RESEARCH ARTICLE OPEN ACCESS

Advances in Energy Detector and a Matched Filter based Spectrum Sensing: A Survey

Yogesh Patidar*, Prof. Kuldeep Pandey**
*(Department of Electronics and Communication Engg, BCE RKDF University, Bhopal
** (Asst. Prof., Department of Electronics and Communication Engg, BCE RKDF University, Bhopal
** Corresponding Author:Yogesh Patidar*

ABSTRACT
The electromagnetic spectrum, licensed to use by governments, is a limited natural resource.The concept of cognitive radio networks (CRNs) has evolved in past few decades and recently implemented in some areas of wireless communication, namely IEEE 802.11af, IEEE802.15.4m, ECMA 392 and IEEE 802.22, as a technique to use underutilizedspectrum. The key development areas in CRNs are spectrum sensing and monitoring, spectrum analysis, spectrum mobility and spectrum decision. Research articles have classified Spectrum sensing as narrowband and wideband spectrum sensing. This paper presents the fundamentals of narrowband spectrum sensing and reviews the implementation and challenges associated with energy detector (ED) and a matched filter (MF) based spectrum sensing.

Keywords-Cognitive radio networks, energy detector, matched filter, probability of detection, probability of false alarm, probability of miss detection, receiver operating characteristics

I. INTRODUCTION

The Federal Communications Commission's (FCC's), the federal agency responsible for implementing and enforcing America's communications law and regulations, similar to Telecom Regulatory Authority of India (TRAI) in India, spectrum use measurement reveals that some spectrum bands are underutilized at different times in different geographic locations [1]. In static spectrum allocation fixed channels are assigned to users known as a licensed user or Primary Users (PU). When such PU is not present at a specific time the allocated spectrum band remain free and results in underutilization of spectrum bands as shown in figure 1. These free spectrum bands, for a particular time duration and at a specific geographic location, are called spectrum holes.

Cognitive Radio Networks (CRN) plays a vital role in improving spectrum efficiency. Cognitive radio (CR), as defined in [2], is an intelligent wireless communication system that senses and learn its surrounding radio environment and adapt its state to internal changes.

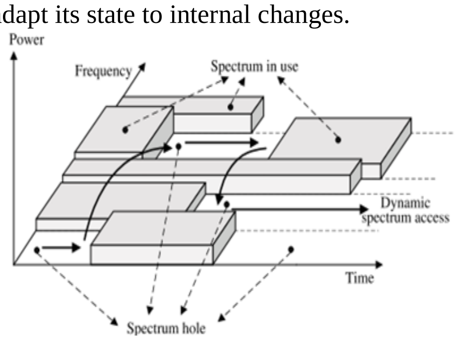

Fig.1: Spectrum hole [2]

In CRN's the unused spectrum is used opportunistically by the CR 's, also known as Secondary Users (SU) or unlicensed users, temporarily without interfering the PU.The CRN's employ Dynamic Spectrum Allocation (DSA) for opportunistically using the underutilized spectrum. The DSA works on a cognitive cycle with spectrum sensing, spectrum analysis, spectrum mobility and spectrum sharing as four main phases[3]. In the spectrumsensing phase, CR finds the spectrum holes which then analyzed for suitability of transmission and assigned to SU in spectrum analysis phase. Meanwhile, the CR continuously sense the spectrum for new spectrum hole and presence of PU on its licensed band. As soon as PU appear on its licensed band, the spectrum mobility comes into play and assign new spectrum hole to SU and vacate the PU's licensed band. Spectrum sharing is all about coordination of available spectrum holes between all SU's.

In section II we have given a mathematicalfoundation for spectrum sensing which further applied to a matched filter based detection and energy detector in section III and section IV respectively. Section III and section IV also cover the research advancements and MATLAB simulation.

II. SPECTRUM SENSING (SS)

The conventional definition of spectrum sensing is to detect unused spectrum bands or spectrum holes of PU's. The various aspects of spectrum sensing include sensing approaches, enabling or sensing algorithms, challenges, cooperative sensing, multi-dimensional spectrum sensing and standards that employ sensing[4]. Researchers have classified Spectrum sensing algorithms as coherent and noncoherent algorithms. The coherent spectrum sensing algorithms, such as matched filter, require the prior information of PU whereas noncoherentalgorithms, such as energy detector, investigate channel for spectrum holes without any prior information of PU.To explore further spectrum sensing techniques, we first present the mathematical framework and common terminologies used in energy detector and a matched filter based spectrum sensing. These techniques use the Neyman-Pearson (NP) approach for spectrum sensing [5]. Consider a simple binary hypothesis testing problem to choose one of the two hypotheses, $\mathcal{H}_0$ and$\mathcal{H}_1$.

$\mathcal{H}_0 : y[n] = w[n]$ (Noise only)
$\mathcal{H}_1 : y[n] = x[n] + w[n]$ (Signal with noise)

Where $\mathcal{H}_0$is a null hypothesis which represents noise ($w[n]$) only or absence of signal and $\mathcal{H}_1$is the alternative hypothesis which represents thepresence of a signal($x[n]$) with noise ($w[n]$).We assume that $w[n]$ isWhite Gaussian Noise (WGN) whichiszero-meanGaussian noise process with autocorrelation function $r_{ww}[k] = E(w[n]w[n+k]) = \sigma_\omega^2 \delta[k]$ where $\delta[k]$ is a unit Dirac delta function. Now with $x[n] = A$ (DC level), the probability density function (PDF) or the likelihood corresponding to the two hypotheses can be given as:

$$p(y[n]: \mathcal{H}_0) = \frac{1}{(2\pi\sigma_\omega^2)^{\frac{1}{2}}} e^{-\frac{(y[n])^2}{2\sigma_\omega^2}} \quad (1)$$

$$p(y[n]: \mathcal{H}_1) = \frac{1}{(2\pi\sigma_\omega^2)^{\frac{1}{2}}} e^{-\frac{(y[n]-A)^2}{2\sigma_\omega^2}} \quad (2)$$

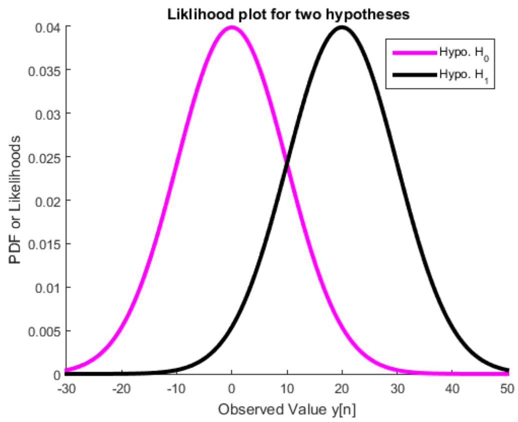

Figure 2:PDF or Likelihood plot for the two hypotheses

The Fig.2 gives a plot of two densities. According to observation$y[n]$, we choose $\mathcal{H}_0$ if $p(y[n]: \mathcal{H}_0) > p(y[n]: \mathcal{H}_1)$ and $\mathcal{H}_1$if$p(y[n]: \mathcal{H}_0) \le p(y[n]: \mathcal{H}_1)$. These two conditions can be summarized as Likelihood Ratio Test (LRT), where we choose $\mathcal{H}_0$ if $L(y): \frac{p(y[n]:\mathcal{H}_1)}{p(y[n]:\mathcal{H}_0)} < 1$ and $\mathcal{H}_1$ if $L(y): \frac{p(y[n]:\mathcal{H}_1)}{p(y[n]:\mathcal{H}_0)} \ge 1$. LRT test for above given noise and signal statistics decide $\mathcal{H}_0$ if $y[n] < \frac{A}{2}$ and $\mathcal{H}_1$ if $y[n] \ge \frac{A}{2}$. Fig.3 shows result of MATLAB simulation for a signal $x[n] = 20$ and WGN with $\sigma_\omega = 10$. The value $\frac{A}{2} = 10$ is a threshold of the detector. The area shown with horizontal green line gives the Probability of Detection(P_D). In above detection process there are two types of possible errors: Type I error is area shaded with red lines where noise is present and we choose it as noise with signal. This is also known as Probability of False Alarm(P_{FA}). Type II error is area shaded with Blue lines, where a signal with noise is present and we choose it as only noise. This is also known as Probability of Miss Detection(P_{MD}). A good detector is one with maximum P_D and minimum P_{FA} but here we find a tradeoff between $P_{FA}$and P_D, hence we cannot minimize P_{FA} while we maximize P_D. NP theorem define LRT as an optimal detector which maximizes P_D for a given $P_{FA} = \alpha$ where threshold γ is given by

$$P_{FA} = \int_{\{y[n]:L(y)>\gamma\}} p(y[n]: \mathcal{H}_0)\, dy = \alpha. \quad (3)$$

The curve $P_D$versus P_{FA}, known as Receiver Operating Characteristics (ROC), gives the detection performance of a NP detector.

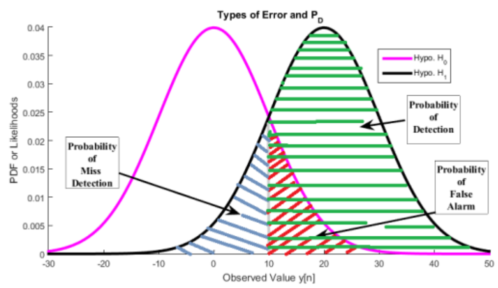

Figure 3: Types of error and P_D

III. MATCHED FILTER BASED SS

It is coherent spectrum sensing technique where prior information of PU is required to detect the presence of PU. For a known signal $x[n]$, and additive WGN $w[n]$, the likelihoods corresponding to the two hypotheses can be given as:

$$p(\bar{y}: \mathcal{H}_0) = \frac{1}{(2\pi\sigma_\omega^2)^{\frac{N}{2}}} e^{-\frac{\|\bar{y}\|^2}{2\sigma_\omega^2}} \quad (4)$$

$$p(\bar{y}: \mathcal{H}_1) = \frac{1}{(2\pi\sigma_\omega^2)^{\frac{N}{2}}} e^{-\frac{\|\bar{y}-\bar{x}\|^2}{2\sigma_\omega^2}} \quad (5)$$

Where $\bar{y} = [y[0], y[1], y[2], \dots\dots\dots\dots\ y[N-1]]^T$ and N is the number of sample in an observation. The log LRT gives the test statistics:

$$T[Y] = \sum_{n=0}^{N-1} Y[n]x[n] = \bar{x}^T \bar{y} \quad (6)$$

As discussed in theprevious section P_{FA} and P_D are calculated as:

$$P_{FA} = P_r\{T(Y) > \gamma^{'}; \mathcal{H}_0\} = \mathcal{Q}\left(\frac{\gamma^{'}}{\sigma_\omega \|\bar{x}\|}\right) \quad (7)$$

$$P_D = P_r\{T(Y) > \gamma^{'}; \mathcal{H}_1\} = \mathcal{Q}\left(\frac{\gamma^{'} - \|\bar{x}\|^2}{\sigma_\omega \|\bar{x}\|}\right) \quad (8)$$

Form (7), we can calculate $\gamma^{'}$ for different values of P_{FA}(using NP theorem). Fig.4 shows the theoretical and MATLAB simulated P_D performance of matched filter detector for different values of SNR.

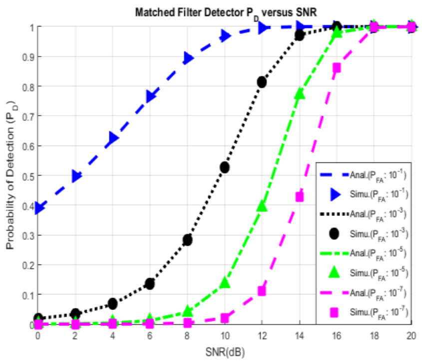

Figure 4: Matched filter detector P_DVs. SNR

From (7) and (8), we get ROC as:

$$P_D = \mathcal{Q}\left(\mathcal{Q}^{-1}(P_{FA}) - \sqrt{\frac{\|\bar{x}\|^2}{\sigma_\omega^2}}\right) \quad (9)$$

In [6] it is proved that matched filter maximizes SNR and is an optimum for signal detection when the signal is known. In [7] PU's prior information requirement at physical and MAC layer is discussed with the issue of timing and carrier synchronization. In [8] a matched filter based validated MATLAB simulation is given to detect frequency modulated signals at 100 MHz, which meet the requirements of IEEE802.22 standards. In [9] robustness of coherent detectors is analyzed under uncertainty of physical systems. In [10] multiple thresholds based spectrum sensing is discussed where matched filter is used to detect PU with different power levels.

IV. ENERGY DETECTOR BASED SS

It is noncoherent spectrum sensing technique where PU is unknown(signal with an arbitrary covariance matrix) to SU. For simplicity, we consider a signal $x[n]$, a zero mean , white Gaussian random process with variance σ_x^2, which can be further extended to non zero mean signal with an arbitrary covariance matrix. We assume additive WGN $w[n]$, with variance σ_ω^2, is independent of signal. The likelihoods corresponding to the two hypotheses can be given as:

$$p(\bar{y}: \mathcal{H}_0) = \frac{1}{(2\pi\sigma_\omega^2)^{\frac{N}{2}}} e^{-\frac{\|\bar{y}\|^2}{2\sigma_\omega^2}} \quad (10)$$

$$p(\bar{y}: \mathcal{H}_1) = \frac{1}{(2\pi(\sigma_x^2+\sigma_\omega^2))^{\frac{N}{2}}} e^{-\frac{\|\bar{y}\|^2}{2(\sigma_x^2+\sigma_\omega^2)}} \quad (11)$$

Where $\bar{y} = [y[0], y[1], y[2], \dots \dots \dots \dots\ y[N-1]]^T$ and N is the number of sample in an observation. The log LRT gives the test statistics:

$$T[Y] = \sum_{n=0}^{N-1} Y^2[n] = \|\bar{y}\|^2 \quad (12)$$

From (12) the test statistics, is equal to the energy of received signal and hence the name energy detector implies, is a Chi-squared random variable with N degree of freedom.The P_{FA} and P_D for an energy detector are calculated as:

$$P_{FA} = P_r\{T(Y) > \gamma^{'}; \mathcal{H}_0\} = \mathcal{Q}_{\chi_N^2}\left(\frac{\gamma^{'}}{\sigma_\omega^2}\right) \quad (13)$$

$$P_D = P_r\{T(Y) > \gamma^{'}; \mathcal{H}_1\} = \mathcal{Q}_{\chi_N^2}\left(\frac{\gamma^{'}}{\sigma_x^2+\sigma_\omega^2}\right) \quad (14)$$

Fig.5 shows the theoretical and MATLAB simulated P_D performance of energy detector for different values of SNR. We note that probability of detection increases monotonically with SNR

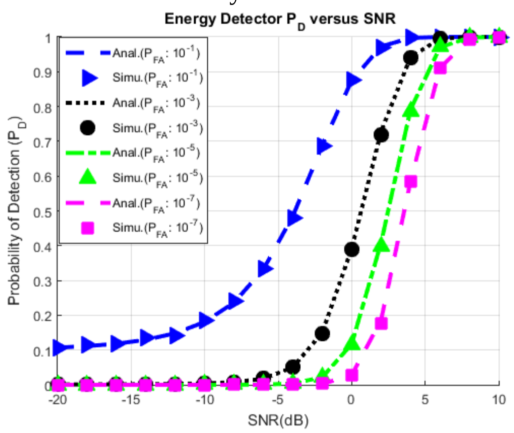

Figure 5: Energy detector P_DVs. SNR

From (13) and (14), we get ROC as:

$$P_D = \mathcal{Q}_{\chi_N^2}\left(\frac{\sigma_x^2 \mathcal{Q}_{\chi_N^2}^{-1}(P_{FA})}{\sigma_x^2+\sigma_\omega^2}\right) \quad (15)$$

The distribution of energy detector output is central Chi-squared random variable when only noise is present whereas it is noncentral Chi-squared random variable when noise with theunknown signal is present [11]. This characteristic of energy detector ensures the detection of unknown PU with low computational complexity. In [12] a validated model for Energy detector performance in signal uncertainty with noise uncertainty and without noise uncertainty is introduced. This work shows degradation of performance of energy detector in signal uncertainty with noise uncertainty and motivatesresearchers to study the performanceof other techniques under signal uncertainty. In [13] energy detector, for Rayleigh fading channel, based on adaptive sensing scheduling is introduced which utilize outdated channel state information for spectrum sensing. In [14] energy detection based spatial spectrum sensing is introduced to overcome the problem of noise uncertainty with lower computational complexity. In [15] effect of in-phase and quarter- phase imbalance(I/Q) is studied on PU performance, and a four-level hypothesis spectrum sensing is introduced to overcome I/Q imbalance.

V. COMPARISON OF A MATCHED FILTER AND ENERGY BASED SPECTRUM SENSING TECHNIQUES

A matched filter based spectrum sensing technique is employed for only narrowband spectrum sensing whereas energy detector based spectrum sensing employed both for narrowband and wideband spectrum sensing. A matched filter based spectrum sensing has high computational complexity and implementation cost in comparison to the energy detector based spectrum sensing. Being coherent technique in a matched filter based spectrum sensing each SU require PU information storage in its database whereas energy detector has no such information requirements.

VI. CONCLUSION

As in thedevelopment of spectrum sensing techniques, the test statistics,ROC, P_{FA},and$P_D$of the detector are important parameters. Hence first we covered, the mathematical development and MATLAB simulation of these parameters for energy detector and a matched filter based spectrum sensing. A matched filter based spectrum sensing is coherent technique with high computational complexity and implementation cost in comarison to the noncoherent technique, energy detector based spectrum sensing. This survey highlights improvements and introduce new domain to study in detection algorithms.

REFERENCES

[1] “Spectrum Policy Task Force Report,” Federal Communications Commission, USA, Report ET Docket No 02-135, November 2002.
[2] Simon Haykin, Cognitive radio: Brain-empowered wireless communications, *IEEEJournal on Selected Areas in Communications*, *Vol.23, No.2,* February 2005,201-220.
[3] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, Shantidev Mohanty, NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey, *Computer Networks, Volume 50, Issue 13,* 2006, 2127-2159.
[4] Tevfik Yucek and Huseyin Arslan, A survey of spectrum sensing algorithms for cognitive radio applications, *IEEE Communications Surveys andTutorials, Vol.11, No.1,* First Quarter 2009, 116-130.
[5] Steven M. Kay, *Fundamental of statistical signal processing volume II detection theory* (Upper Saddle River, NJ USA: Prentice Hall PTR, 1998).
[6] John G. Proakis, *Digital Communications, Fifth Edition*(McGraw Hill Education, New Delhi, India, 2014).
[7] D. Cabric, S. M. Mishra and R. W. Brodersen, Implementation issues in spectrum sensing for cognitive radios, *Thirty-Eighth Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, 2004, 772-776 Vol.1.
[8] A. F. Eduardo and R. G. G. Caballero, Experimental evaluation of performance for spectrum sensing: Matched filter vs. energy detector, *IEEE Colombian Conference on Communication and Computing*, Popayan, Colombia, 2015, 1-6.
[9] R. Tandra and A. Sahai, SNR Walls for Signal Detection, *IEEE Journal of Selected Topics in Signal Processing, Vol.2, No.1*, Feb. 2008, 4-17.
[10] X. Zhang, R. Chai and F. Gao, Matched filter based spectrum sensing and power level detection for cognitive radio network, *IEEE Global Conference on Signal and Information Processing*, Atlanta, GA, 2014, 1267-1270.
[11] H. Urkowitz, Energy detection of unknown deterministic signals, *Proceedings of the IEEE, Vol.55, No.4,* April 1967, 523-531.
[12] M. Lopez-Benitez and F. Casadevall, Signal Uncertainty in Spectrum Sensing for Cognitive Radio, *IEEE Transactions on Communications, Vol.61, No.4,* April 2013, 1231-1241.
[13] A. Abu Alkheir and H. T. Mouftah, An Improved Energy Detector Using Outdated Channel State Information, *IEEE Communications Letters, Vol.19, No.7,* July 2015, 1237-1240.
[14] C. Liu, M. Li and M. L. Jin, Blind Energy-based Detection for Spatial Spectrum Sensing, *IEEE Wireless Communications Letters, Vol.4, No.1,* February 2015, 98-101.
[15] O. Semiari, B. Maham and C. Yuen, On the Effect of I/Q Imbalance on Energy Detection and a Novel Four-Level Hypothesis Spectrum Sensing, *IEEE Transactions on Vehicular Technology, Vol.63, No.8,* October 2014, 4136-4141.

*Yogesh Patidar. “Advances in Energy Detector and a Matched Filter based Spectrum Sensing: A Survey.” International Journal Of Engineering Research And Applications (IJERA), vol. 08, no. 01, 2018, pp. 25–28.