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Narrowband Spectrum Sensing in Cognitive Radio: Detection Methodologies

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***Abstract*—** With the rapid development in the technology, and every device connected to the internet and increase in wireless sensing devices, the spectrum is becoming more and more congested. To solve the spectrum scarcity problem, Cognitive Radio technology is used. The details about the function of cognitive radio such as spectrum sensing, spectrum management, spectrum decision and spectrum handoff are illustrated in this paper. Cognitive radio senses the spectrum for the presence of idle spectrum and allocates the unused frequency band to the cognitive user. When the secondary user is transmitting the data, the cognitive radio senses for the unused spectrum. If the primary user wants to access the channel, then the cognitive radio allocates the secondary user in the nearby unused frequency band. In this paper we are mainly focusing on narrow band spectrum sensing. Under narrow band spectrum sensing various detection techniques such as Energy detection, Matched filter, Covariance detector, Waveform detector and Cyclo-stationary detection are discussed in detail below. The efficiency of the spectrum sensing can be increased with the cooperative spectrum sensing in which multiple secondary users cooperate in sensing the spectrum.

***Keywords*—** Cognitive Radio, Spectrum Sensing, Narrowband Spectrum Sensing, Wideband Spectrum Sensing, Cooperative Sensing.

I. INTRODUCTION

With the gradual increase of new host and the expansion of wireless applications and new business services, spectrum resources are becoming scarce as the spectrum is limited. Internet and IOT are the major drives, and this domain is being used by many other industries. With the development in 4G technology, people can get information from around the world in hand within a few seconds, this is due to wireless access and the internet. Though communication provides better user experience, the frequency band for a user is fixed and new users cannot be allotted another band as it is a non-renewable resource. As more and more technologies are using wireless services for their communication, the demand for spectrum is increasing. Due to the fixed (static) allocation of a frequency band to an individual user, new users cannot be able to use the frequency band. Cognitive Radio has emerged as a promising technology in resolving this issue. It detects the idle frequency band: allocates this band to the new users.

As the word cognition indicates the mental ability to acquire knowledge through sense and experience. The objective of the paper is to elaborate Spectrum Sensing and Narrowband Sensing Techniques, as it is vital for establishment of cognitive radio. Spectrum Sensing determines in knowing the existence of primary users within the geographical area, which helps in allocating empty band to the secondary users. Various aspects of spectrum sensing are discussed in this paper. The main focus of this paper is to compare the several aspects of spectrum sensing techniques in Narrowband. CR is the key to solve the existing congested traffic problem which solves spectrum shortage and low utilization.

II. COGNITIVE RADIO

Cognitive Radio (CR) is a form of intelligent radio, which senses the presence or absence of the licensed frequency spectrum, deals with the problem of underutilization of the spectrum and also helps in recognizing the white spaces. Cognitive Radio makes efficient utilization of the spectrum. One of the important features is to sense, learn, measure and aware of the parameters that are related to channel characteristics. In the spectrum, the user is allocated a fixed frequency band and is termed as Primary Users (PU) or licensed users having the highest priority. Secondary Users (SU) are those, not having direct access to the allocated.

III. COGNITIVE RADIO CYCLE

Figure.1 shows the basic cognitive radio tasks, spectrum sensing, and spectrum analysis and spectrum decision in the radio environment.

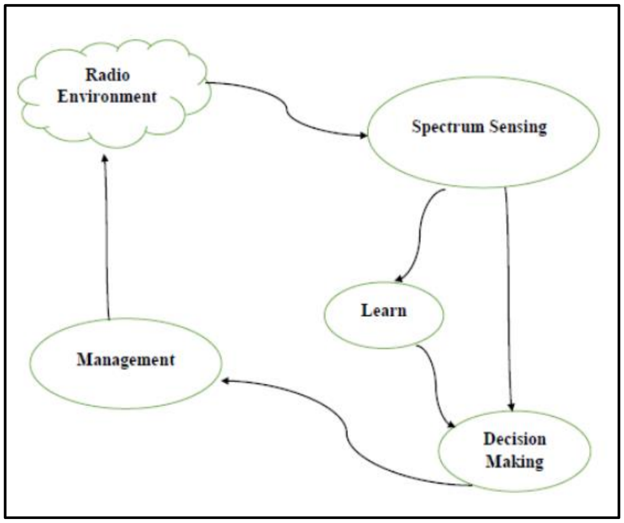

Figure 1.Cognitive Cycle

The basic functions of the Cognitive Radio CR are:

A. Spectrum Management

It determines how long the channel can be utilized by the secondary user when not used by the primary user. Management is the process where the radio frequencies are regulated to ensure efficient use. The licensed, unlicensed and unused spectrum bands are spread over a large number of frequencies in the cognitive radio networks. These unused spectrum bands show different properties according to the time varying radio environment. The Cognitive radio has to decide the best available spectrum band, such that it fulfils the QoS requirements.

B. Spectrum Sharing

The idle spectrum of the licensed user is shared with the secondary user. It distributes the spectrum holes fairly with the usage cost. Since it requires coordination among the CR users, it includes much of the functionality of MAC protocol.

Spectrum sharing consists of four steps which are:

- *Spectrum Sensing*: The goal of the sensing technique is to check for the status of the spectrum. Also, to check the activity of licensed user by sensing periodically. The CR transceiver looks for an idle band i.e., spectrum holes without causing interference to the primary network. Sensing can be of centralized and distributed.
- *Spectrum allocation*: When spectrum is available, a channel is allocated. This allocation depends on the availability of the channel and also internal/external policies.
- *Spectrum access*: When the nodes are trying to access the available spectrum, spectrum access helps to prevent colliding and overlapping of the spectrum.
- *Transmitter-receiver handshake*: The transmitter-receiver handshake is essential for effective communication in cognitive radio, after the determination of the spectrum.
- *Spectrum mobility*: The spectrum mobility is important in the communication between the nodes. If a particular part of the spectrum is required by the licensed user, communication should be continued by utilizing another free part of the spectrum. It deals with the hand-off strategy when the PU returns. When a primary user is active or ready to use, the priority of using that band switches from unlicensed user to licensed user. The change in the allocation of the spectrum band is termed as hand-off. The corresponding protocol parameters at different layer are adjusted to the new frequency band. While the secondary user is switched for another idle band, it maintains proper communication requirements. The purpose of the spectrum mobility in CR networks is to safeguard smooth and fast transition leading to minimum degradation.
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C. Spectrum Handoff

The cognitive radio has the ability to adapt to the frequency operation. Due to this, the network protocol changes its mode of operation from one mode to another. The main goal of mobility management is for these transitions to be completed without any disturbance and in a time efficient manner. The mobility management should have an awareness of the duration of the spectrum handoff, from the sensing algorithm. When the mobility management learns about the latency, its job is to confirm that the communication of the CR user should undergo on minimum performance degradation. The spectrum management functionalities cooperate with communication layers. The spectrum management needs QoS information, sensing, scheduling, transport and routing for the decision of the appropriate spectrum band. From Figure.2, link layer information and sensing delays information are required for the estimation of spectrum handoff latency. The transport layer and application layer should know the latency, for the route recovery by using the spectrum handoff. Due to this, spectrum handoff is very important in the communication layers.

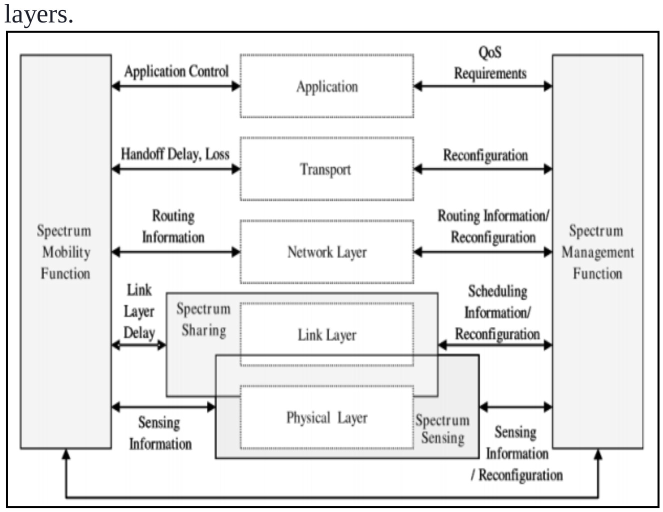

Figure 2.Handoff decision and network communication

IV. COGNITIVE RADIO CYCLE HYPOTHESIS

In this paper, two hypotheses are stated that is, **MITOLA** and **AKYILDIZ,** taken as reference to identify the characteristics of the cycle.

A. Cognitive Cycle: Mitola

Dr. Joe Mitola stated that 'A cognitive radio is a really smart radio that would be self- , RF- and user-aware, and that would include language technology and machine vision along with a lot of high-fidelity knowledge of the radio environment. According to the Figure.3, the six stages of the cognitive cycle is briefed as follows:

- *Observe*: Being aware about the wireless environment within a locality and acquire knowledge by sensing and signalling algorithms.
- *Orient*: After sensing, the signal has to evaluate the information for determination and significance to establish a priority among the users.
- *Plan*: Cognitive radio selects the alternative goal for better optimization after evaluation.
- *Decide:* It compares the various parameters and makes a decision.
- *Act:* The decision made is implemented accordingly. If any changes occurs later then it is reflected within the radio.
- *Learn*: While the process is continuing, it acquires the knowledge about various changes made in parameters to improve in further cycles.

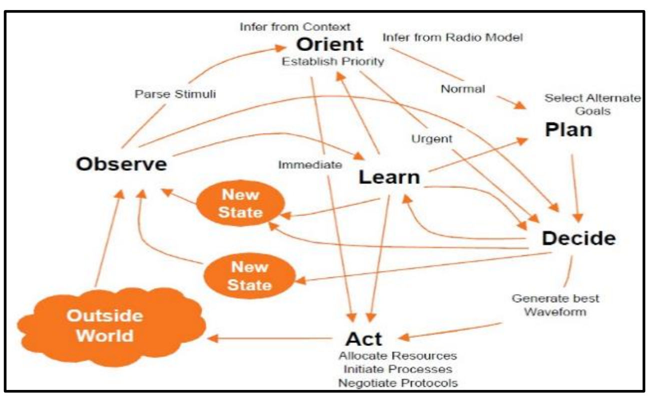

Figure 3. MITOLA Cycle

B. Cognitive Cycle: Akyildiz

According to AKYILDIZ, the radio environment is first scanned for any white spaces in the spectrum, to make it available for the secondary users. Spectrum mobility vacates the secondary user after primary user is active and allocates the different empty frequency band. Spectrum sharing allows the secondary user to share the spectrum with the primary user as shown in Figure.4. Spectrum sensing is an awareness process that monitors the environment and checks the usage of the band within the locality for white space. In spectrum decision, the cognitive radio after sensing it decides the time to start, operating frequency and other technical parameters.

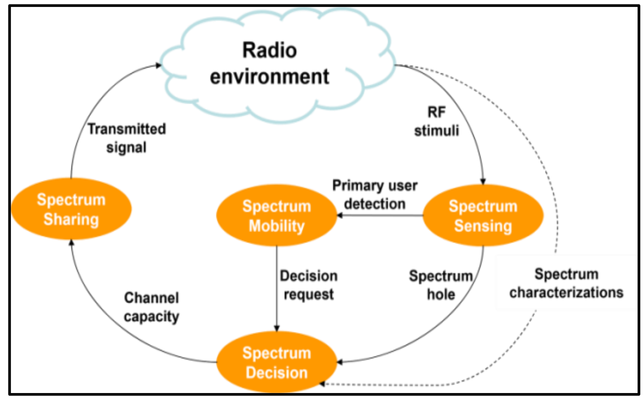

Figure 4. AKYILDIZ Cycle

V. SPECTRUM SENSING

The purpose of the spectrum sensing is to discover the status of the spectrum and also the action of the licensed user by sensing the target frequency band periodically. Particularly, a cognitive radio transceiver will detect if there are any spectrum holes available and it will find out the technique of accessing it without making interference with a licensed user's transmission.

Cognitive radio senses the spectrum even when the secondary user is transmitting the data continuously, in order to prevent interference with the primary user. Spectrum sensing is further categorized into Narrowband sensing and Wideband sensing. In Narrowband it allocates the spectrum for a particular user, while in Wideband it allocates the spectrum for many cognitive users over a wide range of frequency. Different type of Sensing was shown in Figure 5.

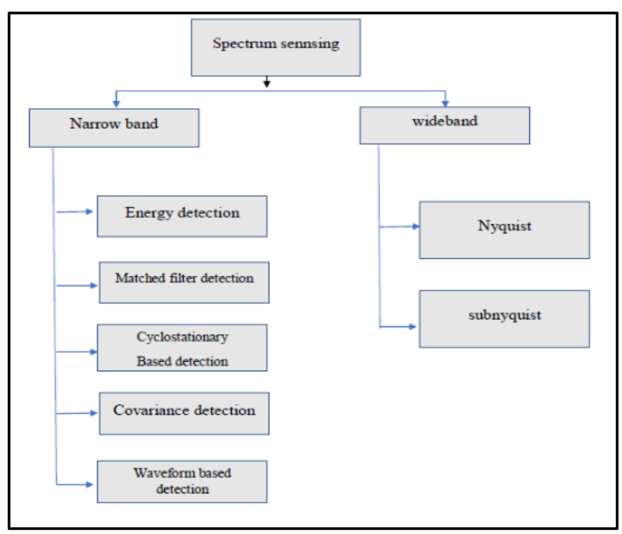

Figure 5. Type of Spectrum Sensing

VI. NARROWBAND SPECTRUM SENSING

In the Narrowband Spectrum Sensing, the secondary users are allocated in the narrow frequency range and senses for the particular frequency bands. The Secondary Users knows the frequency band over which sensing will be performed, i.e. the radio front-end starts with a tuneable band pass filter (BPF) that scans one frequency band at a time. TV broadcasting is an example of narrowband sensing, where the centre frequency and bandwidth of each band are pre-defined and sensing is performed band by band.

In a narrowband channel the bandwidth of the message signal will not exceed the channel coherence bandwidth also frequency responses are flat. Narrowband signals can be processed by receiver with low complexity and low power consumption processors. The frequency assortment is limited in such a way that the channel frequency can be viewed as level and the bandwidth of the interest is not effective for data transfer ability of the channel.

After selecting a suitable frequency band, communication can start, but high dynamics of radio environment can allocate it to the primary user. Hence before communication begins, secondary users (SU) narrowband sensing is executed for a selected band as a second phase of sensing to confirm for the absence of primary user (PU). Once it allocates, continuous sensing and monitoring is required.

VII. SENSING METHODS

The mostly used spectrum sensing techniques are given as:

- Energy Detection
- Matched Filter Detection
- Cyclo-stationary based Detection
- Waveform Detection
- Wavelet Detection
- Covariance Detection

A. Energy Detection

Energy detection is the most preferred and simplest spectrum sensing method, when the prior knowledge about the primary users are not available. It consumes very less power during sensing. The energy sensed at the spectrum is compared with the fixed threshold value to detect the presence or absence of the Primary Users. The whole method is shown in Figure.6.

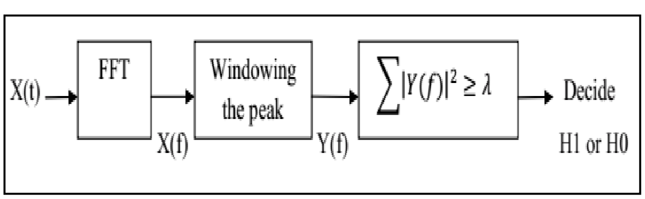

Figure 6. Energy Detection Block Diagram

The energy detection method does not need to know the pattern of the signal, it just compares the energy of the received signal with a fixed threshold, to check the status of the spectrum. Analytically signal detection can be explained with the hypothesis test. If x(t) is the energy received by the cognitive radio user.

$$x(t) = w(t) - - - - - - - - - H_0$$
$$x(t) = s(t) + w(t) - - - - - - - - - H_1$$

x(t) = energy of the received samples at the signal detector
w(t) = additive white noise
s(t) = energy of the primary user signals sensed.
H_0 states that the only noise is received and the primary user signal is absent.
H_1 states that along with the noise, samples of primary user signal are received.
Since noise in the environment is unpredictable, using a fixed threshold value at the receiver leads to an increase in the false alarm of detection. This method has the low probability of detection of PU's.

B. Matched Filter Detection(MFD)

Matched filter detection is the coherent spectrum sensing method, in which the parameters of the Primary Users are known beforehand, such as its operating frequency, modulation type, bandwidth and frame format etc. In this, unlike the energy detection method, a dynamic threshold value is used to compare the sensed energy. This is one of the advantages of this method as the noise in the environment is unpredictable. It detects the presence of PU in less time with high probability. The block diagram of the detection process is shown in Figure 7,8.

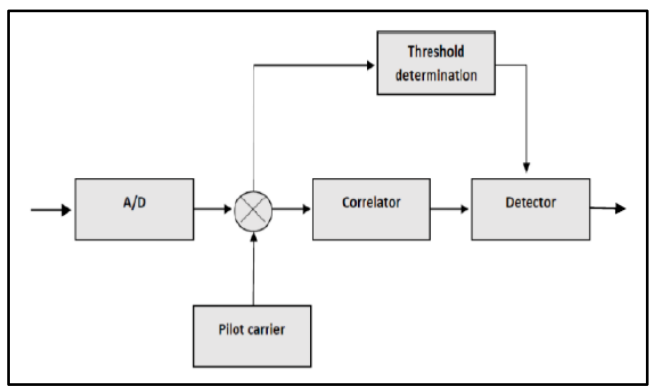

Figure 3.Matched Filter Detection (MFD)

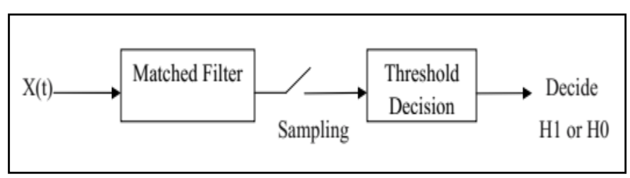

Figure 4.Matched Filter Detection (MFD)

In the matched filter detection, the sensed signal is correlated with the known signal and then the output of this is compared with the dynamic threshold to detect the presence or absence of the primary users. It performs well in low SNR of the sensed signal, as it maximizes the output SNR in the presence of the additive noise.

The test statistic is given by:

$$TMF = \sum y(n)^* x(n)$$

Where x(n) denotes the PU signal, y(n) denotes the SU signal, and TMF denotes the test statistic of the matched filter detector. The test statistics, TMF, is then compared with a threshold in order to decide about the spectrum availability. The SU received signal, as well as the PU signal, are approximated to be random Gaussian variables.

$$if \begin{cases} TMF \geq \lambda, & Primary\ User\ is\ Present \\ TMF < \lambda, & Primary\ User\ is\ Absent \end{cases}$$

C. Cyclo-stationary Detection

This method helps in detecting the presence of the primary user by exploiting the cyclo-stationary features such as hopping sequence, periodicity and pulse train. This method performs better in low SNR because it distinguishes primary signal from noise, as noise is random in nature it does not have cyclic features. It is the preferred method when the prior knowledge of the primary user is not available. The block diagram of the detection method is shown in Figure 9.

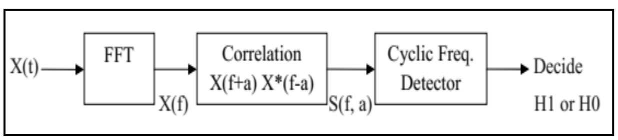

Figure 5.Cyclostationary Detection

Spectral correlation is the parameter used for detecting the presence of the primary user. By this method modulation scheme of the primary user can also be determined. The two dimensional spectral correlation is given by the formula.

$$R_y(t+\tau) = R_y(t+T_0,\tau)$$

The Fourier transform of the above equation is given by the formula

$$R_y^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int y\left(t+\frac{\tau}{2}\right) y(t-\frac{\tau}{2}) e^{-2\pi\alpha t} dt$$

This above equation is cyclic autocorrelation function. Spectrum correlation function is found by cyclic autocorrelation and can separate noise from primary signal. When α is equal to zero spectrum correlation becomes power spectral density

$$s_y^{\alpha}(F) = \lim_{\Delta t\to\alpha} \lim_{T\to\alpha} \frac{1}{T}\frac{1}{\Delta t} \int_{-\frac{\Delta t}{2}}^{\frac{\Delta t}{2}} Y_T\left(t, f+\frac{\alpha}{2}\right) Y_T^*(t, f-\frac{\alpha}{2})\, dt$$

D. Waveform Detection

Waveform based detection is a coherent sensing type, that relies on prior knowledge of the primary user signal construction. When the known signal is present, there will be decision made based on the statistics formed by correlating the received signal. It makes use of midambles, preambles, spreading sequence.

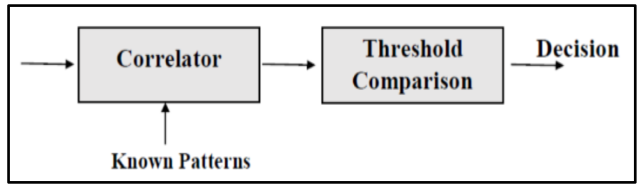

Figure 6.Waveform detection Block diagram

If the same receiving model given as shown in figure.10 is assumed, then metric of comparison using correlation is

$$E = Re\left[\sum_{n=0}^{N-1} y(n)x^*(n)\right]$$

Where * denotes complex conjugate of the transmitted signal. When the primary user signal occupies the band, could be rewritten as

$$E = \sum_{n=0}^{N-1} |x(n)|^2 + Re\left[\sum_{n=0}^{N-1} w(n)x^*(n)\right]$$

whereas when the band is free, metric is simply the correlation between noise and transmitted signal and is given below,

$$E = Re\left[\sum_{n=0}^{N-1} w(n)x^*(n)\right]$$

E. Wavelet Detection

The wavelet approach offers advantages in terms of both implementation cost and flexibility for signal detection over wideband channels, in adapting to the dynamic spectrum in contrast to the conventional implementation of multiple narrowband band pass filters (BPF) . By employing a wavelet transform of the power spectral density (PSD) of the observed signal x(t), the singularities of the PSD S(f) can be sighted and thus the vacant frequency bands can be found. One major issue in the implementation of this approach is the high sampling rates characterizing larger bandwidths. The block diagram of the detection method is shown in Figure.11.

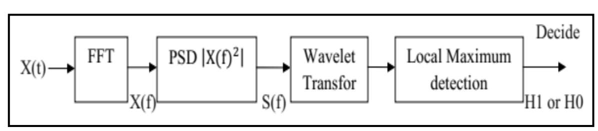

Figure 7.Wavelet Detection

Let the signal received from all primary users is presented as

$$y(n) = \sum_{k=0}^{K} P_K\, x_K\,(n) + w(n)$$

Where $P_k = 1$ denote presence of k[th] primary users, $P_k = 0$ denotes no signal from k[th] primary users and w(n) denotes additive white Gaussian noise with unit variance.

Estimated power spectral density of received signal is S (f)

$$S(f) = \frac{1}{N}\sum_{k=0}^{\frac{N}{L}-1}\left|\sum_{l=0}^{L-1} y(l+kL)e^{-\frac{j2\pi ft}{N}}\right|^2$$

Let $\varphi(t)$- wavelet smoothing function used to extract features of $S_y(f)$

$$W_y(s;f) = S_y(f) * \varphi(f)$$

$\varphi_s(f)$ is dilated version of $\varphi(f)$ by a dynamic scale factor of, s = 2j , 1 ≤ j ≤ J so

$$\varphi_s(f) = \frac{1}{s}\varphi\left(\frac{f}{s}\right)$$

Frequency boundaries were decided by derivative of local maxima of wavelet modulus

$$f_k = \arg\left[\frac{max}{f_{min} \le f \le f_{max}}\right]\left|\prod_{j=1}^{J} W_y(2^j;f)\right|$$

Spectral boundaries constant coefficient α_k

$$\alpha_k = \frac{1}{f_k - f_{k-1}}\int_{f_{k-1}}^{f_k} S_y(f)df - N_0 , 1 \le k \le K$$

$\alpha_k S$ = 0 denotes spectrum band is decided to be unoccupied or free to use.

F. Covariance Based Detection(CBD)

It uses sample covariance matrix along with Singular Value Decomposition for detecting the presence of primary user signal. The correlation amongst the received signal samples imparts a specific structure to the covariance matrix. The ratio of the maximum Eigen value to the minimum Eigen value of the covariance matrix calculated value serves as the test statistics, and then it is compared with a threshold to decide. Prior information of the primary user and the transmission channel is not necessary.

Let the signal received from all primary users is presented as

$$y(n) = Px(n) + w(n)$$

The value of P =1 indicate occupancy of primary signal and P= 0 indicate absence of signal. Covariance received signal

$$C = \frac{1}{N}\sum_{n=L-1}^{N-1}(y[n]y^H[n])$$

$$y[n] = y[0]y[1] \ldots\ldots\ldots\ldots\ldots y[N-L-1]$$

So, $C = PC_s + \sigma^2 I_L$

C_s is a covariance matrix of signal column vector of length L as

$x[n] = x[0]x[1] \ldots\ldots\ldots\ldots\ldots x[N-L-1]$ σ^2 Denotes noise variance and I_L denote identity matrix L X L, λ_{max} and λ_{min} are maximum and minimum Eigen values of covariance matrix.

The test metric for CBD id denote by E depends upon λ_{max} and λ_{min} i.e.

$$E = \frac{\lambda_{max}}{\lambda_{min}}$$

Decision based on the threshold value μ

$$\theta = \begin{cases}\theta_0 & if\ E > \mu \\ \theta_1 & if\ E < \mu\end{cases} \qquad \begin{pmatrix}\theta_0 & for\ \ P = 0 \\ \theta_1 & for\ P = 1\end{pmatrix}$$

Table 1. Advantages and Disadvantages of Spectrum Sensing Detection Methods

Sl. No.	Detection Method	Advantage	Disadvantage
1	Energy Detection	1) Easy to implement. 2) Low computational cost. 3) Does not require prior information of the primary user.	1) Poor performance for low SNR. 2) Cannot differentiate users
2	Matched Filter	1) Optimal performance. 2) Low computational cost.	1) Requires prior information of the primary user.
3	Cyclo-stationary	1) Valid in low SNR region. 2) Robust against interference.	1) Requires prior information of the primary user. 2) High computational cost.
4	Wavelet	1) Effective for wideband signal	1) Does not work for Spread Spectrum Signals. 2) High Computational Cost
5	Waveform	1) Perform well even under low signal to noise ratio unlike energy based detectors	1) Prior knowledge of received signal is needed at the receiver

VIII. COOPERATIVE SENSING

When secondary users are located in different geographical area in order to sense the spectrum effectively cooperative spectrum sensing method is used. The efficient spectrum sensing can be achieved in cooperative sensing method, in which each cognitive user shares the information along with the presence of cooperation among them. This eliminates fading, shading and noise instability along with decreasing the sensing time of the secondary user thereby increasing the transmitting data rate.

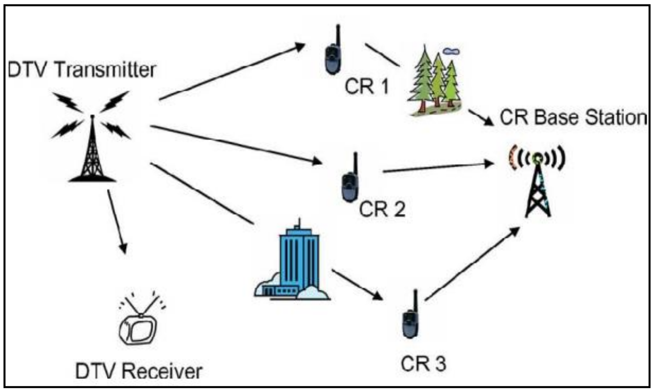

Figure 8. Cooperative spectrum sensing in CR networks

In general cooperative spectrum sensing consists of the following steps.

- Every CR independently performs measurements for its local spectrum sensing and then makes a binary decision to check on whether the PU is present or not.
- These binary decisions by all CR are forwarded to a common receiver which is a base station (BS) in a cellular network or an access point (AP) in a wireless LAN.
- Those binary decisions are combined by a common receiver and a final decision is made in order to infer the absence or presence of the PU in the observed band

The methods are divided into three types:

- Centralize Sensing
- Distributed Sensing
- External Sensing

A. Centralize Sensing

In Centralized Sensing, all the clients send their detecting results to the Fusion centre (FC) or master node, which controls the channel and joins the received signal and sends these signals to each users present in network through broadcasting channel and each secondary users collaboratively senses for the spectrum and detect the presence of primary users in the network.

B. Distributed Sensing

Here all the cognitive radio's sends the data to each other instead of reporting to master node and chooses spectrum within the locality by making their own decision. Among the two users, the user nearer to the primary transmitter can detect the idle spectrum very easily than the far user and sends the observation to the secondary user when the signal to noise ratio (SNR) of primary signal is very less. It helps in minimizing the interference with primary user.

C. External Sensing

External sensing is another technique used for obtaining the spectrum information. In this technique sensing is performed by an external agent and information about the channel occupancy is forwarded to CRs. With the help of external sensing some problems regarding internal sensing are solved where sensing is performed internally by cognitive transceivers. Collocated sensing is another name for internal sensing. The main advantage of external sensing is to prevail over fading, uncertainty because of shadowing and to overcome the hidden primary user problem. As the CR does not spend time for sensing, as a result spectrum efficiency is increased.

IX. SPECTRUM SENSING IN CURRENT WIRELESS STANDARDS

Recently many wireless standards started adopting cognitive features although it is very difficult to expect a use of underutilized spectrum in opportunistic manner in wireless standards.

A. IEEE 802.11K

It is extension of IEEE 802.11. In this standard the sensing information is used to improve the traffic distribution .WLAN devices is connected to FC that has large signal level. In 802.11k, when FC with large signal level is full of capacity then new users are allocated to one of the underutilized FC.

B. Bluetooth

In Bluetooth standard, a new technology is introduced called AFW (Adaptive Frequency Hopping) to minimize interference between wireless technologies dividing 2.4GHZ unlicensed radio spectrum. In these IEEE 802.1.b/g devices, cordless phones and microwave ovens share the same wireless frequency with Bluetooth. There are many advantages of adopting AFH like clashing with WLAN signals are avoided , better bit error (BER) performance can be accomplished. AFH involves a sensing algorithm for determining whether ISM band has other devices present or to avoid them. The algorithm is based on information combined to decide which channel is occupied and which channel is vacant.

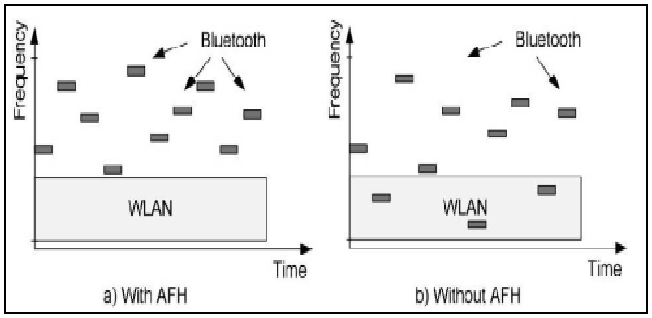

Figure 9. Bluetooth transmission with and without adaptive AFH

C. IEEE 802.22

This standard is known as cognitive radio standard because it contains cognitive attributes. This standard is still in growing stage. The most distinct feature of IEEE 802.22 is its spectrum sensing requirement. The sensing is predicted by two stages: Fast and Fine sensing, a crude sensing algorithm is used for example Energy detector. The fine sensing started with fast sensing results. Fine sensing involves more reliable sensing because more powerful tools or methods are used.

X. CONCLUSION

Cognitive radio is one of the mile stone in wireless communications. Algorithms discussed in this paper have their own advantages and disadvantages. Some trade-off between complexity and performance is to be made to decide good algorithm for specific application. Some precise sensing algorithms like cooperative detection etc. are emerging day today. Spectrum is an extremely profitable asset in wireless communication systems, and it has been a point of convergence for innovative work endeavours throughout the most recent quite a few years. Cognitive radio, which is one of the endeavours to use the accessible spectrum more efficiently through shrewd spectrum usage, has turned into an energizing and guaranteeing idea. One of the imperative components of cognitive radio is sensing the accessible spectrum opportunities.

ACKNOWLEDGMENT

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