the aggregation of x(n), n = 0, 1, ... , N − 1. Such a likelihood ratio test decides H_1 when $T_{LRT}(x)$ exceeds a threshold γ, and H_0 otherwise.

If we assume Gaussian distribution for both noise and received signal, that is, η(n) ∼ N (0, σ_n^2 I) and s(n) ∼ N (0,R_s), the LRT becomes the estimator-correlator (EC) [19] detector for which the test statistic is given by

$$T_{EC}(x) = \sum_{n=0}^{N-1} x^T(n)\, R_s(R_s + \sigma_n^2 I)^{-1} x(n) \ldots\ldots (3)$$

Here, $R_s(R_s + \sigma_n^2 I)^{-1} x(n)$is the minimum mean squared error estimation of the source signal s(n). Hence $T_{EC}(x)$ can be seen as a correlation between source signal and received signal. It also signifies that in absence of a-priori information about source signal s(n), LRT method is useful. Improvements on LRT method have been proposed in the form of Bayesian Method and Generalized Likelihood Ratio Test (GLRT) [19, 20].

2) Matched Filter Detection

A Matched Filter may be considered as a special case of LRT where [21], where noise distribution is assumed to be Gaussian and all information about the transmitted signal is known. Such information includes parameters like bandwidth, modulation, frequency etc. so that signal can be demodulated at the receiver end. A matched filter is thus a linear filter which senses the spectrum and detects presence of primary user by maximizing the output signal to noise ratio (SNR) for a known transmitted signal. Mathematically, a Matched filter can be depicted as

$$T_{MF}(x) = \sum_{n=0}^{N-1} s^T(n)\, x(n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where s(n) is the known transmitted signal and x(n) is received signal.

A matched filter is an optimal method [22] for primary user detection when all primary user transmitted signals are known to cognitive users. It is particularly useful in transmissions where a known pilot signal is used like TV transmissions etc. Matched filter method required less time for detection as fewer samples are required but this efficiency in time is achieved at the cost of simplicity, as it poses the condition of a-priori information of all PUs.

3) Cyclostationary Detection

Signal used in practical communication contains various distinctive features that can be exploited for detection. Features of the transmitted signals are the results of redundancy added by coding, modulation and burst formatting schemes. Like OFDM, space-time coded signals etc. such signals have a special statistical feature called cyclostationarity, that is, their statistical parameters vary periodically in time. This cyclostationarity can be extracted by the spectral-correlation density (SCD) function [12, 23, 24, 25]. SCD function of noise has zero values at all non-zero cyclic frequencies. Hence, we can distinguish signal type and also from noise by analyzing the SCD function. In general, the received signal can be written as

$$y(t) = x(t) \otimes h(t), \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

It can be shown that the SCD function of y(t) is

$S_y(f) = H(f + \frac{\alpha}{2})H^*(f - \frac{\alpha}{2})\, S_x(f)$……………..(6)

Where $*$ denotes the conjugate, α denotes the cyclic frequency for x(t), H(f) is the Fourier transform of the channel h(t), and $S_x(f)$ is the SCD function of x(t). Thus, the unknown channel could have major impacts on the strength of SCD at certain cyclic frequencies.

This approach of detection needs a very high sampling rate, computational complexity, due to large samples needed to compute SCD function. The strength of SCD could be affected by the unknown channel. The sampling time error and frequency offset could affect the cyclic frequencies and hence, are the major drawbacks of this method.

2. Sensing methods where prior information of the primary signal is not known to secondary users. Such methods need only noise power information ***(Semi-Blind detection)***

Parametric methods described above are difficult to implement because reliable a-priori information of primary users, noise distribution etc. are required for accurate detection. Semi-Blind methods eliminate the need of information about transmitted signal, utilizing only noise power information to detect primary users.

1) Energy Detection

Even If the source signal information is unknown, presence of a primary user can be detected by measuring the energy of the transmitted signal and comparing it to a noise threshold. Advantages of this method are simplicity to implement as there is no dependence on prior knowledge of transmitted signals. But it suffers from the drawback that in case of fluctuations in signal strength, probability of false detection P_{fa}or probability of missing P_m increases. Also it performs poorly in scenarios where transmitted signal is spread over a wide frequency band e.g. spread spectrum signals [12]. Other mathematical techniques like fuzzy logic approach have been explored to improve the accuracy of energy detection method [26].

2) Waveform based detection

If the pattern of transmitted wireless signal like pilot signals or wireless metropolitan area network (WMAN) signals is known, then, accuracy of energy detection technique can be improved by comparing received signal with a time-shifted copy of itself [27]. This detection happens over a short time period in the time domain. Waveform-based sensing is advantageous because of improved accuracy and low convergence times but at the same time it suffers from time-synchronization problems [18].

3. Sensing methods where no prior information of primary user, source signal or noise distribution is required ***(Totally Blind detection)***

Due to very low likelihood of availability of detailed prior information about source signal, there has been considerable interest in spectrum sensing techniques where no prior information of primary user, noise characteristics etc. are required for spectrum sensing [28]. Most promising technique for totally blind detection is ***Eigen Value based*** detection. Eigen value based detection techniques are better than semi blind techniques such as Energy detection as no source signal or channel information is needed. Also it eliminates the time-synchronization errors observed in waveform based sensing.

3.3. *Cooperative Sensing*

In cooperative sensing, in order to improve the performance of the spectrum sensing, an access point is introduced in channel. This point or master node can collect the channel state information and make the final decisions whether PU is present or not[8]. It can be classified into two categories.

1) Centralized sensing technique

In this technique, Spectrum Server called fusion center (FC) can be used to enable coexistence of radios in a shared environment in a centralized fashion. The centralized spectrum server obtains information about neighborhood and interference through local measurements from different terminals and then offers suggestions for the efficient spectrum use. The spectrum information can be gathered from several separate secondary networks [27]. Problem with this technique is that there is need of infrastructure network and sometimes in case of multi user environment, bandwidth required for reporting becomes huge[29].

2) Decentralized sensing technique

In this approach each node is connected to another one to form structure like ad-hoc networks. Here, a Cognitive Radio will independently detect the channel and will vacate the channel when it finds a primary user without informing the other users. Thus Cognitive Radio users may experience *hidden terminal problem* [30] and detection of false alarm leading to unwanted interference at the primary receiver. This is the main drawback of this technique when compared to coordinated techniques.

4. CHALLENGES AND ISSUES IN COGNITIVE RADIO

Despite progress in research on Cognitive radio techniques, issues remain in implementation of available theoretical methods due to several limitations [31]. Some of these limitations are discussed below.

1. Hidden terminal problem

This problem is characterized by missing detection of primary user due to location of transmitter w.r.t the primary receiver. This causes interference with primary user transmission. Cooperative sensing addresses this problem to some extent by information sharing but other techniques still require better solutions [32].

2. Hardware requirements

Most of the detectors are based on Energy Detection techniques because of simplicity of implementation. However, these energy detectors suffer from some drawbacks as already discussed in Section III. Also, presence of several identically distributed spectrally superimposed signals will confuse most energy detection schemes, preventing the interceptor from determining anything more than the knowledge that signals are present in the environment. Another significant drawback is that energy detection cannot distinguish among different types of transmissions or interference from signals. More computationally extensive techniques still lack in hardware implementation because of various logistical, design and financial limitations [5].

3. Scanning a very wide spectrum range

A cognitive radio needs to continuously scan a very wide range of frequency bands in order to sense and identify spectrum holes. To sense a very largefrequency band, a sufficiently large sampling rate will be needed. Simple hardware implementation of such a wideband cognitive system is still a challenge.

4. Security

In cognitive radio, security concerns remain a concern and security standards need to be developed. Some common scenarios have been explored. For e.g. a malicious user can impersonate a primary user and compromise the cognitive network. It has been named as primary user emulation (PUE) attack [33]. A primary user authentication scheme is proposed in [34]. Primary user identification using a public key encryption system is discussed in [35] as a mitigation exercise to repair a compromised network.

5. DYNAMIC SPECTRUM MANAGEMENT

Dynamic spectrum management (DSM) efficiently solves problem of spectrum scarcity and spectrum under-utilization in wireless communication. This technology covers frequency assignment with dynamic channel/spectrum allocation (DSA) and contains information about spectrum sensing for both primary and secondary users.

Cognitive radio has been one of the most vital applications of dynamic spectrum management.DSM manually allocates un-used spectrum, after link adaption as it combines unused channel on basis of pre cancellation of estimated interference for multiple user (i.e. both primary and secondary users). DSM is a promising tool for many radio technologies in wireless communication, as it provides broad bandwidth for spectrum sensing.

DSM is studied in depth in various research works [12][36].

6. CONCLUSION & FUTURE WORK

In this paper, Cognitive Radio and various spectrum sensing techniques have beenreviewed. Performance and accuracy of individual spectrum sensing techniques have been investigated with attention to newer approaches to detection problem. Challenges have been discussed. More research is needed to simplify cognitive radio implementation models, associated security aspects and accuracy of spectrum sensing techniques. In particular, the efficacy of spectrum sensing algorithms in noisy and fading environments needs attention. In this paper we have assumed Gaussian noise distribution in most cases. However, for practical implementation scenarios, more research is needed to evaluate and improve performance of spectrum sensing techniques in impulse noise environment.

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