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The Emerging Spectrum Sensing Techniques in Cognitive Radio Network

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Abstract— **Fixed spectrum assignment to the various operators or users leads to highly inefficient utilisation and exploitation of the spectrum. Wireless communication based on Cognitive Radio Networks (CRN) seems to be a promising solution for the better utilization of this inadequate resource. The most challenging and tricky issue in cognitive radio system is spectrum sensing by the Secondary Users (SUs). The main objective of sensing the spectrum is to check whether it is being used by the primary user (PU) at the given instance. The basic emerging techniques are matched filter detection, energy detection and cyclostationary feature detection. Here the emerging approaches for spectrum sensing have been presented with their respective advantages and disadvantages.**

Index Terms— **Cognitive Radio, Spectrum Sensing, Non Co-operative Sensing**

I. INTRODUCTION

Vigorous research is being carried out on Cognitive Radio (CR) all over the world [1]. The term CR was coined by Mitola in the year 2000 [2][3]. The available electromagnetic radio spectrum is getting crowded day by day due to ever increasing demand for wireless devices and applications. The available band is distributed to various licensed users for different uses and applications. The spectrum allocated for TV broadcasting mostly remains underutilised. The conventional approach of static spectrum allocation is very inflexible. Due to scarcity of spectrum it is difficult to allot spectrum for new services. It is difficult even to enhance the existing ones. We need to come up with a means so that the spectrum is exploited efficiently creating opportunities for dynamic spectrum access. [4]-[6]. This has forced Federal Communications Commission (FCC) to think of an essential alternate in the form of Cognitive Radio (CR) Technology [7]-[11] to resolve the issue of spectrum allocation. The licensed users are called Primary Users (PUs) and the unlicensed users are Secondary Users (SUs). IEEE 802.22 group [12] has been formed so that an air interface can be made available for Opportunistic Spectrum Access (OSA).

A CR can dynamically alter its parameters based on feedback from the environment. Functionality of a CR can be broadly categories into four main parts i.e, spectrum sensing, spectrum management, and spectrum sharing and spectrum mobility. Spectrum sensing is the most important and the most crucial function of a CR. There are various spectrum sensing techniques. They are primarily primary transmitter or non-cooperative detection, receiver or cooperative detection and interference detection. Mostly, the transmitted signal is analysed for the presence of the PU. Here, in the subsequent sections, we will discuss Primary transmitter based detection techniques and compare their relative performance in details for a better understanding of the design concepts of a CR, various issues and challenges that the process of spectrum sensing has to face are discussed in section 2. Section 3 describes classification of various spectrum sensing techniques and presents a detailed comparison. Section 4 bears the conclusion with a summary.

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II. CHALLENGES IN SPECTRUM SENSING IN COGNITIVE RADIO

In cognitive radio, PUs has higher priority rights compared to SUs over the use of spectrum. SUs cannot cause interference to primary users. Once presence of a PU has been sensed the SU has to change the radio parameters to exploit the available unused part of the spectrum in such a way that PU is not interfered with. There are several challenges that have to be overcome before the spectrum can be sensed successfully and handed over to the next stage for further efficient digital processing.

a) Capability of the Available Hardware

Spectrum sensing for cognitive radio applications requires high sampling rate, high resolution analog to digital converters (ADCs) with large dynamic range and high speed signal processors. Noise variance estimation techniques have been popularly used for optimal receiver designs like channel estimation, soft information generation as well as for improved handoff, power control, and channel allocation techniques [13]. A cognitive radio is required to process transmission over a much wider band for utilizing any available opportunity which impose additional requirements on the radio frequencies (RF) components such as antennas and power amplifiers. Furthermore, high speed processing units (DSPs or FPGAs) are needed for performing computationally demanding signal processing tasks with relatively low delay.

b) Hidden Primary User Problem

The hidden primary user problem is similar to the hidden node problem in Carrier Sense Multiple Accessing (CSMA). It can be caused by many factors including severe multipath fading or shadowing observed by secondary users while scanning for primary users' transmissions. Here, cognitive radio device causes unwanted interference to the primary user (receiver) as the primary transmitter's signal could not be detected because of the locations of devices. Cooperative sensing is proposed in the literature for handling hidden primary user problem [14]–[16].

c) Detecting Spread Spectrum Primary Users

For commercially available devices, there are two main types of technologies: fixed frequency and spread spectrum. The two major spread spectrum technologies are frequency hopping spread-spectrum (FHSS) and direct-sequence spread spectrum (DSSS). Fixed frequency devices operate at a single frequency or channel. An example to such systems is IEEE 802.11a/g based WLAN. FHSS devices change their operational frequencies dynamically to multiple narrowband channels. This is known as hopping and performed according to a sequence that is known by both transmitter and receiver. DSSS devices are similar to FHSS devices; however, they use a single band to spread their energy. Primary users that use spread spectrum signalling are difficult to detect as the power of the primary user is distributed over a wide frequency range even though the actual information bandwidth is much narrower [17]. This problem can be partially avoided if the hopping pattern is known and perfect synchronization to the signal can be achieved. However, it is not easy to design algorithms that can do the estimation in code dimension.

d) Sensing Duration and Frequency

Primary users can claim their frequency bands anytime while cognitive radio is operating on their bands. In order to prevent interference to and from primary license owners, cognitive radio should be able to identify the presence of primary users as quickly as possible and should vacate the band immediately. Hence, sensing methods should be able to identify the presence of primary users within certain duration. This requirement poses a limit on the performance of sensing algorithm and creates a challenge for cognitive radio design. Selection of sensing parameters brings about a tradeoff between the speed (sensing time) and reliability of sensing. Sensing frequency, i.e. how often cognitive radio should perform spectrum sensing, is a design parameter that needs to be chosen carefully. The optimum value depends on the capabilities of cognitive radio itself and the temporal characteristics of primary users in the environment [18]. If the status of primary users is known to change slowly, sensing frequency requirements can be relaxed. A good example for such a scenario is the detection of TV channels. The presence of a TV station usually does not change frequently in a geographical area unless a new station starts broadcasting or an existing station goes offline. In the IEEE 802.22 draft standard , for example, the sensing period is selected as 30 milliseconds. In addition to sensing frequency, the channel detection time, channel move time and some other timing related parameters are also defined in the standard [19]. Another factor that affects the sensing frequency is the interference tolerance of primary license owners. For example, when a cognitive radio is exploiting opportunities in public safety bands, sensing should be done as frequently as possible in order to prevent any interference. Furthermore, cognitive radio should immediately vacate the band if it is needed by public safety units. The effect of sensing time on the performance of secondary users is investigated in [20]. Optimum sensing durations to search for an available channel and to monitor a used channel are obtained. The goal is to maximize the average throughput of secondary users while protecting primary users from interference. Similarly, detection time is obtained using numerical optimization. Channel efficiency is maximized for a given detection probability. Another method is given in [21] where the guard interval between orthogonal frequency division multiplexing (OFDM) symbols is replaced by quiet periods and sensing is performed during these quiet periods. Hence, sensing can be performed without losing useful bandwidth. Sensing time can be decreased by sensing only changing parts of the spectrum instead of the entire target spectrum. A sensing method is developed in [22] that adapt the sweeping parameters according to the estimated model of channel occupancy. This way, a better sensing efficiency is obtained and sensing duration is reduced over non-adaptive sensing methods.

A channel that is being used by secondary users cannot be used for sensing. Hence, secondary users must interrupt their data transmission for spectrum sensing. This, however, decreases the spectrum efficiency of the overall system. To mitigate this problem, a method termed as dynamic frequency hopping (DFH) is proposed in [23]. DFH method is based on the assumption of having more than a single channel. During operation on a working channel, the intended channel is sensed in parallel. If there is an available channel, channel switching takes place and one of the intended channels becomes the working channel. The access point (AP) decides the channel-hopping pattern and broadcasts this information to connected stations.

e) Decision Fusion in Cooperative Sensing

Sharing, collecting and collating information is a difficult task cooperative sensing. Soft information-combining techniques show better performance than hard information-combining method in terms of the probability of missed opportunity [24],[25]. However, if the number of users are high then hard methods are as good as soft one[26]. The optimum fusion rule for combining sensing information is the Chair-Varshney rule which is based on log-likelihood ratio test [27]. Likelihood ratio test are used for making classification using decisions from secondary users [28]–[31]. Various, simpler, techniques for combining sensing results are employed in [32]. The performances of equal gain combining (EGC), selection combining (SC), and switch and stay combining (SSC) are investigated for energy detector based spectrum sensing under Rayleigh fading. The EGC method is found to have a gain of approximately two orders of magnitude while SC and SSC having one order of magnitude gain. When hard decisions are used; AND, OR or M-out-of-N methods can be used for combining information from different cognitive radios [33]. In AND-rule, all sensing results should be H_1 for deciding H_1, where H_1 is the alternate hypothesis, *i.e.* the hypothesis that the observed band is occupied by a primary user. In OR-rule, a secondary user decides H_1 if any of the received decisions plus its own is H_1. M out of N rule outputs H_1 when the number of H_1 decisions is equal to or larger then M. Combination of information from different secondary users is done by Dempster-Shafer's theory of evidence [34]. Results presented in [35] shows better performance than AND and OR-rules. The reliability of spectrum sensing at each secondary user is taken into account in [35]. The information fusion at the AP is made by considering the decisions of each cognitive radio and their credibility which is transmitted by cognitive radios along with their decisions. The credibility of cognitive radios depends on the channel conditions and their distance from a licensed user. Required number of nodes for satisfying a probability of false alarm rate is investigated in [36].

f) Security

In cognitive radio, a selfish or malicious user can modify its air interface to mimic a primary user. Hence, it can mislead the spectrum sensing performed by legitimate primary users. Such a behavior or attack is investigated in [37] and it is termed as primary user emulation (PUE) attack. Its harmful effects on the cognitive radio network are investigated. The position of the transmitter is used for identifying an attacker in [38]. A more challenging problem is to develop effective countermeasures once an attack is identified. Public key encryption based primary user identification is proposed in [39] to prevent secondary users masquerading as primary users. Legitimate primary users are required to transmit an encrypted value (signature) along with their transmissions which is generated using a private key. This signature is, then, used for validating the primary user. This method, however, can only be used with digital modulations.

III. CLASSIFICATION OF TECHNIQUES

As already mentioned earlier, spectrum sensing is the most important and the most crucial function of a CR. A CR looks for white holes or unutilized frequencies in the spectrum. Then these spectrum holes are exploited for CR communication. Also a CR has to be aware of the presence and return of the PU so as to cause minimum interference. But, it is difficult for a CR to detect and transmit at the same time. Hence, we require such spectrum sensing techniques which can detect the presence of PU in the minimum time period and be able to transmit or communicate more.

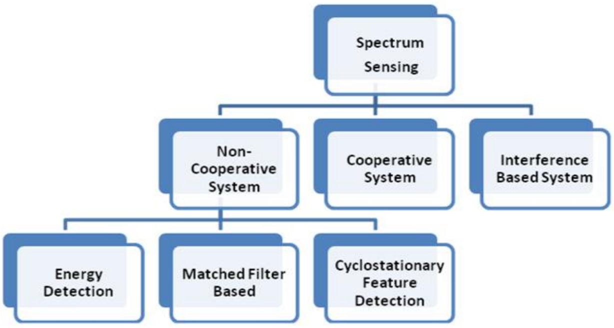

Figure 1 : Spectrum Sensing Techniques [40]

Spectrum sensing techniques have been broadly classified in three categories [40] as shown in Figure 1. We will discuss transmitter detection techniques. In transmitter detection or the non–cooperative technique, the spectrum sensing is focused on the sensing of the presence of the PU. If a PU is transmitting then the CR hops to other frequencies for CR communication. We create a binary hypothesis model for transmitter detection as defined in [41]. The outcome of the hypothesis decides whether the PU is present or not. Let the signal received by the SU be defined as

$$x(t) = \{n(t)H_0\} \quad (1)$$

$$x(t) = \{hs(t) + n(t)H_1\} \quad (2)$$

Here x(t) is the signal received by CR, s(t) is the transmitted signal of primary user, n(t) is the Additive white Gaussian noise (AWGN) and h is the amplitude gain of the channel. H0 implies that the primary user is present and H1 implies that the primary user is absent. Matched filter based, energy detection based and cyclo-stationary feature detection based spectrum sensing is implemented based on this hypothesis. In the subsequent sections we will discuss these techniques in detail and also compare their performance in terms of accuracy and design complexity.

a) Matched Filter Detection

A matched filter is a linear filter designed to provide the maximum signal-to noise ratio at its output for a given transmitted waveform [42]. Figure 2 depicts the block diagram of matched filter. The signal received by CR is input to matched filter which is $r(t) = s(t)+n(t)$. The matched filter convolves the r(t) with h(t) where $h(t) = s(T-t + \tau)$. Finally the output of matched filter is compared with a threshold λ to decide whether the primary user is present or not.

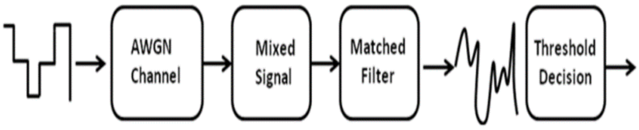

Figure 2: Block Diagram of Matched Filter [41]

If the channel is AWGN and the waveform of the PU is known to the CR then a Matched filter based detector is optimal. In this case, CR should have knowledge about the waveform of primary user in terms of its parameters like modulation type and order, the pulse shape and the packet format. We can achieve this coherency by introducing pilots, preambles, synchronization word or spreading codes in the waveform of primary users. However, each CR should have the information of all the primary users present in the radio environment. This is a big limitation. Advantage of matched filter is that it takes less time for high processing gain. However major drawback of Matched Filter is that a CR would need a dedicated receiver for every primary user class. Matched filter requires prior knowledge about primary user's waveform. Hence, it requires less sensing time for detection. For the case of BPSK in which the two pulses are say, p (t) and –p(t). The correlation coefficient c of these pulses is -1. Under good SNR conditions the receiver computes the correlation between p(t) and received pulse. If correlation is 1 we decide p(t) is received, otherwise we will decide that –p(t) is received. When SNR conditions are not good then correlation coefficient is no longer +1 or -1, but has smaller magnitude, thus reducing the resolution.

b) Energy Detection

If CR can't have sufficient information about primary user's waveform, then the matched filter is not the optimal choice. However if it is aware of the power of the random Gaussian noise, then energy detector is optimal. In [41] the authors proposed the energy detector as shown in Figure 3. The input band pass filter selects the center frequency fs and bandwidth of interest W. The filter is followed by a squaring device to measure the received energy then the integrator determines the observation interval, T. Finally the output of the integrator, Y is compared with a threshold, λ to decide whether primary user is present or not.

In a non- fading environment, probability of detection P_D and probability of false alarm P_F are given by following formulas [42]:

$$P_D = P(Y > \lambda/H_1) = Qm(\sqrt{2\lambda}, \sqrt{\lambda}) \quad (3)$$

$$P_F = P(Y > \lambda/H_0) = \Gamma(m, \lambda)/\Gamma(m) \quad (4)$$

Where Y is the SNR, m=TW is the (observation/sensing) time bandwidth product Γ(m) and $\Gamma(m, \lambda)$ are complete and incomplete gamma functions respectively.

Qm( ) is the generalized Marcum Q-function. In a fading environment the amplitude gain of the channel varies due to the shadowing or fading effect which makes the SNR variable. P_F is same as that of non-fading case because P_F is independent of SNR. P_D gives the probability of detection conditioned on i nstantaneous SNR. In this case average probability of detection may be derived by averaging (2) over fading statistics:

$$P_D = \int x Qm(\sqrt{2\gamma}, \sqrt{\lambda}) f\gamma(x) dx \quad (5)$$

Where fγ(x) is the probability distribution function of SNR with fading, a low value of P_D indicates absence of primary user with high probability; it means that the CR user can use that spectrum. A high value of P_F indicates minimal availability of spectrum. In [41] the authors suggest that in fading environment, where different CR users need to cooperate in order to detect the presence of the primary user. In such a scenario a comprehensive model relating different parameters such as detection probability, number and spatial distribution of spectrum sensors and more importantly propagation characteristics are yet to be found. One of the main problems of energy detection is that performance is susceptible to uncertainty in noise power. It cannot differentiate between signal power and noise power rather it just tells us about absence or presence of the primary user.

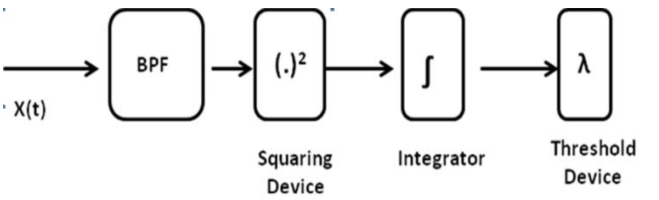

Figure 3: Block Diagram of Energy Detector [41]

Energy detector measures the energy received from primary user during the observation interval. If energy is less then certain threshold value then it declares it as spectrum hole. When there is no primary user, even then energy detector detects that primary user is present under low SNR conditions. This is the main drawback of energy detection that it can't distinguish between noise and energy of the signal. Under low SNR conditions energy detector deducts that primary user is present all around the spectrum for white noise.

c) Cyclostationary Feature Detection

Periodicity is built-in modulated signals as they are coupled with pulse trains, sine wave carriers, hopping sequences or cyclic prefixes [43]. Even though the data is stationary random process, these modulated signals are characterized as cyclostationary Their statistics, mean and autocorrelation, exhibits periodicity. These features are detected by analyzing a spectral correlation function. The periodicity is provided for signal format so that receiver can use it for parameter estimation like pulse timing, carrier phase etc. This periodicity can also be used in the detection of random signals with a particular type of modulation with the noise and other modulated signals.

Cyclostationary feature detection method has outperformed simple energy detection and match filtering based detection. As discussed, a matched filter requires prior knowledge about primary user's wave whereas a energy detector does not require any sort of prior knowledge about primary user's waveform. Although energy detector is easy to implement, it is highly susceptible to in band interference and changing noise levels. It cannot differentiate between signal power and noise power.

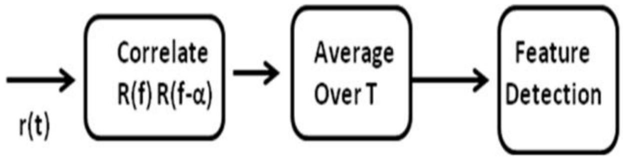

Figure 4: Block Diagram of Cyclostationary Feature Detector [41]

Implementation of spectrum correlation function for Cyclostationary feature detection is depicted in Figure 4. Detected features are the number of signals, their modulation types, symbol rates and presence of interferers. If the correlation factor is greater than the threshold then it means that there is a primary user in radio environment. Although it performs better than energy detector because it can differentiate between signal power and noise power, it is computationally very complex that requires long processing time, which generally degrades the performance of Cognitive radio. The main advantage of cyclostationary feature detection is that it can extract features from the waveform.

d) Comparison of the Spectrum Detection Techniques

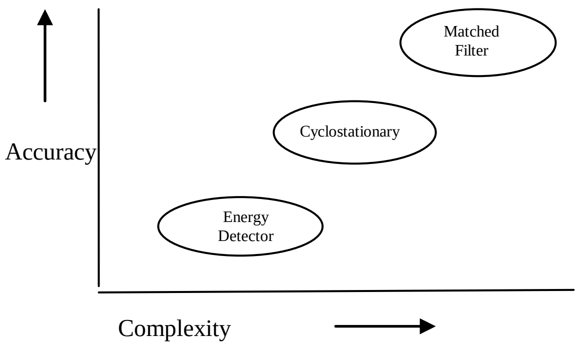

Figure 5: Comparison in terms of complexity and accuracy of different spectrum sensing techniques

As shown in Figure 5, complexity wise, energy detection outperforms the rest. However, accuracy wise, matched filter based detection shows better results.

Accuracy wise energy detector scores very poorly as compared with the other two. It cannot distinguish between

between signal power and noise power. The noise may not be stationary and its variance may not be known. Other problems with the energy detector include baseband filter effects and spurious tones. In the presence of co-channel or adjacent channel interferers, noise becomes non-stationary. Hence, energy detector based schemes fail while cyclostationarity-based algorithms are not affected.

On the other hand, cyclostationary features may be completely lost due to channel fading. Model uncertainties cause an SNR wall for cyclostationary based feature detectors similar to energy detectors. Furthermore, cyclostationary based sensing is known to be vulnerable to sampling clock offsets.

Matched-filtering is known as the optimum method for detection of primary users when the transmitted signal is known. The main advantage of matched filtering is the short time to achieve a certain probability of false alarm or probability of miss detection as compared to other methods that are discussed in this section. Matched-filtering requires cognitive radio to demodulate received signals. Hence, it requires perfect knowledge of the primary users signalling features such as bandwidth, operating frequency, modulation type and order, pulse shaping, and frame format. Moreover, since cognitive radio needs receivers for all signal types, the implementation complexity of sensing unit is impractically large. Another disadvantage of match filtering is large power consumption as various receiver algorithms need to be executed for detection.

IV. Conclusion

Our aim was to analyze the performance of existing spectrum sensing techniques in CRN, these being, energy detector, matched filter detector and cyclostationary feature detector. From the analysis, it is well understood that while selecting a sensing method, some tradeoffs has to be considered. The characteristics of primary users are the main factor in selecting a method. Other factors include, required accuracy, sensing duration requirements, computational complexity, and network requirements. Detection of traffic in a specific geographic area can be done locally using one of the algorithms discussed in this paper.

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