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Techniques for Spectrum Sensing in Cognitive Radio Networks: Issues and Challenges

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Abstract - *The explosion of wireless applications has created an ever increasing demand for radio spectrum and this has put a lot of pressure on service providers to meet the end user's requirement for higher bandwidth. In present scenario, the access to radio spectrum for most of the wireless applications/services is based on some well-coordinated but static spectrum allocation principle. However many studies have revealed the low utilization efficiency of radio spectrum by such an allocation principle. The idea of Cognitive Radio stands up for dynamic bandwidth access and efficient bandwidth allocation beyond its previous limits. This paper presents one of the necessary components of a cognitive radio system i.e. Spectrum Sensing. Various techniques that can be used for sensing the unused spectrum by secondary (unlicensed) users are presented and discussed.*

Key Words: Cognitive Radio, Dynamic Spectrum Access, Spectrum Sensing

1. INTRODUCTION

Wireless communication technology is proliferating into all aspects of computing and communication. The data rates required for various services are also increasing day by day with data applications (like digital audio, digital images and videos) consuming very large bandwidth than basic telephony services. Such a phenomenal increase in number of mobile devices and data services is expected to continue in the near future and this creates an ever increasing demand for more bandwidth. As predicted in [1], monthly global mobile data traffic will surpass 15 exabytes per month by 2018 as compared to nearly 18 exabytes of traffic for the whole of 2013.

Today's wireless networks are particularized by static spectrum assignment policies. Government agencies control the licensing of the radio spectrum and spectrum assignment is done mostly on a long term basis to licensed service providers only. The frequency spectra (fixed) allocated for various services in International regions as well as Indian context has been provided in [2]. Despite having many advantages like simplicity, guarantee of continuous access to spectrum and better service quality, static spectrum allocation can lead to wastage of limited wireless spectrum. A number of studies have been performed regarding spectrum utilization and it has been found that spectrum utilization is concentrated only on certain portions of the allocated spectrum and a significant portion remains unutilized because of the static allocation of the spectrum [3]-[5]. This is as illustrated in Fig.1 [6]. In addition, a huge portion of allocated spectrum is used occasionally. Hence it is evident that the concept of spectrum scarcity is misleading and underutilization of available spectrum is the major concern that needs to be taken care of in order to fulfill customers' day by day increasing demands.

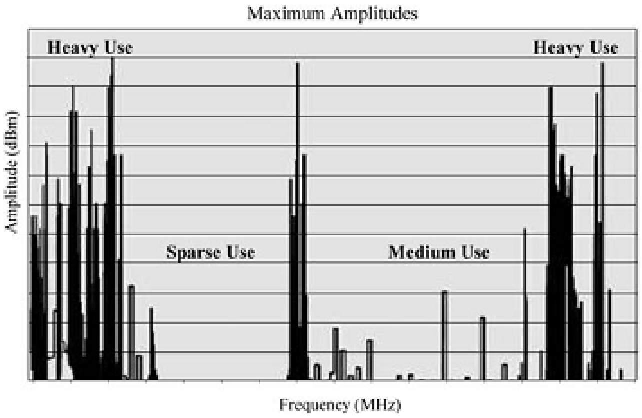

Fig.1. Spectrum Utilization [6]

Not only the availability of limited amount of spectrum but also the inefficiency in its current utilization methodology necessitates the shift to a new communication paradigm in order to improve spectrum utilization efficiency. It has been recommended by FCC as well that significantly higher spectrum utilization efficiency can be achieved by developing a technique that allows wireless users to share a wide range of available spectrum [7]. The concept of Cognitive Radio was proposed in this context by Mitola in his Ph.D. dissertation [8]. The idea envisioned the possibility to enable a radio device to adapt its operational parameters in response to its operating environment [9]-[10]. It was proposed that under-utilized portions of the allocated radio spectrum be opportunistically utilized using novel devices called Cognitive Radios by employing a tactic called Dynamic Spectrum Access (DSA). These under-utilized or free portions of spectrum are called "white-spaces" or "spectrum holes". Future communications are hence expected to be driven by Cognitive Radio Networks wherein the devices would be able to sense their environment and then perform according to the condition thereby leading to an optimum use of the in hand resources.

The next part the paper is as follows. In section 2, an overview of Cognitive Radios and their main characteristics are described. Section 3 explains the various spectrum sensing techniques that can be employed in designing a cognitive radio along with their relative comparisons. Section 4 presents our conclusions.

2. COGNITIVE RADIOS

Cognitive Radios are devices which are capable of observing the external radio environment; orient themselves to the current situation and then act accordingly in order to communicate with other devices while maintaining the prescribed quality standards. Cognitive Radio is the effective solution that enables a network to efficiently utilize the spectrum in a dynamic manner. Users in a cognitive radio network (CRN) are categorized in two parts: (i) Primary Users (PU) that are licensed to use a specific portion of the spectrum, and (ii) Secondary or Cognitive Users (SU or CU) use the spectrum licensed to some primary user in an opportunistic manner, without creating any interference problem for the licensed primary user. The secondary user would search for “white-spaces” or “spectrum holes” in its vicinity and would then rapidly alter its transmission parameters according to the prevailing conditions. Spectrum holes are those portions of frequency spectra which have been actually assigned to a licensed primary user, but, at a given time and location, that portion is not occupied by that primary user [11]-[12]. Whenever the primary user accesses that portion of spectrum, the secondary users have to vacate that spectrum band immediately since it should not pose any interference to the primary user.

Every Cognitive Radio has two main characteristics: (i) Cognitive Capability and (ii) Reconfigurability. The former refers to the device’s ability to sense its surrounding radio environment, learn from the stimuli and be able to make some decision for the future course of action. On the other hand, reconfigurability refers to the ability of that device by which it can change its characteristics and adapt to the surroundings as per the decision made previously by using the cognitive capability [6] [8] [11]-[12].

2.1. Cognitive Capability

The word ‘cognition’ means “thinking and awareness”. The cognition is defined as psychological action to acquire knowledge and understanding through the senses, experience, and thought. The same capability is found in a Cognitive radio where the device is expected to sense the external radio environment and acquire knowledge about its current state and adapt itself dynamically. The sequence of operations that are required to perform adaptive operation is called Cognitive Cycle, which is as shown in Fig.2 [8] [12]. The constituents of a basic cognitive cycle are as below [6] [8] [11]-[14]:

- *Spectrum Sensing* refers to the detection of available portions of the spectrum which are currently unused by the primary customers. A cognitive radio monitors the available spectrum bands, captures their information, estimate the interference temperature of radio environment and detect possible spectrum holes. A number of techniques like Energy Detection, Cyclostationary Feature Detection, and Matched Filtering etc. The details of all these techniques are presented in subsequent sections.

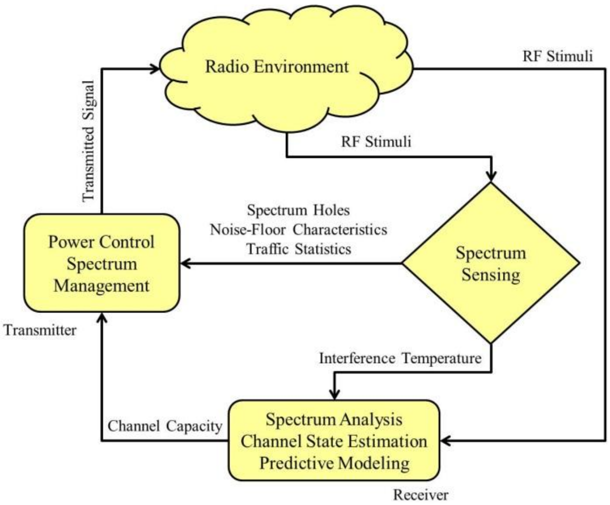

Fig.2. Basic Cognitive Cycle [8] [12]

- *Spectrum Analysis* is the process which takes input about available spectrum holes from spectrum sensing block and performs channel identification wherein several parameters are evaluated and encompasses for each spectrum hole sensed by the previous process. The important parameters include BER, time delay, channel state information (CSI), information capacity of the channel etc.
- *Spectrum Decision/Management* is the stage of cognitive cycle where actual decision regarding the best available spectrum hole is taken on the basis of analysis done by the previous stage. Parameters like transmission mode, data rate, transmit power control, transmission bandwidth etc. are taken into consideration here. The decision can be for a stand-alone device itself or on the basis of some cooperation among a group of cognitive radios.

2.2. Reconfigurability

Once a suitable spectrum hole has been identified, it is obviously required to make the device able to perform communication on that much identified channel. This ability of a device to adjust its operational parameters for communication on the run without any modifications in the already installed hardware is called Reconfigurability. The various parameters that may be altered in response to the changing environment include (i) operating frequency, (ii) modulation technique, (iii) transmission power and (iv) data rate etc. It is also necessarily required that these operational parameters can be altered not only in the beginning of the communication process but also during the same. Also required is a feedback channel between the transmitter and the receiver part at all times so as to convey information on the performance of the forward link to the transmitter [6] [8] [11]-[12].

3. SPECTRUM SENSING IN COGNITIVE RADIOS

Spectrum sensing is the most important task in the cognitive cycle for the realization of cognitive radio. It is the first task to get knowledge about the current spectrum usage and presence of primary customers in a given terrain at that time. In the beginning, Geo-location method, i.e. keeping and updating a centralized database with relevant information of primary users (like user's location, power as well as expected duration of usage) and broadcasting this information on regional beacons, was considered first for getting spectrum availability in the first CR standard IEEE 802.22. It was actually suitable for registered TV bands, but its cost, required modifications in the existing primary users' networks as well as operational overhead prevent its wide use. Spectrum sensing techniques were therefore proposed as an alternate solution [15]-[17].

In a cognitive radio network, a basic need is to avoid interference to potential primary users in their era and cognitive radios or by providing high priority to primary users than secondary users for radio spectrum which is already provided to primary customer. On the other side, primary users' network infrastructure remains unchanged for sharing spectrum with cognitive networks. Therefore, such spectrum sensing techniques are required which would enable cognitive radios to independently detect the presence of primary users. Conventionally spectrum sensing is measuring the spectral constituents or sensing the interference over the spectrum, but when cognitive radios are considered, it means to determine the usage of spectrum in more than one dimensions like time, frequency, code and space [15] [18]. It also provides basic info like carrier frequency, type of modulation, signal waveform and bandwidth for transmission. This requires very complex computational signal analysis techniques in the following steps also.

Spectrum Sensing in cognitive radios can be performed by applying two main approaches [19]-[20], viz. (i) Time Domain, and (ii) Frequency Domain. The former, also called indirect method, utilizes the autocorrelation properties of a signal to perform its estimation whereas in the latter, also called direct method, estimation is done from the actual signal itself.

In spectrum sensing the detection performance is important for any type of network it may be primary or cognitive. Performance criteria for any of the spectrum sensing algorithm are based on the following three metrics [11] [16]:

- *Probability of False Alarm*, which means the probability with which a cognitive radio would detect that a spectrum, is occupied when it is actually free. A false alarm will reduce the spectral efficiency.
- *Probability of Mis-Detection*, which denotes the probability with which the cognitive radio will sense that the spectrum is free but is actually occupied by some primary user at that given time. Higher is this metric, more is the possibility of interference to the primary user.
- *Expected Detection Delay* corresponds to the average number of samples a detector takes to arrive at a decision.

4. SPECTRUM SENSING TECHNIQUES FOR COGNITIVE RADIOS

A number of different techniques have been presented for identifying the presence of signal transmissions in the surroundings of a user. The classification of these techniques is as shown in Fig.3 below. These are

- Cooperative Detection
- Non-Cooperative Detection (Transmitter Detection)
- Interference Based Detection.

This section presents some techniques for spectrum detection.

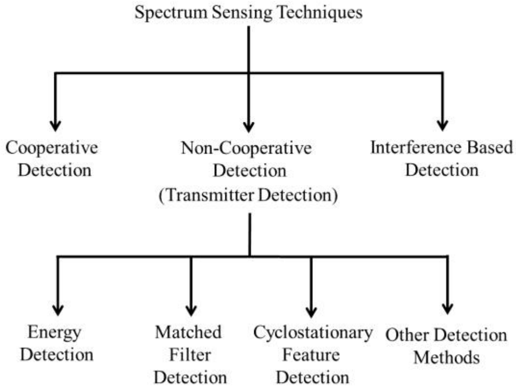

Fig.3. Classification of Spectrum Sensing Techniques

4.1. Non-Cooperative Detection

These detection techniques are based on the fact that there is no signaling or transfer of any type information between the primary and secondary users. These are also called Transmitter Detection techniques since the secondary users watch out if any primary user is actually actively present in the local environment. These techniques involve detection of weak signals from a primary user solely by observations made by the secondary user itself. The basic idea behind this technique is to decide between the following two hypotheses [6] [15] [16] [17]:

$$Y(t) = n(t) \qquad H_0 \ (Spectrum\ Hole)$$

$$Y(t) = h * s(t) + n(t) \qquad H_1 \ (Spectrum\ Occupied)$$

where,

$Y(t)$ = signal received by the cognitive radio, *s(t)* = signal transmitted by the primary user,

n(t) = Additive White Gaussian Noise (AWGN),

and h is the complex gain of the ideal channel, H_0 shows null hypothesis, which give the indication about the possibility of a spectrum hole and H_1 presents alternative hypothesis, which give indication that spectrum is already occupied by primary user. The techniques which are conventionally present in the literature for transmitter detection are Energy Detection, Matched Filter Detection, and Cyclostationary Detection which are given in the next sub-sections.

1) Energy Detection: This approach, also known as radiometry or periodogram, is the simplest way of spectrum sensing in high SNR conditions since it is easier to implement and no need of any prior knowledge about the primary signal because it has low computational complexities [6] [14]-[15] [19] [21]-[22]. A conventional energy detector arrangement is as depicted in Fig.4. The received signal is band-passed for desired frequency and bandwidth after which its energy is estimated by a squaring device. This is followed by an Integrator which sums up the detection over a period of T seconds. Then the output is compared with a properly set threshold in the Decision Block, to decide on the two hypotheses discussed earlier.

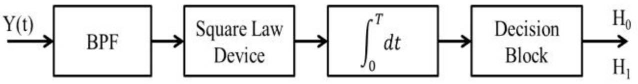

Fig.4. Block Diagram of an Energy Detector [15]

A number of drawbacks associated with an energy detector arrangement in context of cognitive radios diminish its simplicity and cost effectiveness. These include (i) the susceptibility of threshold to unknown and ever changing noise levels, (ii) inability to discriminate between modulated signals, noise and interference, (iii) inability to deal with spread spectrum signals, and (iv) longer computation time to achieve a given accuracy level [14] [17] [22].

2) Matched Filter Detection: If there is some priori knowledge regarding the primary signal, the optimum detection technique is employing a matched filter followed by a threshold test since it maximizes the signal-to-noise-ratio [23]. The main advantage of this technique is that it requires very less time to achieve a certain probability of misdetection but on the cost of increased computational complexity. However, the reqiuement for matched filtering is to effectively demodulate of primary user signals. For this, the knowledge of parameters like operating frequency, modulation type and order, pulse shape and packet format is a must [17] [22] [24]. Fig. 5 shows the block diagram of a detector based on matched filter.

Fig.5. Block Diagram of Matched Filter Detector [15]

This technique gives better results as compared to Energy Detection method but still there are some issue as well such as, (i) higher computational complexity, (ii) higher power consumption, (iii) need for performing timing and carrier synchronization, and (iv) requirement of a dedicated receiver for every primary user type.

3) Cyclostationary Feature Detection: This technique is a specific case of a more general technique called Feature Detection. The fact that there are certain specific features associated with the signals transmitted by primary user is utilized in this technique of detecting the presence of a primary user. Cyclostationary features of the received signals helps in the detection method. Generally, the statistics of most of the transmitted signals are periodic. This is because of the inherent periodicities of modulated signals such as carrier frequency, modulation rate, hopping sequences, cyclic prefixes etc. The modulated signals can be characterised as Cyclostationary even though the user data is a stationary random process. The periodic signal cause Cyclostationary features like mean or auto-correlation. Such features can also be introduced intentionally to estimate various parameters like carrier phase, pulse timing, direction of arrival etc., and sense the spectrum in a better way [14] [17] [22].

The techniques of Cyclostationary feature detection was first introduced in [25]. One of the prominent features of this technique is its ability to differentiate between random noise and primary user's signals. Because wide sense stationary process (WSS) nature of noise cause no correlation, as compare to modulated signals of primary users are Cyclostationary and also possess spectral correlation between widely separated spectral components. The cyclic spectral density (CSD) function of a received signal can be obtained by using the follwing expression[25]-[26]:

$$S(f,\propto) = \sum_{\tau=-\infty}^{\infty} R_y^{\propto}(\tau)\, e^{-j2\pi f\tau}$$

where,

$$R_y^{\propto}(\tau) = E[y(t+\tau)\, y^*(t-\tau) e^{j2\pi\propto t}]$$

$R_y^{\propto}(\tau)$ = cyclic correlation function (CAF) and

α = cyclic frequency variable,

y(t) = complex received signal at receiver,

E[•] = expectation operator,

* = complex conjugate.

The CSD function attains its peak value when the cyclic frequency equals the fundamental frequencies of transmitted signal x(t), i.e. $\alpha = (k/T_x)$ with T_x being the period of x(t). Power Spectral Density (PSD), which is a real-valued one dimensional transform, is a special case of CSD, which is generally a complex valued two dimensional transform, with $\alpha = 0$.

This detection technique performs much better than Energy Detection due to certain advantages which include (i) better detection robustness in low SNR scenarios, (ii) ability to differentiate primary users' signals from noise, and (iii) ability to effectively distinguish among different modulation types. But these benefits come at certain costs which include (i) significantly longer observation time, (ii) very high computational complexity, (iii) impairment due to frequency selective fading, and (iv) unpredictable results under scenario of primary emulation attacks [27]-[29].

4) Waveform based Sensing: In wireless systems, it is a common practice to embed known patterns in users' signals for synchronisation and other purposes. These patterns include preambles, midambles, pilot patterns and spreading sequences etc. Spectrum Sensing can be satisfactorily performed by correlating the received signal with a known copy of itself, in the presence of above mentioned known patterns [30]-[32]. This method is also called coherent sensing. It has been seen that the performance of such an algorithm increases as we increase the length of the known pattern. It has been shown in [30] that this technique outperforms energy based detection in convergence time and accuracy but is prone to synchronization errors [33] as well.

5) Radio Identification based Sensing: In this technique, complete information about the spectrum characteristics is obtained by extracting several features from the received signal and by employing certain classification methods it is used to select primary user transmission technology with high probability. Different methods have been proposed wherein features like amount of energy detected, channel bandwidth and its shape, center frequency, standard deviation of instantaneous frequency and maximum duration of signal etc. are extracted from the received signal and then analysed for determining the possible transmission technology in use by the primary user. Such identification enables cognitive radio with a higher dimensional knowledge as well as providing higher accuracy [14] [34].

4.2. Cooperative Detection

The performance of non-cooperative detection techniques which are presented in previous subsection is severely limited by received signal strength which is further contaminated by shadowing effects and multipath fading. If the received SNR is too low, it would be impossible to detect the primary user even with a very long sensing time. Cooperative Spectrum Sensing is thereby suggested as a viable solution in the above mentioned scenario. In this technique, information from multiple secondary users are incorporated together and analyzed for primary user detection. As effects of multipath fading depend upon receiver's geographical location and vary significantly over small distances, it is expected that users placed at different locations will experience different fading. Hence, uncertainty due to fading can be overcome if users cooperate with each other and share their individual sensing results to others as well, so that better decision regarding spectrum occupancy can be made [17] [22]. Cooperative sensing effectively decreases the probability of false alarm and probability of mis-detection and can also provide solution to hidden primary user problem. Cooperative Detection can be implemented in the following ways [6] [14] [17] [22] [29]:

1) Centralised Sensing: In this approach, an access point (like a secondary base station) is provided with sensed information by all the cognitive users. This access point then identifies the available spectrum holes using some decision fusion rule and then performs channel allocation to different users as per their requirements. The overhead data required in this scenario is that via which the sensed information is shared with the access point every time when the channel conditions change. In case of a large number of users, the bandwidth requirement for this overhead becomes very large. The observations of cognitive users should be quantized to single bit to overcome huge bandwidth requirement [35].

2) Distributed Sensing: In this method, all the cognitive users share their findings with each other but decide themselves, on the basis of information received from others, on the spectrum they use for transmission. It scores above the centralized scheme in the sense that it is easier to implement as there is no need for backbone infrastructure and hence lower cost. But due to haphazard manner of information exchange, it may not achieve the capacity of a centralized scheme.

3) External Sensing: In this approach, an external agent performs the spectrum sensing job and broadcasts its findings to all the cognitive/secondary users. The above mentioned two sensing techniques can thus also be classified as Internal Sensing techniques. The externals sensing approach addresses several issues that come up in above mentioned two internal sensing techniques [14]. The most important advantage is overcoming uncertainty due to shadowing and multipath effects. It also addresses hidden primary user problem. Also it leads to increase in spectrum efficiency since the cognitive users does not now spend time in sensing. Another advantage is related to power consumption of sensing arrangement in the network on a whole which is duly addressed by external sensing approach.

Cooperative Detection mechanism clearly scores over the non-cooperative technique with the ability to mitigate multipath fading, shadowing effects and building penetration losses [36]. It also enables the designer to impose very less stringent sensitivity requirements on cognitive devices. This in turn leads to lower device cost as it requires less complicated hardware for implementation. But these advantages come at certain cost. Some of these issues are (i) limited amount of available power with cognitive devices to support complicated detection hardware and high computational complexity, (ii) large amount of sensory data exchange, (iii) high power consumption, and (iv) possibility that sensed information may become stale fast due to mobility and channel impairments etc.

4.3. Interference Based Detection

'Transmitter-Centric' would be the apt word for describing the current radio environment. This is because the power at transmitter is designed so as to approach a certain noise floor at the receiver at a certain distance. However interference actually takes place at the receivers since there is a great possibility for some unpredictable interference noise sources to come up and raise the noise floor level at the receiver side. Therefore, a new metric to measure interference, called Interference Temperature, has been proposed in [37]-[38] by FCC, as a shown in Fig.6, so as to take real-time interactions between transmitter and receiver into account in an adaptive manner [6] [12].

Without using conventional transmitter-centric approach, the interference temperature model, through the frequency band of interest, specifies and manages interference at the receiver end by using interference temperature limit.

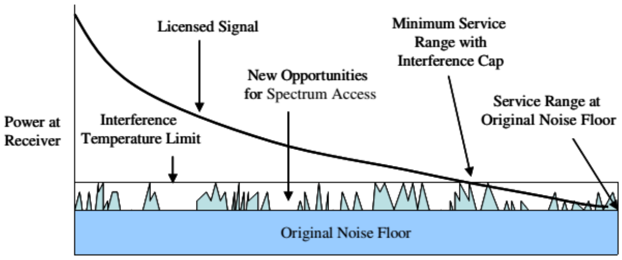

Fig.6. Interference Temperature Model [6] [37]

If any transmission increases the noise floor above the desired interference temperature limit it will be considered as "harmful" as presented in Fig.6. Any secondary user can use this spectrum until the user exceeds this limit by their transmissions.

Secondly, the method does not provide consistent results when the secondary user is unaware of the location of primary users [6].

5. CONCLUSION

Cognitive radios promise innovative technology that will be spinal cord for the future wireless world. The foremost step for successful implementation of cognitive radio networks is to develop the optimum spectrum sensing technique. Most of the techniques presented in this paper are still in their nascent stages of development with their performance limited severely by noise uncertainty, multipath fading, and shadowing, which are the fundamental characteristics of wireless channels. The performance of the energy detector method is susceptible to unknown noise levels and interference as well as its inability to differentiate between modulated signals, noise and interference. It does not work if the signal is spread spectrum in nature, or any time varying signal. On the other hand, Cyclostationary models have been shown to offer many advantages over stationary models. But, it is computationally complex and requires significantly long observation time. It is worth mentioning that not only channel-related, but device-level and network-level uncertainties are also to be dealt with. Energy efficiency and low-cost implementation are also to be kept under consideration.

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