International Journal of Engineering Sciences Paradigms and Researches (IJESPR)
(Vol. 21, Issue 01) and (Publishing Month: June 2015)
(An Indexed, Referred and Impact Factor Journal)
ISSN (Online): 2319-6564
www.ijesonline.com

Research Paper on Non Cooperative Spectrum Sensing in Cognitive Radio

Preeti Garg[1] and Milan Bajaj[2]

[1]M. Tech. Scholar
Bahra Institute of Management and Technology, VPO Chidana, District Sonepat, Haryana (India)
preetigarg81189 @gmail.com

[2]Assistant Professor
Bahra Institute of Management and Technology, VPO Chidana, District Sonepat, Haryana (India)
bajajmilan @hotmail.com

Abstract

Cognitive radio technology has been recently been introduced to opportunistically exploit the spectrum. Secondary users are allowed to utilize licensed spectrum bands as long as they do not cause unacceptable interference with licensed users. Such flexibility alleviates the crowding issue in particular spectrum bands and greatly enhances the efficiency of spectrum utilization. The main challenge in any cognitive radio system is to maximize secondary user's throughput while limiting interference imposed on licensed users. In this regard, finding the optimal and accurate sensing techniques are of great importance in a cognitive radio networks.

This paper presents a comparative performance analysis of three broad non cooperative SS techniques i.e. energy detection, cyclostationary detection and matched filter detection. Simulation is performed for various performance parameters (P_d, P_m, P_f) as a function of SNR.
Simulation is done using MATLAB 2013a. Simulation results obtained for comparative analysis shows that cyclostationary detection scheme provides better performance under low SNR and matched filter scheme maximize SNR value at any value of detection probability.

Keywords: *Spectrum Sensing, Software Defined Radio, Cognitive Radio, Cooperative sensing, Non-Cooperative sensing, energy detection, cyclostationary detection, matched filter detection.*

1. Introduction

Over a last decade wireless communication has become fastest growing field of communication industry. Now, it is hard to imagine life without wireless applications (like cellular telephony, wireless internet) and wireless devices (like mobiles, laptops and tablets etc.). Apart from these new applications like smart home appliances, wireless senor networks, remote telemedicine, automated factories and wireless automation etc. are present everywhere. This results into increase in number of users requiring access of wireless system and services but wireless spectrum is limited. This leads to spectrum scarcity; menses limited spectrum causes hurdles in implementation of new wireless services. Practical measured Spectrum utilization between 0-6 GHz at Berkeley Wireless Research Centre (BWRC) explored in [1]. In [1], measurements shows lower frequency band is highly utilized and at higher frequency spectrum utilization is poor. This poor spectrum utilization is termed as spectrum hole. This indicates that spectrum scarcity is nothing but only a false belief. Basically spectrum scarcity problem is due to fixed spectrum allocation policies, lack of flexibility in system, and inefficient spectrum utilization like utilization of public safety band (410-470 MHz) and unlicensed band (2.4 GHz) is only 16.6% and 1.5% respectively [2]. Apart from these measurements carried out at various countries show 5-50% spectrum utilization [3-5]. This suggests that real problem is not spectrum scarcity but inefficient spectrum utilization. To address this problem Spectrum Policy Task Force (SPTF) prepared a report under guidance of *Federal Communications Commission* (FCC) [6]. This report pointed out at a particular time in licensed spectrum most of allocated channels are completely free, some are partially used and some are heavily used. This report also recommends certain rules and regulation to carry out efficient spectrum utilization. A possible solution to these problem has been provided if licensed spectrum is made available to unlicensed users provided there is no interference with licensed users. This can solve almost all spectrum scarcity problems, and this solution can be achieved via intelligent radio system called CR. CR is a novel technology to solve the spectrum sharing problem and allow secondary users to use spectrum on opportunistic basis, but it is currently a big challenge for spectrum management system. The reason for that is the need for self-adaptability and flexibility of the CR. As CR has to automatically analyse its radio spectrum environment to identify temporarily vacant spectrum and use it by adapting to the environment by changing its transmission parameters. This implies most important part on which overall operation of CR depends is how efficiently it sense radio environment, hence most research currently focuses on SS in CR.

2. Problem Definition

The term Software Defined Radio (SDR) coined by Mitola in 1992. SDRs is a reconfigurable radio system in which radio parameters (like type of modulation, type of coding scheme and transmitting power of PU signal) can be adapted according to changes in the sensing environment or more specifically a radio whose physical layer behavior is defined by software. SDR support broad range of frequencies, air interfaces, application software and has ability to change initial configuration to satisfy user requirements [10].

The term CR was firstly described by Joseph Mitola [8]. According to Mitola "CR as a radio capable of analysing the environment (as channels and users), learning and predicting the most suitable and efficient way of using the available spectrum and adapting all of its operation parameters".

Realization of CR technology is very complex as it involves several field of research like signal processing, smart antennas, hardware architecture, Medium Access Control, communication theory, Dynamic Spectrum Access (DSA) methods, protocol design, cognitive network architecture etc. But performance of collective operation of all these fields depends upon how effectively task of SS is carried out. Moreover real time SS is more critical which include dynamic scenario and continuous changing parameter value.

Hence, main idea of this work centered around SS. Here, problem of SS is formulated as binary hypothesis testing problem to decide presence or absence of primary user. There exists number of SS techniques in literature, among them energy detection, cyclostationary detection and matched filtering are most important. Our objective is to compare performance of these most important existing techniques. This explores reliability and robustness of decision made by SS methods in under different constraints.

3. Cognitive Radio Architecture & Cycle

CR architecture is based on fundamentals design rules by which sensors, Autonomous Machine Learning and SDR may be integrated to create a aware and adaptive system (shown in Figure 1.1).

3.1 CR Functional Components

There are six functional blocks in CR architecture and a specific hardware to implement these function is necessary, although CR is an emerging technology so far, boxes can be considered functional, not physical.

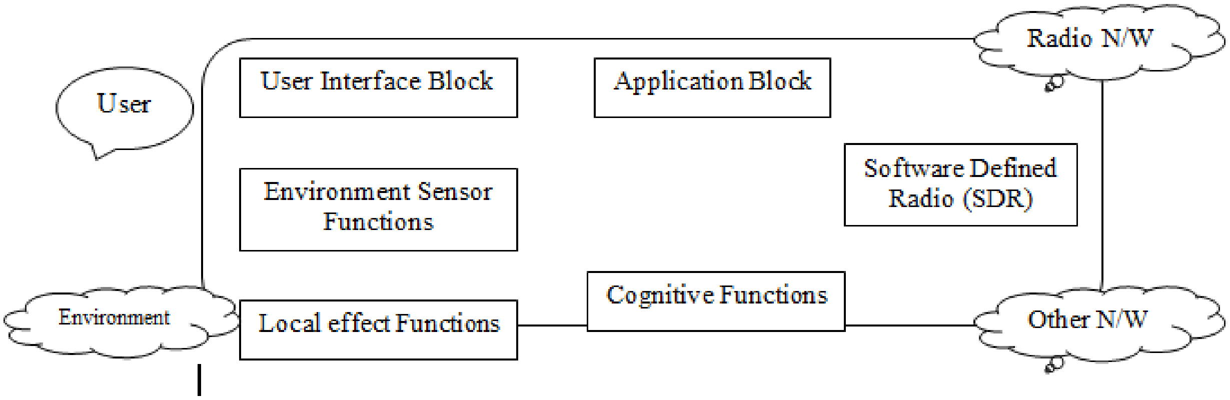

Figure 1.1: Functional Cognitive Radio Architecture

These functional components are [11, 12]:

- User Information Block: This interface block performs audio and video sensing and perception (observation) function.
- Environment Sensor: This block sense environment in terms of location, temperature, accelerometer, compass, etc...
- System applications: This block is responsible for media independent services like playing a network game.
- SDR Block: This block perform functions like RF sensing and SDR radio applications.
- Cognition Control Block: This block perform cognition functions like system control, planning, and learning.
- Local Effect Indicator: Functions performed by this block includes speech synthesis, text, graphics, and multimedia displays.

3.2 Cognitive Cycle

CR architecture and its functional components don’t completely describe each and every aspects of CR. To provide fundamental cognitive capabilities CR architecture is integrated with machine learning. Fundamental capabilities require to observe (sense, perceive), to orient, to plan, to decide, to act and to learn. These capabilities are shown by a sequence of events called cognitive cycle (shown in Figure 1.2). CR system continually observes (senses and perceives) its own environment via user interface and sensors. External stimuli are explored in the orient phase to determine their meanings and their priority. Based upon experience system respond to a stimuli, like particular RF conditions and signals, and more, with an immediate reaction or a planned activity like when PU shows its activity in licensed band, SU has to immediately vacate specified channel. Typically, the reactions and CR behaviors are planned with specifics Cognitive functions. Actions are to save data or to search a new RF channel. In every case, the actions are not always unique. It's possible that the current stimulus is common to more plans so the system should decide. The choice depends by CR experience and user's application. The perception, observation, decision and action functions cause the CR learning i.e. system counts the occurrences of the events (it makes a statistic) and remembers its past decisions based on the external stimuli and user's preferences. The learning also occurs when new decision models and planning tools are embedded in CR system.

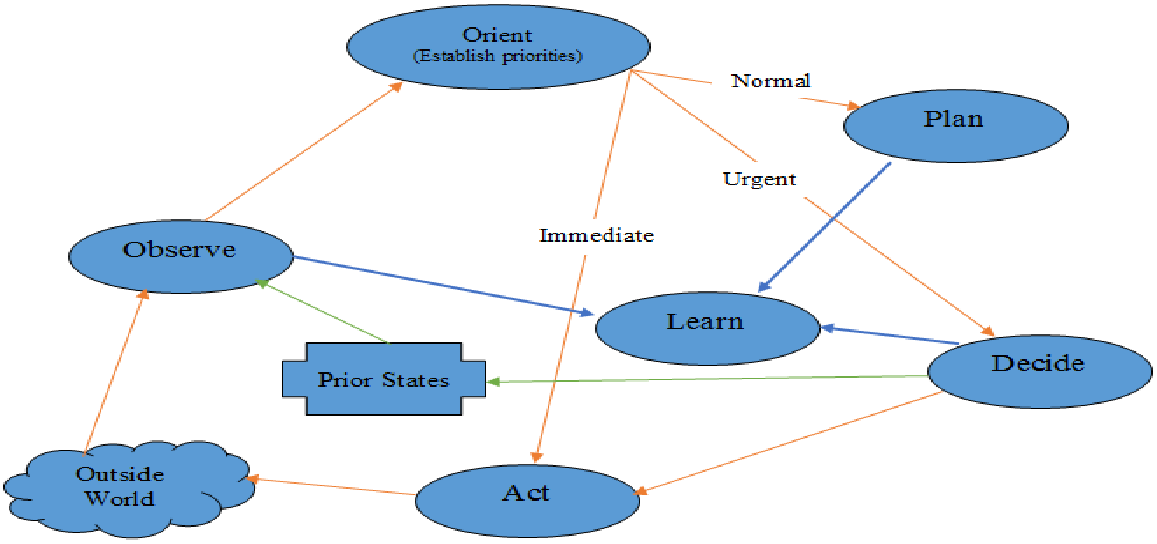

Figure 1.2: Cognitive Cycle

4. Spectrum Sensing Research Methodology

Basically SS should be able to give general picture of entire radio spectrum. This allow CR network to analyse specified spectrum to predict spectrum usage. SS problem is similar to signal detection in noisy environment. Analytically, this can be given by binary hypothesis test as shown in Figure 1.3 [19].

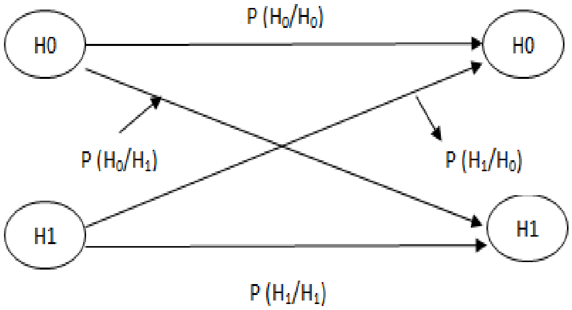

Figure 1.3: Binary hypothesis for SS

$$y(t) = \begin{cases} w(t) & H_0 \\ s(t) + w(t) & H_1 \end{cases},$$

Where,

y(t) is received sample analyzed at every t
w(t) is noise (not necessarily AWGN)
s(t) is desired signal network wants to detect

H0 and H1 are noise only and signal plus noise hypothesis. H0 corresponds to null hypothesis i.e. no PU signal in radio spectrum where H1 represent the condition when PU transmits in spectrum.

There are four possible outcomes of binary hypothesis

- CASE 1: Declaring H0 when H0 is true (H0/H0)
- CASE 2: Declaring H1 when H1 is true (H1/H1)
- CASE 3: Declaring H0 when H1 is true (H0/H1)
- CASE 4:Declaring H1 when H0 is true (H1/H0)

Case 2 is known as correct detection where case 3 and case 4 represent miss detection and false detection respectively. Performance of any detection scheme depends upon miss detection and false detection. A higher value of miss detection leads to interference with PU signal and a higher value of false detection limit complete exploitation of spectrum opportunity.

There are two fold functions of SS, first to determine presence and absence of signal and second, to differentiate PU signal from SU signals. For finding how much effective our detection scheme is performance measure for each SS technique is defined.

Conventionally, sensitivity and specificity are used to determine performance of any SS technique [21]. These performance parameters are measured in term of detection Pd and probability of false alarm Pf, respectively. Pd is probability of correct detection of PU signal provided hypothesis H1 in specified band of frequency. Mathematically,

Pf implies that SS method incorrectly decide PU signal provided H0 hypothesis in specified band of frequency. it is given as,

In any SS scheme, for best performance Pd should be as high as possible and a lower value of Pf is desirable. One more significant parameter of attention is the probability of missed detection Pm. Pm indicates the probability of not detecting PU signal provided H1 hypothesis i.e. it enable to detect when PU actually present. Mathematically,

If Pf and Pm are high, probability of making wrong decision increase and performance of SS technique degrades, as high Pf corresponds to poor spectrum utilization/exploitation by CR and high Pm results in increased interference with PU signal. Hence the main challenge in any SS approach is to keep both Pf and Pm under certain maxima of overall system i.e. minimum value of Pf and Pm which improve total performance.

Number of methods present in literature based upon non cooperative detection, but energy detection, matched filter detection, cyclostationary detection and waveform based detection are important and discussed in detail.

4.1 Energy Detection

In this method energy of received signal is compared with predetermined threshold to make decision about spectrum occupancy. Threshold is set based upon noise floor in the operating environment. This method is especially suited when CR can't gather sufficient information about PU signal i.e. in case of wideband sensing. Critical thing in energy detection is to set appropriate threshold value [22, 23].

If we defined T(y) as test statistics given in form of energy of received signal, energy detection decide among two hypotheses H0 and H1 by comparing T(y) with predefined threshold voltage λ as

$$T(y) \geq \lambda \qquad \Rightarrow H1$$
$$T(y) < \lambda \qquad \Rightarrow H0$$

If threshold λ is low, Pf increases which result into poor spectrum utilization and a higher value of λ leads to higher Pm which in turn cause increase interference with PU signal. Hence always exist a trade-off between Pf and Pm.

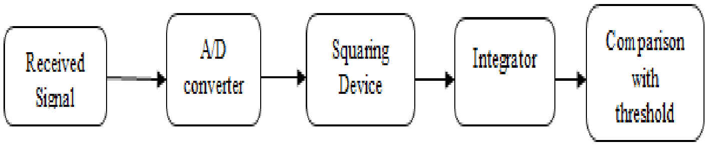

Figure 1.4: Block Diagram of energy detector

Test statistics for energy detector is given as

$$T(y) = \frac{1}{N}\sum_{n=1}^{N} \left| s(n) + w(n) = y(n) \right|^2 .$$

T(y) represent energy of received signal y(n).

4.2 Cyclostationary Detection

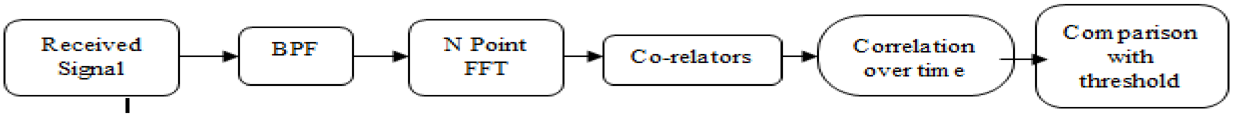

Figure 1.5: Block Representation of Cyclostationary Detector

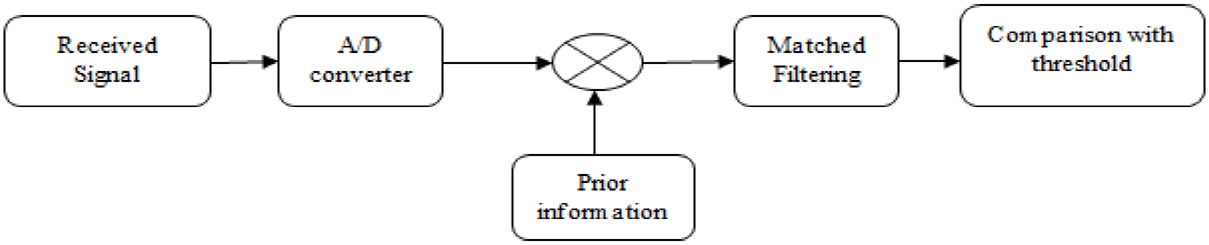

Figure 1.6: Block Representation of Matched Filter Detector

Assuming a complex deterministic sinusoidal PU signal s(t) and it is passed through AWGN channel for Fig. 1.5, resulting into addition of noise w(t);

$$s(t) = A\cos(2\pi ft + \theta)$$

Where, A= Amplitude of PU signal,

f = frequency of signal and

θ = Phase of PU signal (Initial).

The mean value corresponding to y(t) will be, where y(t)=s(t)+w(t).

False alarm Probability

$$P_f = \Pr\langle H1 | H0 \rangle ,$$

$$P_f = \exp\left(\frac{-\lambda^2}{2\sigma_A^2}\right).$$

$$\sigma_A^2 = \frac{\sigma_w^2}{(2N+1)},$$

where λ is threshold value.

Detection Probability

$$P_f = \Pr\langle H1|H1\rangle$$

$$P_d = Q\left(\frac{\sqrt{2\gamma}}{\sigma w}, \frac{\lambda}{\sigma_A}\right)$$

Where, Q(,) = Generalized Marcum Q function

Miss detection probability

$$P_m = 1 - P_d = 1 - Q\left(\frac{\sqrt{2\gamma}}{\sigma w}, \frac{\lambda}{\sigma_A}\right)$$

4.3 Matched Filter Detection

This is an optimal detection scheme but it requires prior information about PU signal such as preamble, signalling for synchronization, pilot pattern for channel estimation etc. at receiver end. Block diagram for matched filter detector is represented as in fig. 1.6.

Here, input signal s(t) is passed through A/D converter to get discrete time signal s(n). This signal further multiplied with prior information s*(n). Test statistics corresponding to matched filtering operation of this multiplied signal is formed which is further compared with threshold value to make decision about presence or absence of PU. This is a coherent detection scheme; test statistics for this is given as

$$T(y) = \sum_{n=0}^{N-1} s(n) \times s^*(n)$$

Where s*(n) is prior information

False alarm probability

$$P_f = \Pr\langle H1|H0\rangle = \Pr[T(y) > \lambda|H0]$$

$$P_f = \exp\left(\frac{-\lambda^2}{E\sigma_w^2}\right)$$

where λ = threshold value,

E = PU signal power

Detection probability [60, 61]

$$P_d = \Pr\langle H1|H1\rangle = \Pr[T(y) > \lambda|H1]$$

$$P_d = Q\left(\sqrt{\frac{2E}{\sigma_w^2}}, \sqrt{\frac{2\lambda^2}{E\sigma_w^2}}\right)$$

As received signal is combination of PU signal and noise so, in this case test statistics become

$$T(y) = \sum_{n=0}^{N-1} y(n) \times s^*(n)$$

Where, y(n) = s(n) · h(n) + w(n),

s(n) = PU signal,

h(n) = impulse response of matched filter,

w(n) = white noise and

s*(n) = prior information.

Miss detection probability

$$P_m = 1 - Q\left(\sqrt{\frac{2E}{\sigma_w^2}}, \sqrt{\frac{2\lambda^2}{E\sigma_w^2}}\right)$$

5. Simulation & Results

Energy detection, cyclostationary detection and matched filter detection are three most important SS techniques in literature. Analytical model for these schemes are presented in previous sections. Results based on analytic simulation are presented in this section. Simulation is done using MATLAB 2013a for number of samples = 1000, λ=.5 and SNR variations range from -20 to +10 in dB.

Figure 1.7 explores comparative performance of energy detection, matched filter detection and cyclostationary detection in terms of P_d. This plot yields two very important results. One, consider at SNR= -10 dB P_d achieved by energy detection, matched filter detection and cyclostationary detection is 0.45, 0.01 and 0.76 respectively. This suggests that at -10 dB which is standard for 802.22 working group, cyclostationary detector outperform other two schemes. Cyclostationary detection perform better under low SNR as it exploit built in periodicity of PU signal. It can easily differentiate between PU signal and noise signal because noise signal can never be cyclostationary.

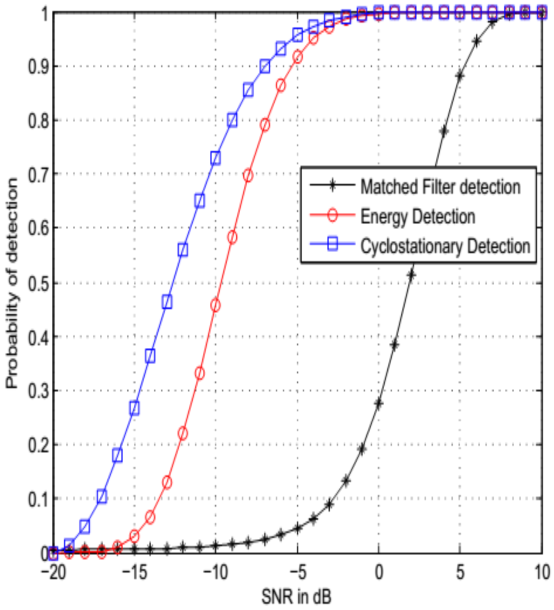

Figure 1.7: Detection probability (P_d) Vs. SNR

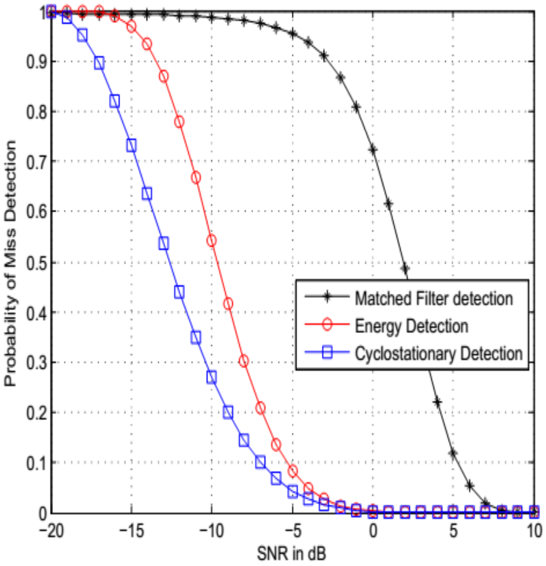

Figure 1.8: Miss Detection Probability (P_m) Vs. SNR

At -18 dB, cyclostationary detection is only scheme that can detect signal with low probability as in this scheme decision statistics is based upon noise rejection property of spectrum. Second, for P_d=0.3, SNR achieved is -16 dB, 0 dB and -12 dB for cyclostationary detection, matched filter detection and energy detection respectively. It shows for a constant detection probability matched filtering maximizing value of SNR. Better performance of matched filtering operation is evident from the fact that it is coherent scheme and requires prior information at receiver end

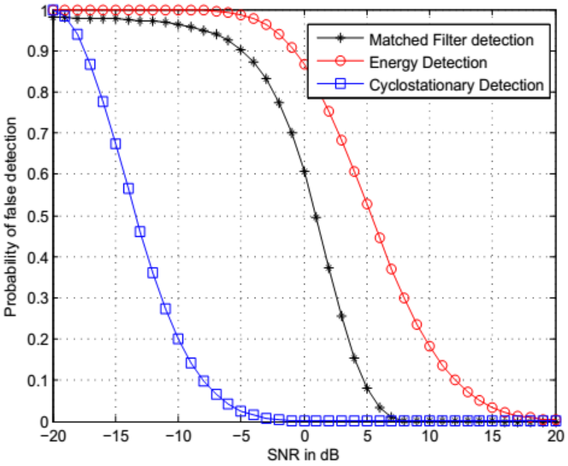

Figure 1.9: False alarm probability (P_f) Vs. SNR

Figure 1.9 shows comparative analysis of three detection schemes in terms of P_f. Performance of energy detection scheme is worst in terms of P_f as it is a complete blind scheme i.e. it does not require any prior information. Analytical model and results obtained suggest that each scheme has its own pros and cons. Matched filter scheme optimize SNR value but it requires prior information. Energy detection is simple to implement but offers high false alarm probability. Cyclostationary detection offer correct decision but its implementation complexity is very high.

6. Conclusion & Future Scope

This paper presents a comparative performance analysis of three broad non cooperative SS techniques i.e. energy detection, cyclostationary detection and matched filter detection. Simulation is performed for various performance parameters (P_d, P_m, P_f) as a function of SNR. Simulation results illustrated that, cyclostationary detection outperforms energy detection and matched filter detection under low SNR because of its ability to differentiate between PU signal and noise signal. For any value of detection probability matched filter detection optimize SNR as compared to other schemes as it is a non-blind technique and require prior knowledge of PU signal.

This work explores various challenges encountered in SS techniques. This thesis explores performance comparison of most important non-cooperative SS techniques. This research work can be extended into numerous ways; some of them are listed below.

- Performance comparison among user mobility.
- Performance comparison under imperfect channel estimation (i.e. diversity detection and fading).
- Performance comparison in correlated and non-identical diversity.
- Performance comparison among diversity reception and Rician fading.

References

[1] M. Islam et al., “Spectrum survey in Singapore: Occupancy measurements and analyses”, International Conference on Cognitive Radio Oriented Wireless Networks and Communications (Crown Com), May 2008, pp. 1–7.

[2] M. Nekovee, “Impact of cognitive radio on future management of spectrum” International conference on cognitive radio oriented wireless networks and communication, 2008, pp. 1-6.

[3] D. Cabric, S. Mishra, and R. Brodersen, “Implementation issues in spectrum sensing for cognitive radios”, Asilomar Conference on Signals, Systems and Computers, vol. 1, Nov. 2004, pp. 772–776.

[4] V. Valenta, R. Marsalek, G. Baudoin, M. Villegas, M. Suarez, and F. Robert, “Survey on spectrum utilization in Europe: Measurements, analyses and observations,” International Conference on Cognitive Radio Oriented Wireless Networks Communications (Crown Com), Jun. 2010, pp. 1–5.

[5] FCC, ET Docket No. 02-155, “Spectrum Policy Task Force Report”, Nov 02, 2002.

[6] FCC, “Spectrum Policy Task Force”, Nov 2002, ET Docket No. 02- 135.

[7] S. Shellhammer, S. Shankar, R. Tandra, and J. Tomcik, “Performance of power detector sensors of DTV signals in IEEE 802.22 WRANs”, ACM TAPAS, Boston, MA, Aug. 2006, pp. 17-26.

[8] J. Mitola, “Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio”, PhD thesis, Royal Institute of Technology (KTH), 2000.

[9] ITU-R Report SM.2152, “Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS)”, 2009.

[10] Mohamed Hamid,“Dynamic spectrum access in cognitive radio networks: Aspects of MAC layer sensing”, PhD Thesis, Blekinge Institute of Technology, 2008.

[11] Joseph Mitola and Gerald Q.Maguire, “Cognitive Radio: Making software radios more personal”, IEEE Personal communications, August 1999, pp. 13-18.

[12] Joseph Mitola III, “Cognitive Radio Architecture: The Engineering Foundations of Radio XML”, Wiley 2006.

[13] S. Haykin, “Cognitive radio: brain-empowered wireless communications”, IEEE trans. on Communications, vol. 23, no 2, 2005, pp. 201–220.

[14] A. Sahai, N. Hoven and R. Tandra, “Some fundamental limits in cognitive radio”, Allerton Conference on Communications, Control and Computing, Urbana, Oct. 2004, pp. 1-11.

[15] A. Ghasemi and E.S. Sousa, “Spectrum sensing in cognitive radio networks: requirements, challenges and design trade-offs”, IEEE Communications Magazine, vol. 46, no. 4, 2008, pp. 32–39.

[16] R. Tandra, S.M. Mishra and A. Sahai, “what is a spectrum hole and what does it take to recognize one ?” proc. of IEEE, vol. 5, no. 97, 2009, pp. 824-848.

[17] T. Yucek and H. Arslan, “A survey of spectrum sensing algorithms for cognitive radio applications”, IEEE comm. Survey and Tutorials, vol. 11, no. 1, 2009, pp. 13-18.

[18] N. Devroye, P. Mitran, and V. Tarokh, “Achievable rates in cognitive radio channels”, IEEE trans. of information theory, vol. 52, no. 5, May 2006, pp. 1813–1827.

[19] H. Urkowitz, “Energy detection of unknown deterministic signals”, Proc. of IEEE, 1967, pp. 523-531.

[20] FCC, “ET Docket No. 03-237”, 07-78 Termination order, 2007.

[21] Raza Umar and Asrar U.K. Sheikh, “A comparative study of spectrum awareness techniques for cognitive radio oriented wireless networks”, Elsevier Physical communication, July 2012, pp. 1-23.

[22] A.P. Hulbert, “Spectrum sharing through beacons”, IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Sept. 2005, pp. 989–993.

[23] B. Wang and K.J. Ray Liu, “Advances in cognitive radio networks: a survey”, IEEE Journal of Selected Topics in Signal Processing, vol. 5, no. 1, 2011, pp. 5–23.

[24] W.A. Gardner, “Exploitation of spectral redundancy in cyclostationary signals”, IEEE Signal Processing Magazine, vol. 8, no. 2, 1991, pp.14–36.

[25] M. Oner andF.K. Jondral, “Cyclostationarity based methods for the extraction of the channel allocation information in a spectrum pooling system”, IEEE Radio and Wireless Conference, Atlanta, Georgia, USA, September 2004, pp. 279–282.

[26] J. Ma, G.Y. Li and B.H. Juang, “Signal processing in cognitive radio”, Proc. of the IEEE, vol. 97, no. 5, 2009, pp. 805–823.

[27] H. Tang, “Some physical layer issues of wide-band cognitive radio systems”, IEEE International Symposium on Dynamic Spectrum Access Networks, Baltimore, MD, USA, Nov. 2005, pp. 151–159.

[28] Thomas Charles Clancy III, “Dynamic Spectrum Access In Cognitive Radio Networks”, PhD Dissertation, 2006

[29] I.F. Akyildiz, B.F. Lo and R. Balakrishnan, “Cooperative spectrum sensing in cognitive radio networks: a survey”, Physical Communication Journal, vol. 4, 2011, pp. 40–62.

[30] G. Ganesan and Y. Li, “Cooperative spectrum sensing in cognitive radio networks”, IEEE International Symposium on Dynamic Spectrum Access Networks, Baltimore, MD, USA, Nov. 2005, pp. 137–143.

[31] S.M. Mishra, A. Sahai and R.W. Brodersen, “Cooperative sensing among cognitive radios”, IEEE International Conference on Communications, June 2006, pp. 1658–1663.

[32] J. Zhao, H. Zheng and G.H. Yang, “Distributed coordination in dynamic spectrum allocation networks”, IEEE International Symposium on Dynamic Spectrum Access Networks, Baltimore, MD, USA, Nov. 2005, pp. 259–268.

[33] A.F. Cattoni, I. Minetti, M. Gandetto, R. Niu, P.K. Varshney and C. Regazzoni, “A spectrum sensing algorithm based on distributed cognitive models‖”, SDR Forum Technical Conference, Orlando, Florida, USA, Nov. 2006, pp. 1-6.

[34] M. Gandetto, C. Regazzoni, “Spectrum sensing: a distributed approach for cognitive terminals”, IEEE Journal on Selected Areas, vol. 25, no. 3, 2007, pp. 546–557.

[35] D. Cabric, S. Mishra, D. Willkomm, R. Brodersen and A. Wolisz, “A cognitive radio approach for usage of virtual unlicensed spectrum”, IST Mobile and Wireless Communications Summit, Dresden, Germany, June 2005, pp. 1-4.

[36] W. Zhang and K. Letaief, “Cooperative spectrum sensing with transmit and relay diversity in cognitive radio networks”, IEEE Trans. on Wireless Communications, vol. 7, no. 12, 2008, pp. 4761–4766.

[37] J.J. Lehtomäki, M. Juntti, H. Saarnisaari and S. Koivu, “Threshold setting strategies for a quantized total power radiometer”, IEEE Signal Processing Letters, vol. 12, no. 11, 2005, 796–799.

[38] A. Sonnenschien and P.M.Fishman, "Radiometric Detection of Spread Spectrum Signals in Noise of Uncertain Power", IEEE

trans. on Aerospace and Electronic Systems, vol. 28, no. 3, July 1992, pp. 654 - 660.

[39] R. Tandra and A. Sahai, “ SNR walls for signal detection”, IEEE trans. on selected topics in signal processing, vol. 2, no. 1, 2008, pp. 4-17.

[40] N. Devroye, P. Mitran and V. Tarokh, “ Limits on communication in a cognitive radio channel”, IEEE comm. Mag., vol. 44, June 2006, pp. 44-49.

[41] A. Taherpour, S. Gazor and M. Nasiri Kenari, “Wide band spectrum sensing in unknown white Gaussian noise”, IET communication, vol. 2, no. 6, July 2008, pp.763-771.