Cognitive radio using spectrum sensing

A summer semester project report

submitted

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Certificate

This is certified that the work contained in this project entitled ”Cognitive radio using spectrum sensing” has been carried out under my supervision and that it has not been submitted elsewhere for a degree.

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Abstract

The enormous usage of electronic devices and wireless appliances, which are mainly used for sharing interactive content like audio, video, etc., has resulted in excessive spectral usage. But, the spectrum hasn't been utilized efficiently and most of the frequency bands are only used for a short time and left unused for the rest of the time. This kind of spectral usage is prevalent in cellular connections. The frequencies that are allotted for cellular connections have been left unused for a long time from late night to early morning and are being extensively used during peak hours mainly the daytime. Generally, the spectrum of radio frequency is distributed in such a way that it is fixed to certain users called licensed users and it cannot be used by unlicensed users even though the spectrum is not in use. This type of spectrum allocation doesn't let unlicensed users access the spectrum even if it is free. This inefficient use of spectrum leads to spectral holes. To overcome the problem of spectral holes and increase the efficiency of the spectrum, the Cognitive Radio (CR) concept is introduced.

1 Cognitive Radio using Spectrum Sensing

1.1 Introduction

The enormous usage of electronic devices and wireless appliances, which are mainly used for sharing interactive content like audio, video, etc., has resulted in excessive spectral usage. But, the spectrum hasn't been utilized efficiently and most of the frequency bands are only used for a short time and left unused for the rest of the time. This kind of spectral usage is prevalent in cellular connections. The frequencies that are allotted for cellular connections have been left unused for a long time from late night to early morning and are being extensively used during peak hours mainly the daytime. Generally, the spectrum of radio frequency is distributed in such a way that it is fixed to certain users called licensed users and it cannot be used by unlicensed users even though the spectrum is not in use. This type of spectrum allocation doesn't let unlicensed users access the spectrum even if it is free. This inefficient use of spectrum leads to spectral holes. To overcome the problem of spectral holes and increase the efficiency of the spectrum, the Cognitive Radio (CR) concept is introduced.
Cognitive radio (CR) is a form of wireless communication in which a transceiver can intelligently detect which communication channels are in use and which are not. It instantly moves into vacant channels while avoiding occupied ones. It does not cause any interference to the licensed user.

The main motto of CR is to provide spectrum access to secondary users through dynamic spectrum access to improve spectrum efficiency. Secondary users are also licensed users who are given access to the spectrum whenever primary users are under-utilizing or not using it. In the Cognitive Radio concept, spectrum sensing plays a vital role in improving the spectrum efficiency by giving information on to what extent the spectrum is being utilized. Spectrum sensing

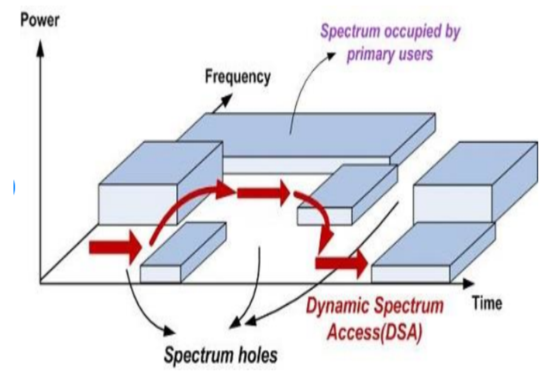

Figure 1: spectral holes

is the most important part of Cognitive Radio system as it has to sense the spectrum in a fading environment.
CR can operate in 3 modes.They are

- Underlay

  Simultaneous cognitive and non cognitive transmissions are allowed as long as the interference level at the primary user side remains acceptable. Exceeding the predefined tolerable interference threshold may degrade dramatically the primary signal.

- Interweave

  This spectral coexistence approach has been proposed in the objective of enabling devices to occupy the spectrum rooms that has been left vacant by non cognitive users. The surrounding environment should be observed to be able to predict the state of each portion of the frequency spectrum, portions of spectrum that are considered as being under-utilized may be accessed by secondary users as long as the primary activity remains idle. In order to facilitate the coexistence of both primary and secondary traffics within the same network in an opportunistic transmission mode, spectrum opportunities should be actively identified and monitored.

- Overlay

  non cognitive users share knowledge of their signal codebooks and messages with the cognitive users. Thus, the cognitive devices may enhance and assist the non cognitive transmission rather than vying for spectrum access. More precisely, cognitive devices overhear the messages sent by non cognitive sources and use these messages either to eliminate the interference generated by the primary communication at the cognitive receiver side or to improve the performance of the primary transmission through relaying the accumulated messages to the primary receiver.

There are some existing techniques used in cognitive radio.

Technique 1 - Spectrum Sensing

Technique 2 - Spectrum Database

2 Spectrum Sensing in Cognitive Radio

To efficiently use the available radio frequency spectrum, the devices should be conscious of their respective surrounding Radio Frequency (RF) environment. Spectrum sensing is used to provide this information on the RF spectrum, i.e., whether the spectrum is free or occupied. Spectrum sensing regularly monitors the spectrum and finds out the underutilized spectrum to allocate it to a user. The licensed users are divided into Primary and Secondary users. The secondary users need to perform spectrum sensing to detect the primary user's signal in the licensed spectrum. If PU's signal is absent, then the secondary users can use that frequency band. If the signal is present, then the secondary users cannot use that frequency band as it results in signal interference. It is the most important and challenging process in cognitive radio as this needs to be done in a fading channel. For a fading wireless channel, the input and output relationship is given as

$$y(t) = hx(t) + n(t)$$

where $y(t)$ is the received signal, h is the channel fading co-efficient, $n(t)$ is additive white gaussian noise (AWGN) and $x(t)$ is the primary user (PU) signal. Spectrum sensing can be divided into two parts. They are

- Non-cooparative.

  Acts on it's own and decides based upon signal detection and preloaded information.There are four methods to do Spectrum sensing.

  - Matched filter Detector
  - Energy detector
  - Cyclo Stationary
  - Waveformbased

- Cooparative

  CR devices share spectrum sensing information between themselves and decides take by control unit or a mesh kind of network

2.1 Limitations of Spectrum Sensing Techniques

Spectrum Sensing is a best CR solution but it requires a large amount of sensing time. It also requires a complex algorithm to achieve reliability.

- Non-cooperative

  - Parallel Sensing

    * In parallel sensing we have Hardware Complexity problem and it is very high in cost.

  – Sequential Sensing

    * Long sensing time as CR devices have to scan the frequencies of primary users one by one to detect availability of spectrum holes.

  – Wave Form

    * Requires prior knowledge of synchronization signature of all primary users in various spectrum bands.

    * This technique is susceptible to synchronization errors which can cause false detection of primary users.

  – Matched Filter

    * Requires prior knowledge of waveform patterns of all primary users in the various spectrum bands.

    * Noise variance and uncertainty makes this technique unreliable as CR devices are unable to detect transmitted signal from primary users.

  – Cyclo Stationary

    * High computational complexity.

- Cooperative

Cooperative sensing technique needs to intelligently combine inputs from various CR devices and ascertain the availability of spectrum holes. The accuracy of the algorithm is critical here as incorrect detection can inversely affect the performance of primary users in spectrum bands. Designing such a 'perfect algorithm' is a challenge.

3 Spectrum Sensing using Energy Detector

The energy detector measures the energy of the received signal to detect the spectrum's availability in a particular frequency band. At the energy detector, a binary hypothesis test is used to formulate the received signal, $y(t)$. The hypothesis test is as follows

$$H_0 \Rightarrow y = n$$

$$H_1 \Rightarrow y = hx + n$$

Hypothesis 0 ($H0$) means the Primary User's signal is absent and Hypothesis 1 ($H1$) means the Primary User's signal is present.

At the energy detector, the received signal is multiplied by the factor $\frac{x^H}{||x||}$.

Therefore,

$$\text{for} H_0, \bar{y} = \frac{x^H}{||x||} y = \frac{x^H}{||x||} n = \bar{n}$$

$$\text{for} H_1, \bar{y} = \frac{x^H}{||x||} y = h||x|| + \bar{n}$$

Let $|\bar{y}|^2$ be the energy of the $\bar{y}$. This value is compared with the threshold value, E_t, to decide the outcome of the energy detector.

$$|\bar{y}|^2 < E_t \Rightarrow H_0$$

$$|\bar{y}|^2 \geq E_t \Rightarrow H_1$$

Practically to carry out energy detection process, energy detector uses a band pass filter to filter the received signal and let's say its bandwidth is B. To calculate the energy of the received signal, a magnitude squaring equipment is used. To increase the accuracy of the energy detector, the energy of the received signal is calculated over specific period of time (T). Then, this calculated energy is compared with the threshold value to determine whether the spectrum is occupied or not. The block diagram of energy detector is shown in the below figure.

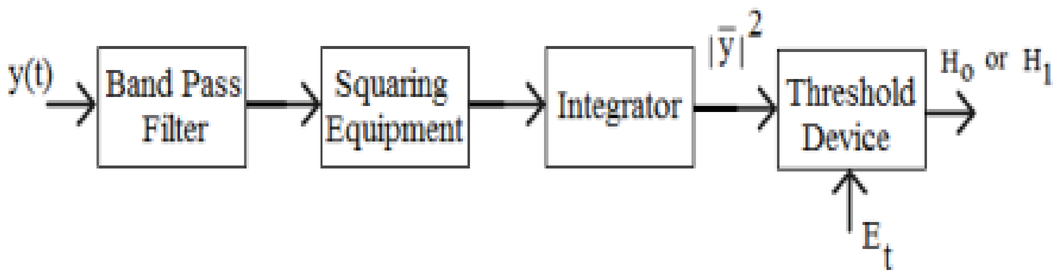

Figure 2: Block diagram of Energy Detector

3.0.1 Performance Parameters of Energy Detector

There are mainly two parameters which can effectively summarize the performance of energy detector. They are

- Probability of Detection (P_D)
- Probability of False Alarm (P_{FA})

1. Probability of Detection The probability of detection indicates the probability that the signal is detected by the energy detector when the spectrum actually contains the signal. It is the probability that H_1 is detected as H_1. The expression for P_D is written as

$$P_D = P(|\bar{y}|^2 \geq E_t | H_1)$$

$$P_D = Q_{X_2^2}\Big(\frac{2E_t}{||x||^2 + \sigma^2}\Big) = e^{-\frac{2E_t}{||x||^2+\sigma^2}}$$

where $Q_{X_2^2}$ is the complementary cumulative distribution function (CCDF) of X_2^2 and X_2^2 represents a central chi-squared random variable which is having two degrees of freedom.

2. Probability of False Alarm

   The probability of false alarm indicates the probability that the signal is detected by the energy detector when the spectrum is empty. It is the probability that H_0 is detected as H_1. The expression for P_{FA} is expressed as

$$P_{FA} = P(|y|^2 \geq E_t|H_0)$$

$$P_{FA} = Q_{X_2^2}\left(\frac{2E_t}{\sigma^2}\right) = e^{-\frac{2E_t}{\sigma^2}}$$

   From their respective expressions, the probability of false alarm is independent of $||x||^2$ and will not vary with respect to time. Therefore, it's average value will as same as P_{FA}. Let $\bar{P}_{FA}$ represents the average value of P_{FA}. Therefore,

$$\bar{P}_{FA} = P_{FA}$$

   Contrary to this, the probability of detection is dependent on $||x||^2$. Therefore, it's average value, $\bar{P}_D$ will not be as same as P_D.

3.1 Receiver operating characteristics

A receiver operating characteristic curve, or ROC curve, is a graphical plot that illustrates the diagnostic ability of a binary classifier system as it's discrimination threshold is varied. The method was originally developed for operators of military radar receivers starting in 1941, which led to its name.The ROC curve is created by plotting the true positive rate (TPR) against the false positive rate (FPR) at various threshold settings. The true-positive rate is also known as sensitivity or probability of detection. The false-positive rate is also known as probability of false alarm .The ROC curve is thus the sensitivity or recall as a function of fall-out. In general, if the probability distributions for both detection and false alarm are known, the ROC curve can be generated by plotting the cumulative distribution function (area under the probability distribution from to the discrimination threshold) of the detection probability in the y-axis versus the cumulative distribution function of the false-alarm probability on the x-axis. The ROC curve was first developed by electrical engineers and radar engineers during World War II for detecting enemy objects in battlefields and was soon introduced to psychology to account for perceptual detection of stimuli. ROC analysis since then has been used in medicine, radiology, biometrics, forecasting of natural hazards,meteorology,model performance assessment,and other areas for many decades and is increasingly used in machine learning and data mining research.The ROC is also known as a relative operating characteristic curve, because it is a comparison of two operating characteristics (TPR and FPR) as the criterion changes. ROC curves are a very powerful tool as a statistical performance measure in detection/classification theory and hypothesis testing, since they allow having all relevant quantities in one plot.

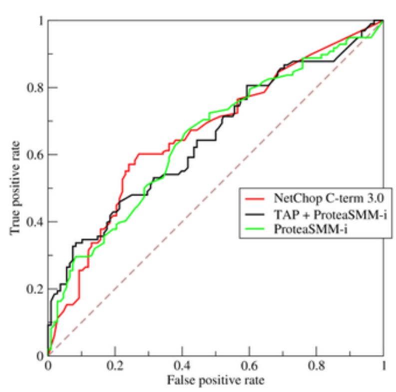

Figure 3: receiver operating characteristic

3.1.1 Simulation Results

To quantify the performance of energy detector, we have plotted Probability of False Alarm vs Probability of Detection curves for different cases. As we are dealing with the probabilities, the axes range from 0 to 1. In each figure, we compared simulation results with theoretical results. In figures, SNRdB represents the signal to noise ratio of the received signal in dB and

$$m = \frac{||x||^2}{\sigma^2 \mathrm{SNR}} \mathrm{where SNR} = 10^{\frac{\mathrm{SNRdB}}{10}}$$

In figure 3, we set m = 1 and SNRdB = 1. From the figure, it can be observed that the simulation results differ slightly from the theoretical results. But in the end, the simulation results curve follows theoretical results curve.

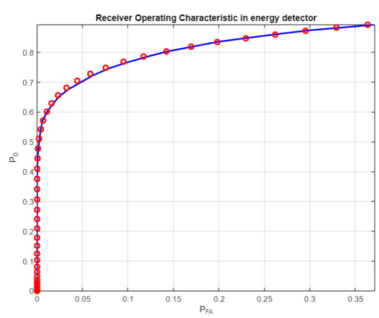

Figure 4: receiver operating characteristics in energy detector

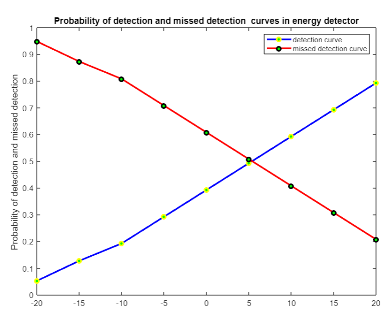

Figure 5: probability of detection and missed detection curve in energy detector

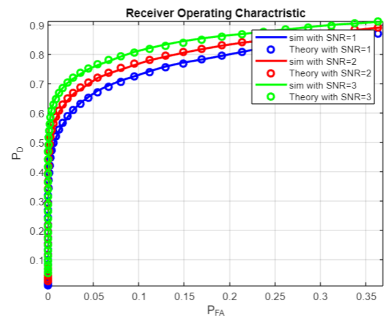

Figure 6: comparision of Receiver operating characteristics for SNR=1dB ,SNR=2dB and SNR=3dB

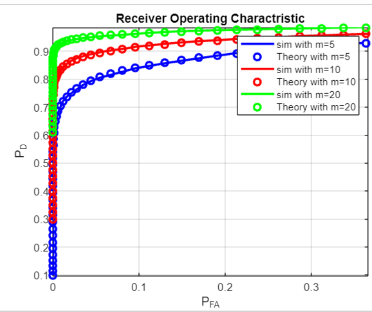

Figure 7: comparision of Receiver operating characteristics for number of input signals m=5 ,m=10 and m=20

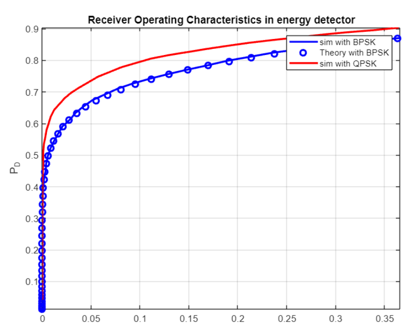

Figure 8: comparision of Receiver operating characteristics for BPSK and QPSK signals in energy detector

3.1.2 Conclusion

A better insight into the need of the spectrum sensing process is given and the it's importance in Cognitive Radio is explained with the help of necessary images. Then, we have implemented the spectrum sensing process using the energy detector with the use of it's block diagram. The performance parameters of the energy detection are discussed and it's performance is quantified with the help of simulation results. From the observation of simulation results, it can be concluded that the energy detector performs extremely good if the signal to noise ratio of the received signal is high as the probability of detection increases with SNR and it is also observed that probability of detection increases with increasing the number of transmitted symbols and also probability of detection increases for Qpsk on comparing with Bpsk. The energy detector correctly detects the spectrum if the SNR of the received signal is high. But the major drawback with energy detection method is that the poor performance under low SNR conditions and also no proper distinction between primary users and noise. Rather the matched filter maximizes the SNR.The require time to achieve the desire probability of detection may be higher. The detection performance depends on the uncertainty of the noise. It is impossible to make distinguish between different primary users because energy detector is not able to differentiate between the sources of the received energy . It cannot be used for the detection of spread signals. The computation of the threshold value used for detection is highly susceptible for the variation of the noise levels which leads to a low SNR environment.

4 Matched filter

The decision making on whether the signal is present or not can be facilitated if we pass the signal through a filter, which will accentuate the useful signal $sig(t)$ and suppress the noise $w(t)$ at the same time. Such a filter which will peak out the signal component at some instant and suppress the noise amplitude at the same time has to be designed. This will give a sharp contrast between the signal and the noise, and if the signal $sig(t)$ is present, the output will appear to have a large peak at this instant. If the signal is absent at this instant, no such peak will appear. This arrangement will make it possible to decide whether the signal is present or absent with minimum probability of error. The filter which accomplishes this is known as matched filter. Main purpose of the filter is, to decrease the noise component and to increase the signal component at the same instant. This is obviously equivalent to maximizing the signal amplitude to the noise amplitude ratio at some instant at the output. It proves more convenient if we go for square of amplitudes. Hence the matched filter is designed in such a way that it will maximize the ratio of the square of signal amplitude to the square of the noise amplitude.

The data is transmitted through awgn channel. Let $sig(t)$ be the transmitted signal, $w(t)$ is the channel noise, $sig(t) + w(t)$ be the received signal, which is given as the input to the matched filter and $sig_0(t) + w_0(t)$ be the output of the filter. Let the matched filter's impulse response be $h(t)$. It had been proven that, impulse response of the optimum system is the mirror image of the desired message signal $sig(t)$ about the vertical axis and shifted to the right until all of the signal $sig(t)$ has entered the receiver. It should be realized that the matched filter is optimum of all linear filters.

The signal component at output of the filter, at the observing instant tm is given by

$$sig_0(t_m) = \frac{1}{2\pi}(s(w))^2 \longrightarrow eq(1)$$

$$sig_0(t_m) = E \longrightarrow eq(2)$$

Hence the output signal component has maximum amplitude of magnitude E, which is nothing but energy of the signal $sig(t)$. The maximum amplitude is independent of the waveform $sig(t)$ and depends only upon its energy.

Spectrum Sensing block using matched filter. Here the transmitted signal is

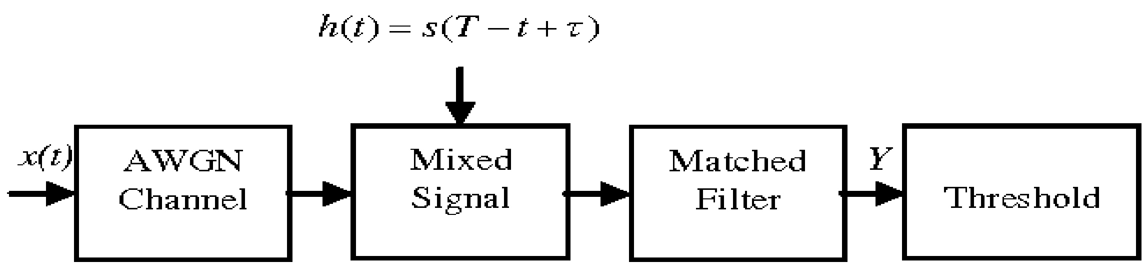

Fig. 2. Block diagram of matched filter detection

Figure 9: Block diagram of spectrum sensing using matched filter

passed through the channel where the additive white Gaussian noise is getting added to the signal and outputted the mixed signal. This mixed signal is given as input to the matched filter. The matched filter input is convolved with the impulse response of the matched filter and the matched filter output is then compared with the threshold for primary user detection.

The threshold of a signal, determined by two possible ways has been discussed here. One way is to estimate the energy of the signal and reduce it to half, fix it as a threshold. Another way is to compute the standard deviation of the signal by computing the mean and use it as threshold. Of the two methods, the former one is theoretically proved to be optimal.

Once the threshold is chosen, presence of signal is determined based on

$$rxd(t) > a : \text{signal present} \longrightarrow eq(3)$$

$$rxd(t) < a : \text{signal absent} \longrightarrow eq(4)$$

where rxd(t) is the matched filter output given by

$$rxd(T) = sig_0(T) + w_0(T) \longrightarrow eq(5)$$

from $eq(2)$

$$rxd(T) = E + w_0(T) \longrightarrow eq(6)$$

If there is no primary user signal, then received signal be

$$rxd(T) = w_0(T) \longrightarrow eq(7)$$

indication of only noise.

4.1 Simulation results

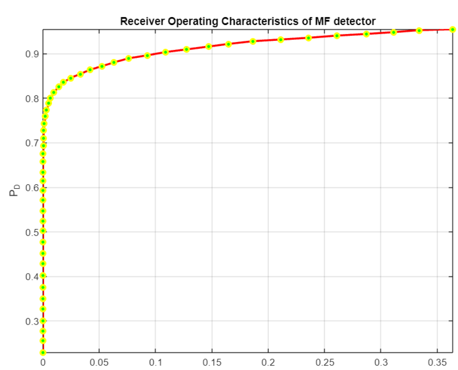

Figure 10: receiver operating characteristics in matched filter detectorr

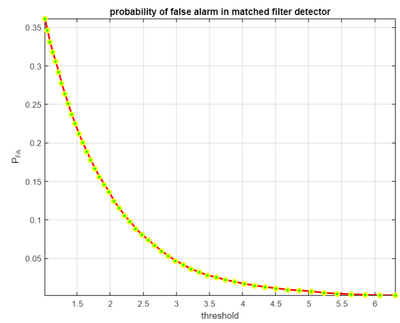

Figure 11: probability of false alarm in matched filter detector

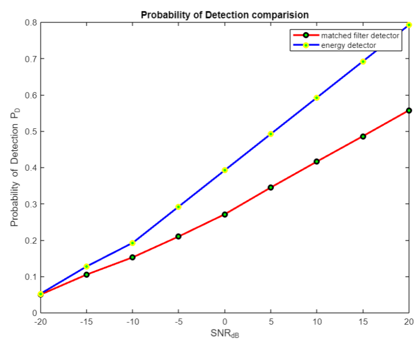

Figure 12: probability of detection of energy detector and matched filter detector

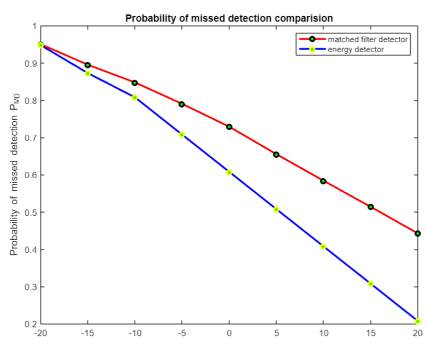

Figure 13: probability of missed detection of energy detector and matched filter detector

4.2 Conclusion

In a cognitive radio network, the transmitted signal characteristics are usually unknown. Therefore, the MFD performance decrease which leads to unwanted signal detection. It requires a specific sensing receiver for different types of the primary user's signals. Large power consumption due to the execution of different receiver algorithms for the detection.

5 Cyclo stationary

The most recent research shows that, the Cyclostationary Detection is the most suitable choice as compared with the ED and the MFD techniques. It is suggested by the many researches as the most suitable option . As the MFD technique requires the prior knowledge about the licensed user's wave but for the ED it is not necessary to have a prior knowledge of the primary user wave . The ED technique is simplest but it is highly sensitive with the changing noise levels . The primary modulated waveforms with the patterns are also characterized as Cyclostationary feature like pulse trains, hoping sequences, and the sine waves. The cognitive radio can detect any specific modulated random signal in a stochastic noisy environment by exploiting the mean and the auto correlation periodic characteristics of the primary waveform. This technique is more effective in an environment where the levels of noise are uncertain. The noise uncertainty is because of the spectral correlation function of the AWGN channel is zero due to the stationary property . The absence or presence of the PU signal can be identified by calculating the spectral correlation of the PU signal at the Cyclostationary detector . The output of the CFD is compared with the predefined threshold value to determine the presence or absence of the PU's signal. Limitations of the Cyclostationary detection The CFD is more robust to uncertain levels of noise and gives much better performance in low SNR regions . However, this technique has its own limitations: High computational complexity. Long sensing time.

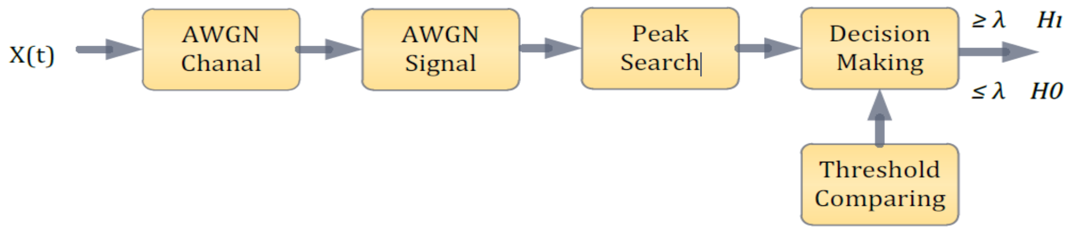

Figure 14: Block diagram of spectrum sensing using cyclo stationary

6 Cooperative

One of most critical components of cognitive radio technology is spectrum sensing. By sensing and adapting to the environment, a cognitive radio is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. To do so, the cognitive radio must continuously sense the spectrum it is using in order to detect the re-appearance of the primary user. Once the primary user is detected, the cognitive radio should withdraw from the spectrum instantly so as to minimize the interference it may possibly incur. This is a very difficult task as the various primary users will be employing different modulation schemes, data rates and transmission powers in the presence of variable propagation environments and interference generated by other secondary users. Another great challenge of implementing spectrum sensing is the hidden terminal problem, which occurs when the cognitive radio is shadowed, in severe multipath fading or inside buildings with high penetration loss while a primary user is operating in the vicinity . Due to the hidden terminal problem, a cognitive radio fails to see the presence of the primary user and then will access the licensed channel and cause interference to the licensed users. In order to deal with the hidden terminal problem in cognitive radio networks, multiple cognitive users can cooperate to conduct spectrum sensing.

Cooperative communications has been recently recognized as a powerful solution that can overcome the limitation of wireless systems . The basic idea behind cooperative transmission rests on the observation that in a wireless environment, the signal transmitted or broadcast by a source to a destination node, each employing a single antenna, is also received by other terminals, which are often referred to as relays or partners. The relays process and retransmit the signals they receive. The destination node then combines the signals coming from the source and the partners, thereby creating spatial diversity and taking advantage of the multiple receptions of the same data at the various terminals and transmission paths. In addition, the interference among terminals can be dramatically suppressed by distributed spatial processing technology. By allowing multiple cognitive radios to cooperate in spectrum sensing, the hidden terminal problem can be addressed. Cooperative spectrum sensing in cognitive radio networks has an analogy to a distributed decision in wireless sensor networks, where each sensor makes a local decision and those decision results are reported to a fusion center to give a final decision according to some fusion rule. The main difference between these two applications lies in the wireless environment. Compared to wireless sensor networks, cognitive radios and the fusion center (or common receiver) are distributed over a larger geographic area. This difference brings out a much more challenging problem to cooperative spectrum sensing because sensing channels (from the primary user to cognitive radios) and reporting channels (from cognitive radios to the fusion center or common receiver) are normally subject to fading or heavy shadowing.

6.1 Cooparative models

Cognitive Radio users cooperate with each other's to achieve the optimal detection performance. The cooperation modeling in the cooperative spectrum sensing is basically concerned with the cooperation behavior of the CR users. There are different approaches which are used for modeling of the cooperation between the CR users. The cognitive relays cooperate with the transmitter for the successful transmission of the data stream towards the destination. The cooperative spectrum sensing can be deployed in two ways

- The soft cooperation
- The hard cooperation

6.1.1 the Soft cooperation

For the licensed spectrum sharing, it is very important for the SU to sense the free holes in the PU spectrum. The role of the CR is very important for sensing the presence or absence of the PU. In the soft cooperation technique, each cognitive relay does not make individual decision about the spectrum presence or absence. Each cognitive relay sends the received data bit directly to the CC. the role of the CC is like a Central Processing Unit (CPU).

The CPU is a final authority for the decision making about the PU spectrum. It gives feedback to each cognitive relay about the presence or absence of the PU. Each cognitive relay helps the SU for searching the decision about the presence or absence of the PU.

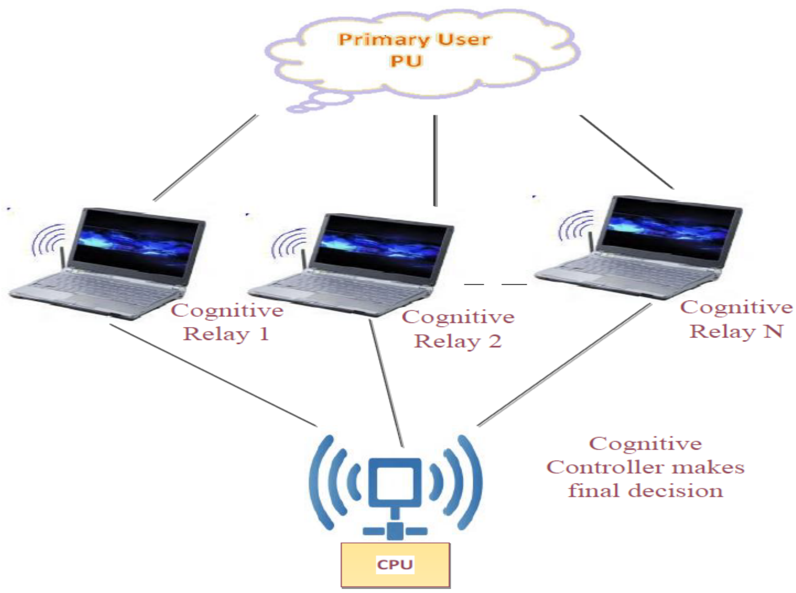

Figure 15: Block diagram of soft cooparative model

6.1.2 Hard cooparative technique

Unlike the soft cooperation, in the hard cooperation technique each cognitive relay makes its own individual decision based on the received data from the source. Then each CR forwards the individual decision towards the CPU. Where the CPU is responsible for making the final decision based on the received individual decisions. It gives feedback to relays about the presence or absence of the PU. It is obvious from the research that, the soft cooperation gives much better performance. It improves the 30-40 overall performance in terms of the spectrum detection and the probability of false alarming.

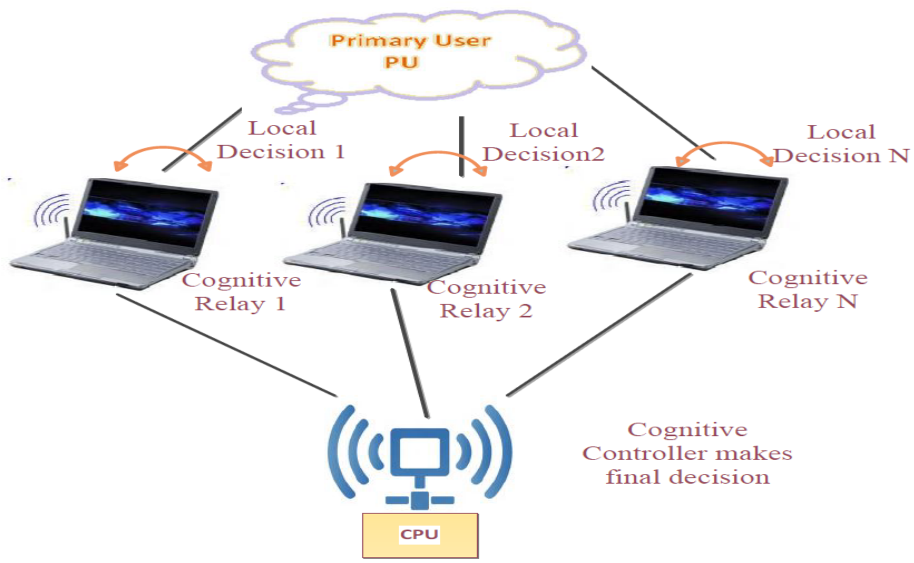

Figure 16: Block diagram of Hard cooparative model

7 Spectrum Database

Federal Communications Commission (FCC) proposed a spectrum database concept to remove complexity of spectrum sensing technique and to use TV white space. All TV stations need to update their next week usage in database maintained by FCC. CR devices can seek free spectrum information from this database. CR devices will have knowledge about free spectrum for use and can negate the need for complex sensing which requires time and money.

7.1 Limitation of Spectrum Database Technique

A significant percentage of spectrum holes are created dynamically for a short duration of time. It is very difficult for a database to update dynamic and real-time activity in spectrum. This presents a massive opportunity loss for CR devices (especially in the IoT ecosystem where several devices need to transmit a small amount of information which can be effectively done on dynamically created spectrum holes).

8 Reference

1. FCC, Spectrum Policy Task Force, 11/2002, ET Docket 02-135.

2. H. Urkowitz, Energy detection of unknown deterministic signals, in IEEE Proceedings, vol. 55, no. 4, April 1967, pp. 523531.

3. H. Sun, D. Laurenson, and C.-X. Wang, Computationally tractable model of energy detection performance over slow fading channels, IEEE Comm. Letters, vol. 14, no. 10, pp. 924 926, Oct. 2010.

4. Q. Chen, F. Gao, A. Nallanathan, and Y. Xin, Improved cooperative spectrum sensing in cognitive radio, in Proc. IEEE VTC 2008 Spring, 2008, pp. 1418 1422.

5. Q. Chen, M. Motani, W.-C. Wong, and A. Nallanathan, Cooperative spectrum sensing strategies for cognitive radio mesh networks, IEEE J-STSP, vol. 5, no. 1, pp. 56 67, Feb. 2011.

6. C.-X. Wang, H.-H. Chen, X. Hong, and M. Guizani, Cognitive radio network management: tuning in to real-time conditions, IEEE Vehicular Technology Magazine, vol. 3, no. 1, pp. 2835, Mar. 2008.

7. C.-X. Wang, X. Hong, H.-H. Chen, and J. S. Thompson, On capacity of cognitive radio networks with average interference power constraints, IEEE Trans. Wireless Comm., vol. 8, no. 4, pp. 1620 1625, Apr. 2009.