COMPREHENSIVE REVIEW ON SPECTRUM SENSING TECHNIQUES IN COGNITIVE RADIO

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Abstract:

In wireless communication, spectrum sensing (SS) is one of the important techniques to study about the radio environment. Spectrum sensing phenomenon is used to estimate the unutilized frequency band of whole radio spectrum. Utilization of available spectrum can be improved by enhancing the spectrum sensing techniques. The performance of available spectrum sensing techniques may degrade substantially in low signal to noise ratio, multipath fading & shadowing environments. This may lead to increase in probability of false alarms and decrease in probability of detection. This paper gives the categorization of different spectrum sensing techniques (SST) and it also explores the different methods used in spectrum sensing. Comparison of energy detector (ED), matched filter detection (MFD), cyclostationary feature detection (CFD), waveform detection (WD) and eigen value detection (EVD based on their methodology and accuracy is also present in this paper. Various issues associated with these spectrum sensing techniques are highlighted here and futuristic solutions proposed for improvement in existing spectrum sensing techniques.

1 Introduction

Cognitive radio technology provides enhancement in utilization of available spectrum area. For the available frequencies, unlicensed user/secondary users are co-transmitting with licensed user/primary users via spectrum hole (SH) access [1]. Where spectrum hole is unutilized frequency band, available for the secondary users. Spectrum opportunities depends upon the absence or presence of primary user signal.

Specifically, cognitive capabilities and re-configurability property of cognitive radio used to recognize free frequency band and improved the performance of detection [2]. By continuously monitoring spectrum, cognitive radio investigates the level of interference and accordingly controls the level of interference so that during transmission no harm will be introduced.

The operation of the cognitive radio is divided in three modes i.e. underlay mode (UM), overlay mode (OM) and hybrid mode (HM). In underlay mode, without any interference both primary and secondary users share the available frequency band. [3,37] In overlay mode, by using spectrum sensing techniques, secondary users detect the unused frequencies band and after that transmits the data without any interference with the primary user. In hybrid mode, both underlay and overlay mode combination has been used. Main functions performed by CR network can be spotted in Figure 1.

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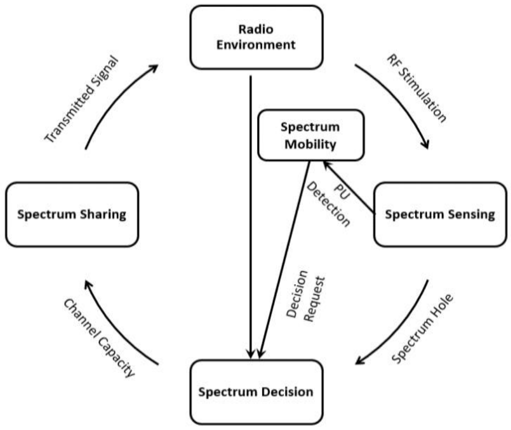

Figure 1. Cognitive Cycle.

(i) **Spectrum sensing**: At this stage, cognitive radio continuously monitors the radio environment and geographically detects possible free frequency band without any interference with any other users.

(ii) **Spectrum decision**: For this, cognitive radio might use data from authorized policies and databases to improve the operations and get available spectrum.

(iii) **Spectrum sharing**: Transmitted cognitive users (Primary user/Secondary user) with selected spectrum band without affected the primary user.

(iv) **Spectrum mobility**: In this case cognitive radio vacates the channel if the primary/licensed user is detected.

Previous researchers focused their researches main on spectrum sensing, as many challenging factors (multipath fading, shadowing and time dispersion) makes it difficult to perform this function [21]. Signal/power content available in the given spectrum band can be calculated by using spectrum sensing technique. But if the term cognitive radio is attached, then it consists of wider knowledge of available spectrum & type of signal. Detailed overview of spectrum sensing technique and existing current challenging factors presented in this paper.

The objective of this paper is to review the spectrum sensing technique and find the latest trends & future scope of SST. The sections of this paper consist of a) Detailed explanation about the spectrum sensing techniques, b) Issues in spectrum sensing techniques, c) Discussion on the implementation of spectrum sensing and how in real time environment by using hardware platforms implementation will take place [5,24]. Various aspects of spectrum sensing are shown in Figure 2.

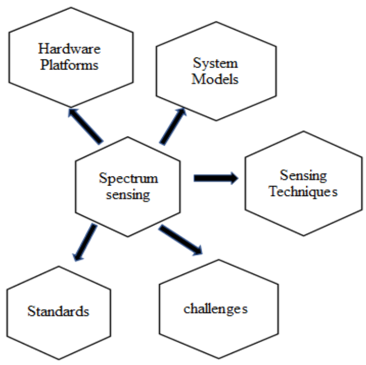

Figure 2. Spectrum sensing aspects.

2 Categorization of spectrum sensing techniques

For better awareness of spectrum, sensing of the spectrum techniques has been implemented. The efficiency of the sensing can be improved by using either single or multiple users in a co-operative manner [4,26]. Numerous classifications of spectrum sensing techniques are available. One of the classifications is Narrowband & Wideband sensing based on the available bandwidth. According to the availability of prior knowledge of the signal, non-blind, semi blind & blind are classifications of spectrum sensing techniques [6,23]. Cooperative & Non-cooperative sensing is the other classification which is based upon the number of users. Another classification is based upon the interference detection which includes Transmitter Detection (TD), Receiver Detection (RD) & Interference Detection (ID) spectrum sensing techniques. Classification of spectrum sensing technique shown in Figure 3.

(i) Narrowband & Wideband Spectrum Sensing: Spectral opportunities of narrow frequency range could be achieved by using narrowband spectrum sensing technique, whereas for wider frequency range wideband spectrum sensing technique has been used [7,17]. According to literature survey energy detector and feature detection are the most widespread spectrum sensing techniques & eigen value-based technique is most advanced technique. In the case of wideband spectrum sensing technique, spectrum can be sensed by simultaneously observing the sub & multiple bands. Nyquist & Sub-Nyquist sensing techniques are the classification of wideband spectrum sensing. If the sampling rate of digital signals are equal or greater than the Nyquist rate, then it lies under the Nyquist spectrum sensing but if the sampling rate of digital signals are less than the Nyquist rate, then it lies under the sub-Nyquist spectrum sensing technique [8,25]. Due to advanced spectral analysis, multi-taper and compressive sensing also found under the wideband sensing technique.

(ii) Cooperative & Non-Cooperative Spectrum sensing: Cooperative sensing appeared when own function of cognitive radio takes place and other name of this sensing is local or single sensing. Energy Detection (ED), Cyclostationary Feature Detection (CFD) and Matched Filter Detection (MFD) techniques come under the cooperative spectrum sensing technique (CSST) [18]. In case of real time, operation of non-cooperative spectrum sensing technique (NCSST) is simple and easy as compared to cooperative spectrum sensing technique. Some of the issues like noise uncertainty, shadowing effect and fading can be resolved by adopting cooperative sensing method [22]. Due to multipath and shadowing effect false probability of detection takes place and results a problem of interference. However, exact detection of primary user signal takes place that’s why detection information shared with the secondary user by using cooperation method. Further classification of cooperative spectrum sensing technique are centralized method, distributed method, and hybrid method. Also, fusion techniques have been implemented in cooperative sensing method instead of non-cooperative sensing technique [9].

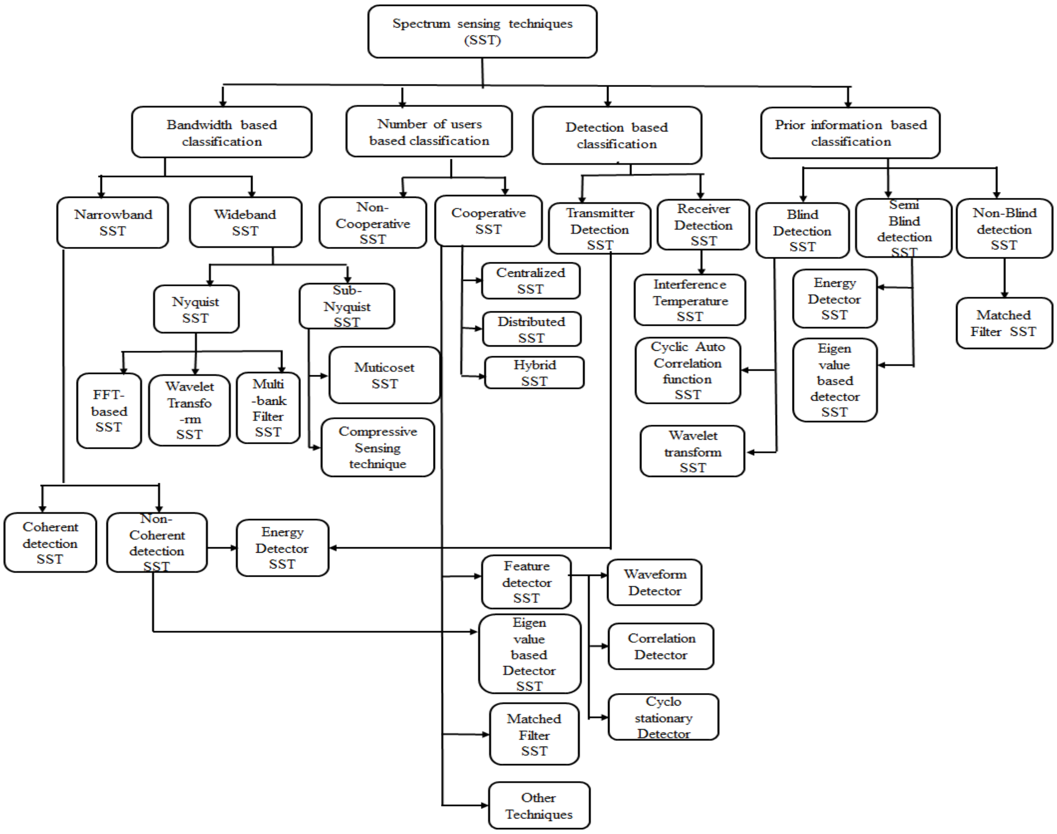

Figure 3. Classification of spectrum sensing techniques.

(iii) Transmitter Detection & Receiver Detection: If the spectrum is detected at transmitter side or receiver end side, accordingly it can be called as transmitter detection & receiver detection. Matched filter detection (MFD), energy detection (ED) technique and cyclostationary feature detection (CFD) algorithms has been used to perform transmitter detection. Operation of the receiver detection is difficult as compared to transmitter detection while limiting the interference to primary users, because the continuous sensing required at the receiver side. Spectrum sensing in case of receiver method depends on the interference temperature limit (ITL) which also depends upon the interference power value of the secondary user (SU) and difference of both the values gives the interference temperature gap (ITG) and these values will be used by the secondary user/unlicensed users. This interference temperature limit (ITL) signifies the tolerance level of primary user where the primary user will work without affecting the performance of any other user and its services. Cognitive user can utilize this interference gap for transmission of secondary users in short range [16].

(iv) Non-blind, semi blind and blind Spectrum Sensing Technique: These are classified depending upon the former information of the signal & noise. Blind techniques only required the knowledge of received signal, no other additional information is required. Cyclic Auto-correlation Function (CAF), Wavelet Spectrum Sensing (WSS) are the categorization of this technique [11]. Prior information of the noise & cyclic frequency is the requirement of semi-blind technique. Energy detection (ED) and detection based upon the eigen values are the category of semi-blind technique. Whereas non-blind technique required both the knowledge of primary user signal and noise information. Matched filter detection (MFD) is the category of this technique [12].

2.1 Comparison of different spectrum sensing techniques (SST)

Energy Detection (ED), Matched Filter Detection (MFD), Cyclostationary Feature Detection (CFD), Waveform Detection (WD) & Eigen Value Detection (EVD) are the basic types of spectrum sensing techniques and by the modification in these techniques, new efficient spectrum sensing techniques would develop [13]. The detection performance of these techniques depends upon some specific features shown in Table (1).

a. Energy detection: No prior information of the primary user signal is required in this technique. Received output from energy detector (E_0) is compared with the threshold value (Υ_0). Figure 4 shows, how the detection of primary user takes place by comparing power spectral density of received signal with set value of threshold.

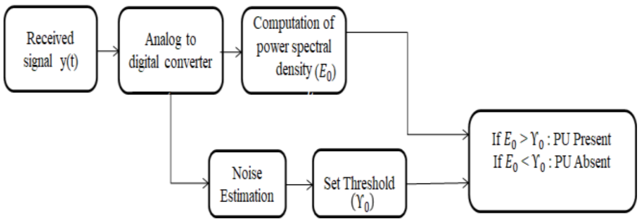

Figure 4. Block Diagram of Energy detector.

Let us assume value of received signal R(n) represented by equation (1).

$$R(n)=M(n)+W(n) \quad (1)$$

Where gaussian noise is represented by W(n) and M(n) is the signal to be detected. Equation (2) is used to calculate energy of the received signal.

$$T=\sum_{n=0}^{N} R(n)^2 \quad (2)$$

Total number of samples are represented by N. Detection of primary user takes place by comparing calculated energy (T) with set value of threshold (Υ_0). Following hypothesis has been used for detection of primary user

R(n)=W (n): H0 (Absence of PU)
R(n)=M(n)+W(n): H1 (Presence of PU)

Processing for detection of primary user in energy detector shown in Figure 5.

Probability of actual detection (P_{ad}) and probability of false alarm detection (P_{fad}), are the two parameters which are used to analyze the performance of energy detector. These two are represented by equation (3) and (4).

$$P_{fad} = Q\left(\frac{\lambda_d - n_s\tau_n^2}{\tau_n^2\sqrt{2n_s}}\right) \quad (4)$$

λ_d is value of detection threshold, calculated by the formula given in equation (5)

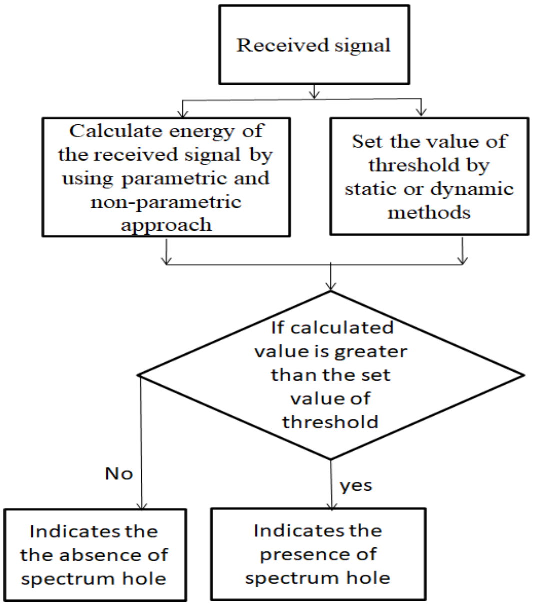

Figure 5. Flow chart for energy detector spectrum sensing technique.

$$\lambda_d = \tau^2(Q^{-1}(P_{fad})\sqrt{2n_s} + n_s)) \quad (5)$$

Q^{-1} shows inverse of Q function.

$P_{ad} = (E_0 > \Upsilon_0;\ H_1)$ (indicates actual presence of primary user)

$P_{fad} = (E_0 < \Upsilon_0;\ H_0)$ (indicates actual presence of primary user)

For better performance, P_{fad} should be minimum and P_{ad} should me maximum. Energy detector performed well in high SNR.

b. Matched filter detection: This spectrum sensing technique is the category of coherent detection method. Secondary user has the prior information of transmitted signal for the detection of primary user signal and it is also called optimum detection method. This method is best suited for Additive Gaussian noise environment because of its capability to maximize the signal to noise ratio of the received signal. For detection of primary user, matched filter correlates the previously detected primary user signal with current received signal. If nature of both signals is different, it indicates the availability of spectrum holes else no availability of free spectrum holes. In short time duration, with fewer received signal it performs actual detection of primary user/licensed user and minimize the probability of false detection (P_{fad}) [10,38]. Block diagram of matched filter detection shown in Figure 6.

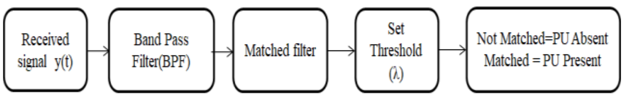

Figure 6. Block Diagram of Matched filter detection.

According to the type of signals, matched filter needs receiver for each signal and executes the algorithms which results in implementation complexity & power consumption [14]. In matched filter detection, exact information of signal like type of modulation, shape of the pulse and operating frequency are required. To maintain synchronization & control in wireless communication networks (WCN) it reveals certain parameters like pilot tones (special secret code embedded with signal), spreading codes & preambles (type of signal used to synchronize transmission timings). By using these two hypothesis methods, primary user detection will take place. The function of matched filter detection followed by equation (6).

$$R(n) = \sum_{h=-\infty}^{\infty} h(n-1)u(n) \tag{6}$$

Where received signal is represented by R(n), u(n) shows the unknown signal and 'h' shows the impulse response of matched filter detection (MFD). The detection of primary user operation in matched filter detection is explained in Figure 7.

MFD (matched filter detection) performance can be analyzed by using following equations (7) and (8)

$$P_{ad} = Q\sqrt{\frac{£s-€p}{€p\tau_p^2}} \tag{7}$$

$$P_{fad} = Q\sqrt{\frac{£s}{€p\tau_p^2}} \tag{8}$$

Value of sensing threshold is represented by $£s$ and calculated by the formula given in equation (9)

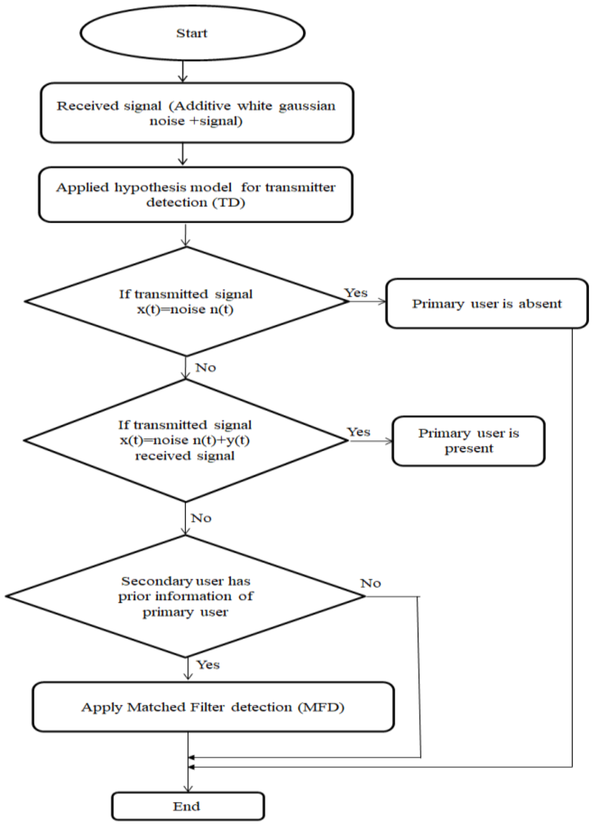

Figure 7. Flow chart for matched filter detector spectrum sensing technique.

$$£s = Q^{-1}(P_{fad})\sqrt{€p\tau_p^2} \tag{9}$$

Where $€p$ indicates energy of the PU signal and τ_p^2 is SD (standard deviation) of PU signal.

c. Cyclostationary feature detection: If there is any periodic variation of mean & autocorrelation w.r.t time present in the received signal, then it indicates the presence of primary user with received signal otherwise it represents noise. In low signal to noise ratio (SNR) environment, cyclostationary technique is applicable because it can easily differentiate between signal and noise [19,20]. Block diagram of cyclostationary feature detection shown in Figure 8.

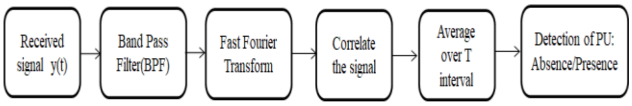

Figure 8. Block Diagram of Cyclostationary feature detection.

If the information of the pilot signal (single frequency signal used for synchronization, control, equalization etc.) in the primary user is known, it will enhance the capability of detection even in the presence of noise. In this technique time-domain to frequency domain transformation followed by hypothesis test takes place to perform the detection. Cyclic autocorrelation function (CAF) for received signal can be expressed by the equation (10).

$$R_y^x = E[Y(t+\tau)\ Y^*(t-\tau) e^{j2\pi\alpha t}] \quad (10)$$

Where α represents the cyclic frequency (CF) and * is the complex conjugation & E[.] denotes the expectation operation. If the Fourier series expansion (FSE) of the CAF is used, then it is called cyclic spectrum density (CSD) and the maximum value will be obtained when fundamental frequency of the transmitted signal will be equal to the cyclic frequency. Fig.9 shows the schematic of cyclostationary feature detection. For detection of primary user signal, cyclostationary feature detector observes the mean & autocorrelation of the received signal.

d. Waveform Detection: Waveform based sensing technique applicable only for those system which consists information of the transmitted signal pattern. Performance analysis of the sensing depends upon the corresponding length of the sensing pattern. If the length of the pattern increases correspondingly sensing performance also increases [39].

The matrix equation based on waveform sensing is expressed by the equation (11).

$$Q = R[\textstyle\sum_{n=1}^{N} y(n) s^*(n)] \quad (11)$$

In this * denotes the conjugation operation. If the primary user is absent, then the metric value is given by the following equation (12).

$$Q = R[\textstyle\sum_{n=1}^{N} w(n) s^*(n)] \quad (12)$$

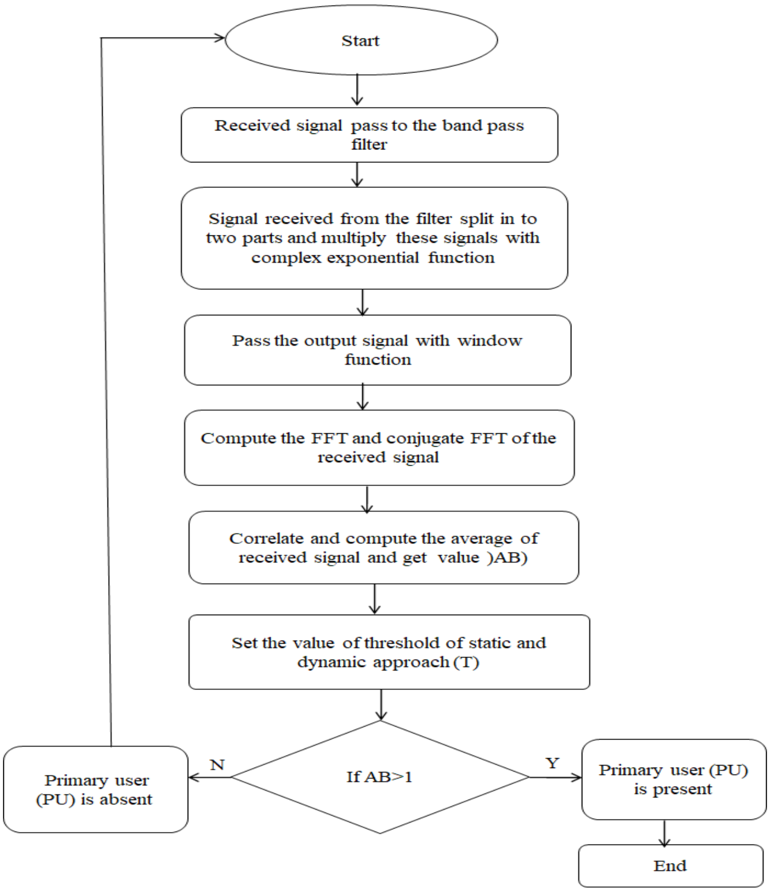

Figure 9. Flow chart for cyclostationary feature detector spectrum sensing technique.

If the case, primary user is present, then the sensing metric (SM) represented by following equation (13)

$$Q= R[\sum_{n=1}^{N} y(n)\, s*(n)] + R[\sum_{n=1}^{N} w(n) s*(n)] \tag{13}$$

e. Eigen value detection: This technique is based upon the formation of matrix from the received signal and calculation of eigen values. Detection of primary user depends upon the comparison with the threshold value. [31].

By comparing the decision metric value with fixed threshold, presence or absence of primary user decision can be made.

Table 1. Comparison of various spectrum sensing techniques.

Features	Energy Detector (ED)	Matched Filter Detection (MFD)	Cyclostationary Feature Detection (CFD)	Waveform Detection (WD)	Eigen value Detection (EVD)
Methodology Adopted	Calculate the value of energy present in the received signal by using parametric and non-parametric approach	Particular waveform pattern protruded in the same direction as the direction of identified licensed user/primary user	Matched the features of received signal with prior available primary user by using cyclic spectrum density (CSD) function	Synchronization is possible in wireless networks due to availability of waveform patterns	Formation of covariance matrix by the eigen values.
Accuracy in terms of sensing	Performance is better in high signal to noise ratio (SNR).	Appropriate for all ranges of signal to noise ratio.	Appropriate for all ranges of signal to noise ratio.	Suitable for all ranges of signal to noise ratio.	Suitable for all ranges of signal to noise ratio.
Level of complexity	Implementation complexities are less	Implementation complexities are high	Implementation complexities are medium	Implementation complexities are medium	Implementation complexities are less
Robustness	Prior information of transmitted signal is not required	Prior information of transmitted signal is required	Prior information of transmitted signal frequency is required	Knowledge of the transmitted signal pattern is required	Does not required any knowledge of the transmitted signal.
Design Choices	Threshold selection is difficult	Accuracy can be improved by considering the characteristic of transmission	Improved the accuracy by considering cyclostationary feature	waveform pattern increased the accuracy level	By choosing different range of eigen value, meliorate accuracy.
Sensing time required	Less sensing time required as compared to feature detection technique	Minimal sensing time required by this technique as compared to other	Maximum sensing time used in this technique	Less time required for sensing	Less time required for sensing

From this research paper, new researchers can easily differentiate between different spectrum sensing techniques in terms of their methodology adopted. In each spectrum sensing technique, presence of free spectrum hole for better utilization of spectrum can be achieved by considering different approaches.

From the survey, it is observed that the signal to noise (SNR) has a great impact on the sensing process. Few spectrum sensing techniques gave better performance in high signal to noise ratio whereas others can give appropriate result for all ranges of signal to noise ratio. Implementation complexities of each spectrum sensing technique can be high or low, which totally depends upon whether there is need of prior knowledge of primary user signal or not. Due to the various issue present in spectrum sensing like interference, channel and noise uncertainty, there is requirement of robustness in spectrum sensing techniques which depends upon the input signal and noise effect [41,42,43]. Design choices of various techniques depends upon the static and dynamic threshold selection, eigen values, cyclostationary and waveform patterns.

Total time of spectrum sensing depends upon the sensing time and transmission time. Sensing time gives the actual detection of free spectrum hole and generally this is less than the transmission time. This survey analyzed the sensing time for different spectrum sensing techniques.

3 Issues in spectrum sensing techniques

Researchers have analyzed many challenges and that will require proper investigation for the improvement in the spectrum sensing. Cognitive radios are blind in nature, so they do not have capability to find out other radios & due to this it becomes crucial to perform sensing operation. In multi-user environment many issues arise like, time required for sensing, methods used for cooperative detection & interference uncertainty. The main target is to achieve accurate and reliable detection of other users. New techniques are required for the detection in wideband range. According to the sensing methods, various challenges are associated with each technique and explained as follows.

(i)Channel Uncertainty: Shadowing and fading are the two parameters which are responsible for false detection of primary user. However, due to hindrances the licensed /primary signal (PU) can experience heavy shadowing & deep fading effect which shows the presence of primary user outside the interference boundary (IB) of the Unlicensed/secondary user (SU). Sometimes in worse fading condition better detection of primary user cannot acquire if only single cognitive radio is available, this limitation can be handled by using multiple cognitive radios. Multiple users share the information of sensing measurements with each other and after compiling the data actual primary user is concluded [30]. For non-fading channel i.e. AWGN (Additive white gaussian noise) probability of detection & probability of false alarm can be determined by the following mathematical equations.

$$P_{DET} = \mathrm{P}(\Upsilon > \frac{\gamma}{H1}) = Q_M\,(\sqrt{2\gamma,\lambda}) \tag{14}$$

$$P_{FALSE\ ALARM} = \mathrm{P}(\Upsilon > \frac{\gamma}{H1}) = \Gamma\,(a, b) \tag{15}$$

Where Γ (a, b), denotes gamma function which is incomplete in nature and $Q_M\,(\sqrt{2\gamma,\lambda})$ is Marcum function [44,45]. Similarly, few analyses for Nakagami fading channel [46].

(ii) Noise Uncertainty: Cognitive radio sensed the primary signal at low value of signal to noise ratio (SNR) which is given by equation (14).

$$\gamma_{min} = \frac{Q(I+D)}{P} \tag{16}$$

Noise power is denoted by P, power transmitted by the primary/licensed user is denoted by Q, for secondary user the interference range is represented by I, whereas D denotes the distance between primary transmitter and receiver section. Practically it is not possible to get the value of noise from the above equation (8). The noise power estimation at the receiver takes place but due to temperature fluctuations, variation in thermal noise & errors will get produced [40].

(iii) Selection of threshold: It is difficult to select the threshold value while maintaining tradeoff between probability of detection and probability of false alarm. If low value of Pd is considered, then the value of Pf increases and result in less utilization of spectrum. The selection of threshold should be such that the value of Pd and Pf remain as low as possible. To obtain fixed level of probability of false alarm (Pf), the value of threshold must be set [27]. CFAR (constant false alarm rate) principle is used to increase or decrease the value of threshold.

(iv) Interference limit during the sensing: Spectrum sensing is a continuous process to sense the spectrum condition, so that it is easily acquired by unlicensed/secondary user. During the transmission process, hindrance is induced by the primary user and the measuring these values is challenging because the actual location of primary user is not known by the secondary user. Sometime the primary user device is not active, in that condition the transmitter cannot find the receiver. So, during the measurement of sensing interference limit, these parameters need to be considered [32,33].

(v) Sensing throughput trade-off: In cognitive radio networks, the concerns of primary user (licensed user) & secondary user (unlicensed user) are conflicting with each other. From primary user's opinion, if the value of probability of detection (Pd) increases, then primary user becomes more secured and from the secondary user's opinion, low value of false alarm probability (Pfa) creates more utilization area of the channel. As a result, secondary users achieve better sensing throughput. Optimization of the sensing time is challenging task to secure the primary user which increased the throughput of the secondary user [28].

(v) Spectrum sensing in co-operative networks: In multi-user environment, several challenges encountered due to less cooperation in multiple primary and secondary users. Delay in cooperation & signaling overhead are the common challenges faced in this type of environment [29].

Various spectrum sensing techniques are available in cognitive radio network and each technique has its own advantages and disadvantages in different aspects. In future, diverse investigation is required, to find issues associated with different spectrum sensing technique (SST). Enhancement in detection capability, accuracy and detection in multi-user network, required more future research.

4 Standards for cognitive radio

First international standard introduced for cognitive radio network is IEEE 802.22 [39]. This standard defines the cognitive radio (CR) techniques that permit the secondary users (SR) to find TV spectrum holes (SH) for very high frequency (VHF) & ultra-high frequency (UHF) bands which lies in the range between 54 MHz to 862 MHz for the deployment of wireless regional area networks (WRAN) in uninterrupted form. To perform the operation for wide frequency range, IEEE 802.22 standard acquired the centralized model that minimized the limitations faced by the primary networks. For radio resource management, IEEE 802.11k standard has been introduced to include noise histogram & channel load report. To reduce the interference among the wireless technologies adaptive frequency hopping (AFH) has been introduced [34,35]. Further, for next generation radio & advanced spectrum management new standards have been targeted by IEEE P1900 also called the SCC41 i.e. standards coordinating committee 41. Some other groups also targeted the other issues like sensing of the spectrum, architecture in white space frequency bands, policy language, interference & coexistence etc. By introducing the new standards, ability & performance of the spectrum will increase [36].

5 Conclusions

Cognitive radio technology (CRT) offers the solution for underutilization of the spectrum. Classification of various spectrum sensing techniques, their comparison, complexity, detection accuracy etc. have been discussed in this paper. Also, research challenges related with spectrum sensing techniques and standards for cognitive radio networks discussed in this review paper. Mainly focused on the narrowband spectrum sensing technique (NSST) like energy detector (ED), cyclostationary feature detection (CFD), matched filter detection (MFD), etc. & their challenges. If the sensing of single band is required, narrowband sensing techniques are preferable. If the sensing operation is performed by the wideband techniques, it gives the idea about the empty sub bands present in the available spectrum. Once a free band is filled by the secondary user (SU) for transmission, then to avoid interference it is essential to monitor it continuously. As compared to narrowband sensing, more power will be consumed by the wideband sensing and this is undesirable as secondary user will only utilize single spectrum. By combining the different spectrum sensing techniques, performance of detection can be improved.

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