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Comparative Analysis of Primary Transmitter Detection Based Spectrum Sensing Techniques in Cognitive Radio Systems

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Abstract A key component in cognitive radios systems is the spectrum sensing. Cognitive radios are increasingly being considered to overcome the shortage and inefficiency of current static spectrum allocations. Spectrum sensing involves the detection of the primary user transmissions on a pre-assigned frequency band. If this particular band is not currently in use, it may be assigned to another user for certain duration of time. There are three main techniques for spectrum sensing: cooperative detection, primary transmitter detection and interference based detection. The focus of this work is on the analysis of an important class of spectrum sensing methods known as the transmitter detection. Generally transmitter detection includes three techniques: energy detection, matched filter detection and cyclostationary feature detection. Using simulations, a comparative analysis of the three techniques has been carried out in terms of probability of primary user detection and probability of false detection. It has been found that cyclostationary feature detection out performs the other techniques as it needs about 16-24 dBs lower SNR to achieve comparable performance levels.

Key words: Cognitive Radio (CR), Spectrum Sensing, Transmitter Detection, Energy Detection, Matched Filter Detection, Cyclostationary Feature Detection

INTRODUCTION

The major challenge in wireless communication is that the spectrum is getting crowded day by day due to the increase in the subscribers, using mobile services. Further, the allocated spectrum has been found to be significantly underutilized. The use of allocated spectrum varies at different times and over different geographical regions. In accordance to a report by Spectrum Policy Task Force of FCC, the spectrum is under or scarcely utilized and this situation is due to the static allocation of the spectrum (FCC, 2002). Thus, to overcome the spectrum deficiencies and the inefficient utilization of the allocated frequencies, it is necessary to introduce new communication models through which frequency spectrum can be utilized whenever the opening (hole) is available. Thus to resolve of the spectrum inefficiency problem, the concept of dynamic spectrum access has been devised. These dynamic techniques for spectrum access are known as Cognitive Radios (CR) (Mitola, J. and G.Q. Maguire, 1999) (McHenry and McCloskey, 2005).

Because of the limited spectrum FCC decided to make a paradigm shift by allowing more and more number of unlicensed users to transmit their signals in licensed bands so as to efficiently utilize the available spectrum. The report published by FCC in May 2004 initiates the idea which allows the use of this underutilized spectrum to unlicensed users (users that are not certified to be served as a primary license holder) to work in television spectrum in areas where the spectrum is not in use (FCC, 2003). Though, these unlicensed users should not create interference to the licensed user. When the licensed user wants to transmit its signal the unlicensed user should vacate the spectrum and should look for some other free space. This could be accomplished by incorporating “Cognitive Radios” to sense unused spectrum (Mitola, J. and G.Q. Maguire, 1999).

Cognitive Radio is characterized by the fact that it can adapt according to the environment by changing its transmitting parameters, such as modulation, frequency, frame format, etc (Ali Gorcin and Bhaskar Thiagarajan, 2007). The main challenges with cognitive radios are that it should not interfere with the licensed users and should vacate the band when required. For this it should sense the signals faster. This work focuses on the spectrum sensing techniques that are based on primary transmitter detection. In this category, three

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major spectrum sensing techniques “energy detection”, “matched filter detection” and “cyclostationary feature detection” are addressed (Parikshit Karnik and Sagar Dumbre, 2004). This work involves the comparative analysis of these spectrum sensing techniques for efficient working of cognitive radios.

The rest of the paper is organized as: In section-II, a brief introduction of cognitive radios and spectrum sensing is presented. In section-III, the system model developed in MATLAB for the analysis of spectrum sensing techniques, more specifically those belonging to class of transmitter detection method is presented. In section-IV, simulation results are presented and discussed whereas the section-V concludes the work.

II. Cognitive Radios and Spectrum Sensing:

Wireless networks are assigned fixed spectrum bands which are made consistent by the government agencies. A fraction of these fixed frequency spectrums are distributed among the authorized users and other services on continuous basis for large areas. As discussed in a report by Federal Communication Commission (FCC) on spectrum usage, the spectrum utilization varies from 15% to 85% depending on the geographical area (FCC, 2002). An additional estimation was given by Jean Pierre Hubaux on spectrum concentration wherein he observed the spectrum allocation and usage at six locations (Locations: New York city; River bend Park, Great Falls, VA; Tyson's Corner, VANSF Roof, Arlington, VA; NRAO, Green bank, WV; SSC Roof, Vienna, VA). The results of this study are shown in Figure-1 (Jean Pierre Hubaux, 2005). It is noticed that the spectrum is highly underutilized although the network operators had spent billions of dollars in order to buy spectrum.

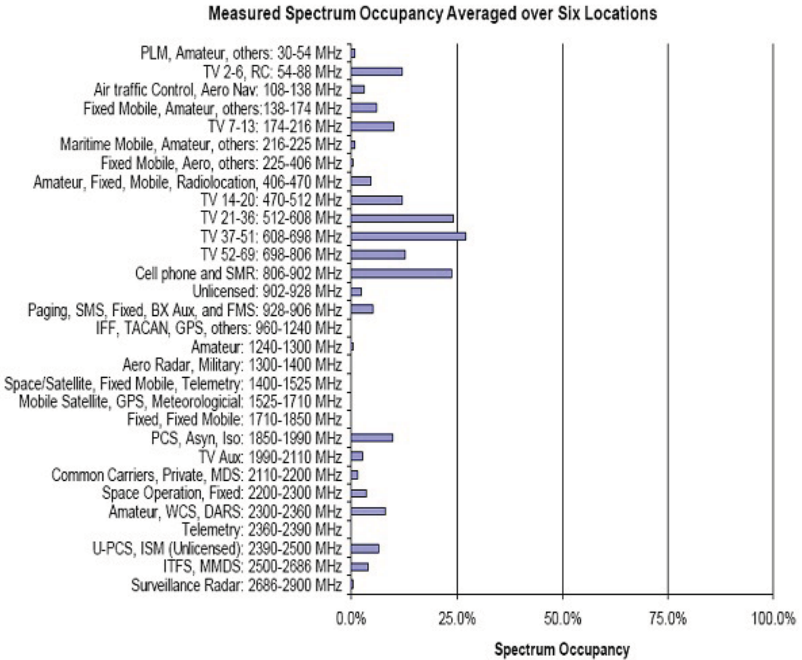

Fig. 1: Spectrum Concentration

The spectrum is underutilized keeping in view the present circumstances; as discussed in the first chapter. It is not possible to replace the whole current system, so the new technique must be able to coexist with already existing communication system and must not interfere with the primary users. We can improve the spectrum utilization by using the cognitive radio technology by adding the secondary users with the primary user (Cabric, D., 2004). The concept behind the Cognitive users is that they have the ability to continuously sense the licensed spectrum to search the unused locations, once the hollow locations are identified; Cognitive radio users utilize those locations for transmission without interrupting the primary users (Mitola, J. and G.Q. Maguire, 1999).

The primary aim of a cognitive radio system is to get hold of a best available channel by using the cognitive capability and re-configurability (Haykin, S., 2005). Cognitive capability is defined as the capacity of the radio system to gather information from the surroundings. It requires very complex or sophisticated techniques in order to observe the sudden variations and changes in the radio environment without interfering with the existing users. Cognitive capability plays a major role to identify the unused or white spaces in the frequency spectrum at a particular time so as to select a suitable spectrum along with the suitable operating parameters. These unused channels are called spectrum holes or white spaces (Haykin, S., 2005). The cognitive radio enables the use of white spaces in the spectrum that become available temporarily. As soon as the primary user returns to its band, 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. A concept of ***Cognitive Cycle*** has been introduced which involves spectrum sensing, spectrum decision, spectrum mobility and spectrum sharing (Ian F. Akyildiz, 2006).

Spectrum Sensing involves the monitoring of the available radio spectrum, gathering information and detection of the spectrum holes. Spectrum sensing includes the collection of data from the radio environment to detect the unused channels present in the spectrum. ***Spectrum Decision*** is used by the cognitive radio to find out the transmission data rate, modes and bandwidth. Then a suitable spectrum band is selected according to the requirements of the user and characteristics of the spectrum. In ***Spectrum Mobility*** process, a cognitive radio user changes the frequency of operation to the best available band. Thus through the dynamic access mechanism, it facilitates the seamless transition to better radio channels. ***Spectrum Sharing*** provides the fair spectrum scheduling method amongst the coexisting cognitive users when multiple such users attempt to access the spectrum. This access needs to be coordinated in order to avoid the collisions in the segments of the spectrum that overlap (Ian F. Akyildiz, 2006).

In spectrum sensing cognitive radio users search for the holes in the frequency bands and if found transmits on that particular frequency. The best method to spot spectrum holes is by following the transmissions of the primary users that are present in the given range; however it is difficult for the cognitive radios to search the whole range of frequencies. There are different techniques used for the spectrum sensing, each has its own limitations. Generally three different techniques are used for spectrum sensing, which are cooperative detection, transmitter detection and interference based detection (Parikshit Karnik and Sagar Dumbre, 2004) (Ganesan, G. and Y. Li, 2007). The focus of this work is on transmission detection techniques which consist of energy detection, match filter detection and cyclostationary detection and are discussed in next section.

III. System Model for Transmitter Detection Based Spectrum Sensing Techniques:

Cognitive users transmit on the unused channels present in the spectrum. The spectrum sensing mechanism allows them to determine the presence of a primary user. In primary transmitter detection based techniques, a cognitive user determines signal strength generated from the primary user. In this method, the locations of the primary receivers are not known to the cognitive users as there is no signaling between the primary users and the cognitive users. The hypothetical mathematical model can be expressed as follows:

$$x(t) = n(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots H_0$$

$$x(t) = h * s(t) + n(t) \ldots\ldots\ldots\ldots H_1$$

Where 'x(t)' is the signal received by the CR user, 'n(t)' is the AWGN noise, 's(t)' is the primary user signal and 'h' is the amplitude of primary user signal. 'H_0' represents the absence of primary user and 'H_1' represents the presence of primary user (Parikshit Karnik and Sagar Dumbre, 2004). The primary transmission detection includes energy detection, match filter detection and cyclostationary detection.

The major task is to analyze the performance of three primary transmitter based detection techniques and to provide a comparison of the techniques that can help improve the band utilization by cognitive users along with the licensed users. For this purpose, a system model for transmitter detection based spectrum sensing techniques has been developed using MATLAB. Figure-7 shows the block diagram of the complete system model. In this model, a radio environment has been created in which 'n' number of primary users are transmitting on different frequencies. It is considered that there are a number of primary users that are transmitting data (signals) in the radio environment and a certain number of cognitive (CR) users are receiving that data that can be used to determine the existence of primary user. The primary users are randomly selected to generate input signals. Those signals are mainly exchanged between primary users. CR users also receive these signals and check the radio environment for the presence or absence of the primary or licensed user. The cognitive radio (CR) users will detect the presence or absence of users by using any of the spectrum sensing techniques like “energy detection”, “matched filter detection” or “cyclostationary feature detection”.

The results are gathered in terms of “probability of primary user detection (Ppd)” and “probability of false detection (Pfd)”. The “probability of primary user detection (Ppd)’ is defined as probability of the correctly detecting the existence of primary user on the particular band. Whereas, the “probability of false detection (Pfd)” implies that a primary user is detected on a given band although no primary user is actually transmitting. These measures are computed at different values of SNR's over a significant number of iterations. For primary user transmissions, a modulation technique is applied at the first stage. This modulation technique can be of any type, but in our model we are using binary phase shift keying (BPSK). In BPSK we transmit cosine for 1 and negative cosine for 0. After this signal is passed through the channel selection block, which is required to assign a different frequency to each primary user. We have considered the GSM range of frequencies for this work. At third step signal is passed through band pass filter for single side band transmission to select the band for a user. The channel model used in this analysis is the AWGN (Additive White Gaussian Noise) and this channel model does not cater for fading, non linearity and interference.

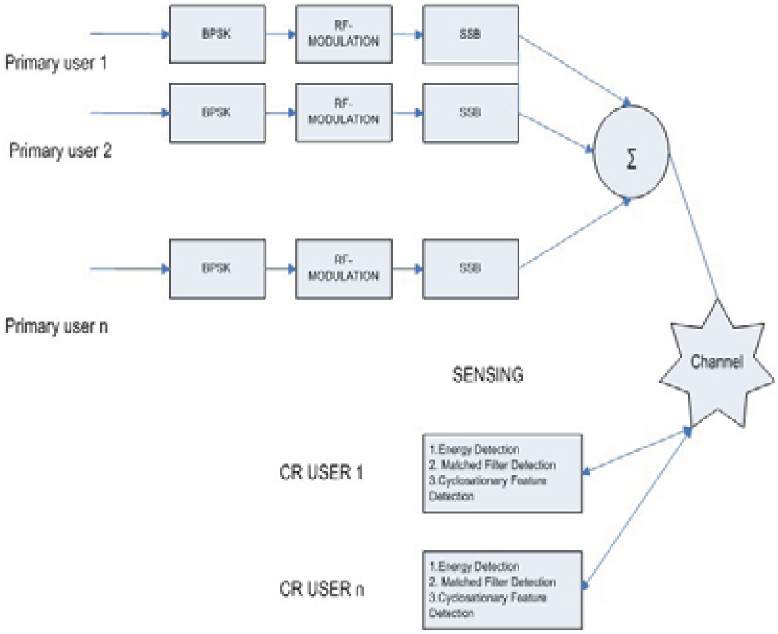

Fig. 2: System Model for Transmitter Detection Based Spectrum Sensing Techniques

A brief description of working and implementation of the three primary transmitter detection techniques being analyzed in this study is as given below;

1. Energy Detection:

Energy detection technique is simple to implement because the receiver does not necessitate any prior information to detect the primary user signal. This technique is used where the receiver does not have much information about the primary user and only the value of white Gaussian noise is known. Mathematical model for energy detection is given by the following equation (Parikshit Karnik and Sagar Dumbre, 2004) (Sahai, A., 2004):

$$Y[n] = \begin{cases} W[n] & H_0 \\ X[n]+W[n] & H_1 \end{cases}$$

H_0 = Primary User Absent
H_1 = Primary User Absent
where n: 1, 2, 3,…N;
N: sampling interval;
W[n]: additive white Gaussian noise; X[n] : Signal

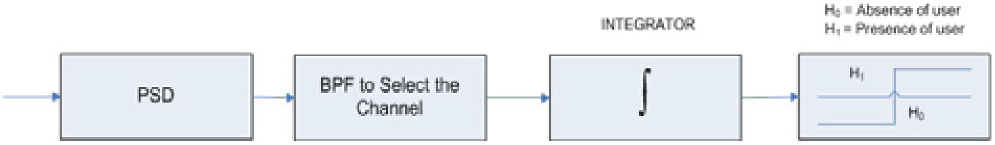

Fig. 3: Block Diagram of Energy Detection

The block diagram for the energy detection technique is shown in the Figure-3 (Parikshit Karnik and Sagar Dumbre, 2004). 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 pre-defined threshold. This comparison is used to discover the existence of absence of the primary user. The threshold value can set to be fixed or variable, based on the channel conditions (Parikshit Karnik and Sagar Dumbre, 2004). The "probability of primary user detection" and the "probability of false detection" for the energy detection method can be calculated by the given equations (Ian F. Akyildiz, 2006).

$$P_d = P\,[Y > \lambda / H1] = Q_m\,(\sqrt{2\gamma}, \sqrt{\lambda}),$$

$$P_f = P\,[Y > \lambda / H0] = \Gamma\,(m, \lambda/2) \,/\, \Gamma\,(m)$$

where λ=SNR,
n=TW (Time bandwidth product),
$\Gamma(.)$= Complete gamma function,
$\Gamma(.,.)$=Incomplete gamma function,
Qm= Generalized Marcum function.

The process flow diagram for energy detection is as shown in Figure-4.

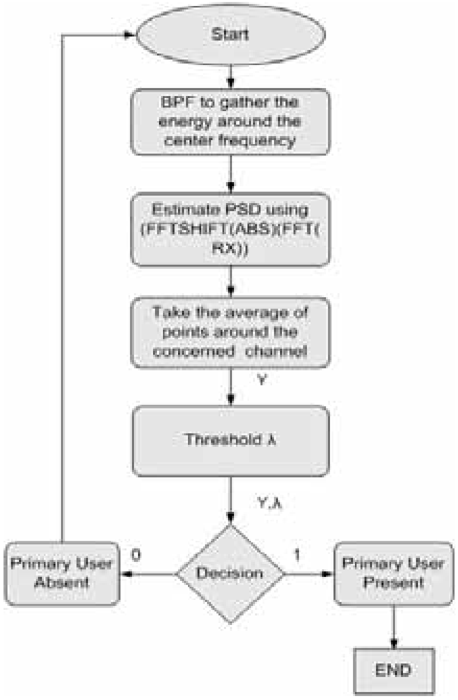

Fig. 4: Process Flow Diagram for Energy Detection

Energy detection technique has a number of limitations of. One of the key problems is the increased sensing time; further, the performance of energy detection suffers in the case when power of the noise is unknown, as we decide the value of threshold depending on the noise power. Power of noise varies continuously depending upon the temperature, interference and other effects, so fixed threshold is the problem. There is some minimum SNR value after which energy detection starts working; below that minimum SNR value this technique does not work. Energy detection method is limited in the sense that differentiation between noise, signal, and interference is not possible; it can only indicate about the existence or absence of the signal. Further this method does not work for the spread spectrum techniques like direct sequence and frequency hopping (Ian F. Akyildiz, 2006) (Sahai, A., 2004).

2. Matched Filter Detection:

In matched filter detection, linear filter is used that maximizes the SNR. Matched filter 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 the 'h', the impulse response of matched filter that is matched to the reference signal for maximizing the SNR. Detection by using matched filter is useful only in cases where the information from the primary users is known to the cognitive users. Block Diagram of this technique is shown in the Figure-5 (Parikshit Karnik and Sagar Dumbre, 2004) and the process flow diagram is in Figure-6.

Fig. 5: Block Diagram of Matched Filter Detection.

Initially the input signal passes through a band-pass filter; this will measure the energy around the related band, then output signal of BPF is convolved with the match filter whose impulse response is same as the reference signal. Finally the matched filter out value is compared to a threshold for detecting the existence or absence of primary user (Parikshit Karnik and Sagar Dumbre, 2004). One of the limitations of this technique is that a known signal is required to construct the reference signal; further this technique is feasible only when licensed users are cooperating. Even in the best possible conditions, the results of matched filter technique are bound by the theoretical bound (Ian F. Akyildiz, 2006).

3. Cyclostationary Feature Detection:

Cyclostationary feature detection is a much optimized technique that can easily isolate the noise from the user signal. In cyclostationary feature detection technique, CR can distinguish between noise and user signal by analyzing its periodicity. The block diagram for the cyclo-stationary feature detection is shown in Figure-7 (Parikshit Karnik and Sagar Dumbre, 2004). The process flow is depicted in Figure-8.

In cyclo-stationary feature detection, modulated signals (transmitted signal) which carry information are usually sine waves; pulse trains i.e. have some periodicity in it. These signals are named as cyclo-stationary since the mean and the autocorrelation functions are periodic. Spectral correlation function (SCF) is used for analyzing the features of signals i.e.; whether exhibit periodicity or not. SCF can clearly distinguish between the noise energy and the modulated signal energy because the noise is wide-sense stationary which has no periodicity. At the first stage, BPF is used to measure the energy around the related band, and then FFT is computed of the signal received from band pass filter. Correlation block will correlate the signal and feature detection block will detect features like modulation type, number of signals and symbol rates (Cabric, D., 2004). Cyclostationary detection can perform better than energy detection and matched filter detection because it has the ability to distinguish between noise and signal (Parikshit Karnik and Sagar Dumbre, 2004). The

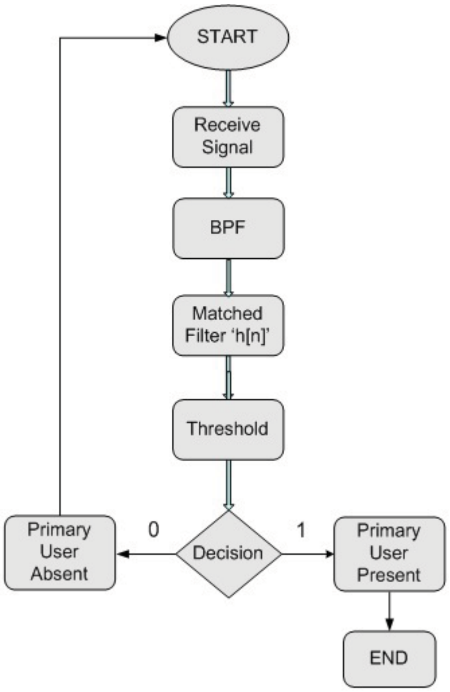

Fig. 6: Process Flow Diagram for Matched Filter Detection

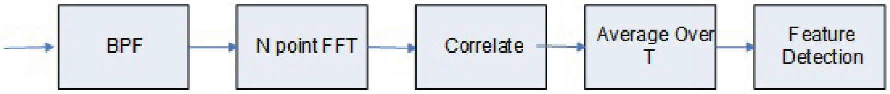

Fig. 7: Block Diagram of Cyclostationary Feature Detection

major advantage of cyclostationary feature detection over other detection techniques is that it performs very well for larger noise on channels. The major limitations of this method are that it requires long processing time and is complex in computation, so difficult to implement. Further, it cannot detect the type of communication, so it reduces the flexibility of cognitive radio (Parikshit Karnik and Sagar Dumbre, 2004).

IV. Results and Analysis:

An extensive set of simulations have been conducted using the system model as described in the previous section. The emphasis is to analyze the comparative performance of three spectrum sensing techniques. The performance metrics used for comparison include the "probability of primary user detection" and "probability of false detection". The number of channels and the number primary users considered in this analysis is twenty five and respectively. The SNR of the channels is considered to be precisely same and the channel model is AWGN with zero mean. The results are shown in Figure-9 and Figure-10.

Probability of Primary Detection:

Figure-9 depicts the "probability of primary user detection" as a function of SNR for the three cases: (i) energy detection, (ii) matched filter detection and (iii) cyclo-stationary feature detection.

It is observed that for energy detection and matched filter detection, much higher SNR is required to obtain a performance comparable to cyclostationary feature detection. For energy detection, about 16 dBs higher SNR is needed to achieve 100% probability of detection whereas for matched filter detection, about 24 dBs higher SNR is required. For cyclostationary feature detection, 100% probability of detection is attained at -8 dBs. Cyclostationary feature detection performs well for very low SNR, however the major disadvantage is that it requires large observation time for occupancy detection. Matched filter detection performs well as compared to energy detection but restriction lies in prior knowledge of user signaling. Further, cyclostationary feature detection algorithm is complex as compared to other detection techniques.

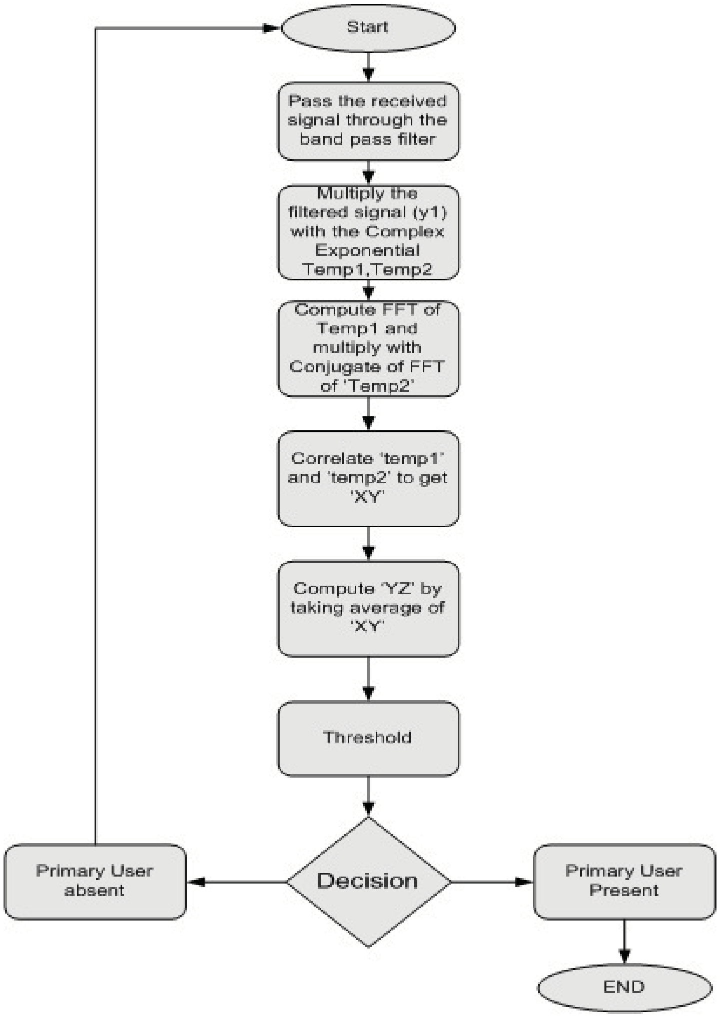

Fig. 8: Process Flow Diagram for Cyclostationary Feature Detection

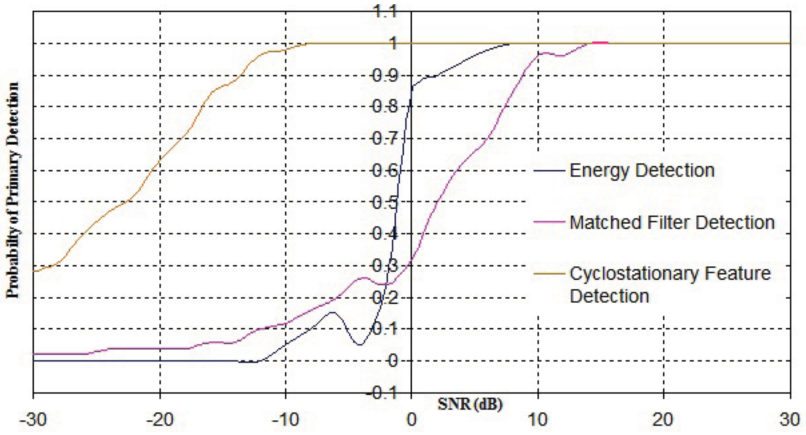

Fig. 9: Probability of Primary Detection

Probability of False Detection:

Figure-10 illustrates the "probability of false detection" for three transmitter detection based spectrum sensing techniques versus SNR.

It is observed that "probability of false detection" of cyclostationary feature detection is much smaller as compared to other two techniques. In fact, it is zero for the range of SNR considered in this study i.e., -30 dB to +30 dBs. It is further seen that the "probability of false detection" for energy detection technique is inversely proportional to the SNR. At low SNR we have higher probability of false detection and at high SNR we have lower probability of false detection, because energy detection cannot isolate between signal and noise. The probability of false detection for energy detection and matched filter detection approaches zero at about +14 dBs and +8 dBs respectively.

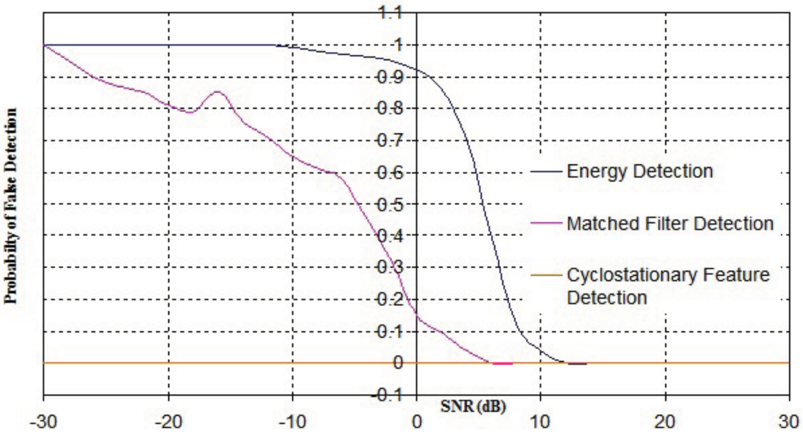

Fig. 10: Probability of False Detection

V. Conclusions:

Wireless spectrum remains underutilized in the present circumstances and to improve the spectrum utilization, cognitive radios are introduced which opportunistically utilize the holes present in the spectrum. One of the most essential aspects of a cognitive radio system is spectrum sensing and various sensing techniques are being used. In this work, we have focused on the transmitter detection based techniques which include energy detection, matched filter detection and cyclostationary detection. Each of the sensing techniques has its own pros and cons. Energy detection has the advantage that no prior information about the primary users is required. This technique does not perform well for the low SNR values; there is a minimum SNR required after which it starts working. The results gathered in our work indicate that energy detection starts working at -7dBs of SNR. Matched filter detection is better than energy detection as it start working at low SNR i.e. -30dBs. Cyclostationary feature detection is better than both energy detection and matched filter detection because it gives better results at the lowest SNR, i.e. for values below -30dBs. The results indicate that performance of energy detection gets better with increasing SNR as the "probability of primary detection" increases from zero at -14 dBs to 100% at +8 dBs and correspondingly the "probability of false detection" improves from 100% to zero. Similar performance is achieved for the matched filter detection as both the "probability of primary detection" and the "probability of false detection" show improvement as SNR varies from -30 dBs to +8 dBs. Whereas the cyclostationary feature detection out performs the other two techniques as 100% "probability of primary detection" and zero "probability of false detection" is achieved at -8 dBs. However, the processing time of Cyclostationary detection is greater than other two techniques.

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