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Research Article

An Investigation into Threshold Selection Methodologies for Spectrum Sensing Techniques in Cooperative Cognitive Radio Networks

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Abstract: This study investigate the optimal conditions for variable SNR values and appropriate threshold values can be examined through concurrent analysis of Pf and Pm when employing energy detector techniques for spectrum sensing. As the proposed method demonstrates higher Pm and lower Pm at low SNR, it fulfills the EDSS optimality criteria for low SNR environments. Additionally, this approach enables threshold verification at high SNR values, and subsequent research could focus on primary user detection. Furthermore, diverse sensing techniques can be applied to contemporary wireless technologies. Additional investigation of various parameters utilizing different methodologies is strongly recommended to improve spectrum sensing outcomes in cognitive radio networks.

Keywords: Spectrum Sensing, Cooperative Cognitive Radio Network, SNR.

1. Introduction

The proliferation of wireless devices has increased dramatically in recent years, driven by advancements in wireless technology. Researchers are developing innovative methods to optimize the use of available wireless resources, with cognitive radio serving as a prime example. As the number of connected devices grows, the demand for spectrum to support these devices is outpacing the available resources. This scarcity of spectrum has made it increasingly challenging to locate unused frequencies. To address this issue and accommodate the rising number of wireless devices and mobile data traffic, cognitive radio technology has been introduced. Cognitive radio is form mobile communication where a transmitter and receiver can automatically detect the communication channels that are occupy or vacant. It quickly moves into empty channels by avoiding the channel that is occupied without causing any disturbance to the licensed user/primary user. There are different techniques to access the licensed user but to detect the location of spectrum holes is one of the most important steps in the radio frequency spectrum utilization. Cognitive radio aims to optimize the frequency spectrum by allowing the cognitive user or the secondary user to detect and then utilize the licensed spectrum incase if the spectrum is not being used by the primary user. In the cognitive radio communication technology, most important requirements of the CUs is the accurate and efficient functioning of the spectrum sensing. Among the various spectrum sensing techniques available, the Energy Detector Spectrum Sensing (EDSS) method is the most widely used in cognitive radio networks. The key parameters for evaluating sensing performance in this technique are misdetection probability (Pm) and false alarm probability (Pf), both of which play a crucial role in the selection of an appropriate threshold. Hence, choosing an optimal threshold is essential for effective energy detection. In non-cooperative spectrum sensing, the performance of cognitive users can degrade due to factors like multipath fading. To mitigate this, Cooperative Spectrum Sensing (CSS) is employed, which improves detection accuracy under fading conditions. In CSS, the Fusion Center (FC) collects sensing data from each cognitive user (CU) and applies cooperative decision rules to effectively manage the licensed spectrum. The threshold selection is an effective way that works on the basis of both the error detection and false alarm under various fading channel which are not included in cooperative scenario in various research papers. Therefore, in this thesis, we analysed these as the main problem. By using energy detection technique we analyse the threshold value based on false alarm and misdetection error to improve the detection and to control the spectrum sensing problem. Analysis was performed under various fading channel using the parameters like SNR, number of samples, time taken and various fading channel which are applied to the energy detection spectrum sensing to calculate the performance. This thesis contents hypothesis which is analysed based on the noise threshold. And the threshold expression which will minimize the error probability. The proposed method was investigated on different fading channels like AWGN, Rayleigh and Nakagami channels.

The functions of a cognitive radio network can be categorized into spectrum sensing, spectrum analysis, and spectrum decision. Spectrum sensing involves measuring, learning, examining, and understanding the necessary parameters related to the frequency band. Its purpose is to provide information regarding spectrum availability, noise levels, transmission power, and interference levels in the radio frequency environment. Spectrum analysis focuses on dynamically selecting an appropriate communication channel that meets the quality of service requirements for various applications. Lastly, spectrum decision integrates the users' needs by accessing the available spectrum.

In a cognitive radio network, spectrum sensing is the initial and crucial step. With the rapid advancement of wireless communication, there is a growing demand for higher data rates. Spectrum sensing is a method used to determine the presence or absence of primary users in a channel. The choice of sensing technique significantly impacts cognitive radio users (CRUs). Without adequate sensing and sampling, there may be instances where weaker signals are undetected, while stronger signals are recognized [15-17].

Spectrum sensing can be categorized into cooperative and non-cooperative types. In cooperative spectrum sensing, cognitive radio devices collaborate to perform spectrum sensing, and decisions are made by a control unit. In contrast, non-cooperative spectrum sensing operates independently, making decisions based on signal detection and preloaded information.

Various techniques exist for spectrum sensing that identify spectrum holes, including matched filter techniques, cyclostationary techniques, energy detection techniques, wavelet detection techniques, and compressed sensing techniques. Among these, the Energy Detection Spectrum Sensing (EDSS) technique is the most widely used. In this approach, the detector compares the measured energy against a threshold value to determine whether the channel is available for secondary users. The threshold can be selected using the following methods:

1. Constant False Alarm Rate (CFAR)
2. Minimized Error Probability (MEP)
3. Constant Detection Rate (CDR) .

1.2.1 CFAR Approach

The Constant False Alarm Rate (CFAR) approach analyzes the threshold based on a predefined false alarm probability (Pf). This method evaluates the threshold value to enhance detection probability. Additionally, it assesses the status of the required spectrum when the distribution is unknown. However, the performance of this method significantly degrades in the presence of interference and noise [1]. Nonetheless, under noisy conditions, the throughput of the spectrum can be improved by fixing the sensing time.

1.2.2 MEP Approach

The Minimized Error Probability (MEP) approach involves obtaining the required threshold by reducing the error probability (Pm). To minimize the overall sensing error, the MEP method has been implemented in various research papers. The optimal threshold value is achieved by decreasing the probability of error [2].

1.2.3 CDR Approach

The Constant Detection Rate (CDR) approach determines the threshold based on a predefined detection probability (Pd) [1]. The CDR method safeguards licensed users from interference by secondary users. However, when compared to the CFAR method, the throughput of the CDR method tends to be lower. By combining the CFAR and CDR methods, it is possible to select a threshold that protects licensed users while maximizing throughput for secondary users [3].

2. Related Work

In cooperative spectrum sensing, enhancing antenna diversity in cognitive radio networks contributes to more effective spectrum sensing among secondary users, especially when the sensing channels are affected by fading. Numerous researchers have proposed various methods in cooperative spectrum sensing to optimize key parameters such as threshold selection, error probability, detection accuracy, and power efficiency.

Verma and Sahu (2016) explored a threshold selection strategy using Constant False Alarm Rate (CFAR) and Constant Detection Rate (CDR) in AWGN channels under a non-cooperative setting in their paper, “Opportunistic Selection of Threshold in Cognitive Radio Networks” (Wireless Personal Communication). While the study focused on threshold selection under AWGN conditions, it did not address the total spectrum sensing error probability in fading environments or the influence of threshold selection in such cases.

Charan and Pandey (2018) proposed a covariance-based sensing method in their work, “Selection of Threshold in Covariance Based Spectrum Sensing for Cognitive Radio Networks*”*. This approach involves optimizing the threshold to minimize spectrum sensing error probability in a non-cooperative scenario.

Umebayashi et al. (2017)**,** in their study “Threshold-setting for Spectrum Sensing Based on Statistical Information,” enhanced sensing performance by utilizing prior information on primary user (PU) spectrum utilization. Their method relied on previous state information to determine optimal threshold settings, assuming known past conditions of the spectrum.

Verma and Sahu (2016) also presented an intelligent CFAR-based threshold selection method in another study. They predetermined the target false alarm probability (Pf) and adjusted the threshold to maximize detection probability (Pd). In the CDR approach, they fixed the detection probability (Pd) and calculated the threshold to reduce false alarms.

Koley et al. (2015) examined a gradient-based spectrum sensing approach in low SNR conditions in "Gradient Based Real-Time Spectrum Sensing at Low SNR." Their application of the constant detection rate provided robust protection for licensed spectrum users, although at the cost of reduced throughput compared to CFAR.

Sharifi and Niya (2018) introduced a multi-level hypothesis testing approach in "Cooperative Spectrum Sensing in the Presence of Primary User Emulation Attack in Cognitive Radio Network". This method enhanced spectrum sensing for secondary users, although it required higher energy consumption as the number of cooperative users increased.

Kenan Kockaya and Ibrahim Develi (2020**)** used a combination of matched filter and energy detection techniques under various noise channels in "Spectrum Sensing in Cognitive Radio Networks: Threshold Optimization and Analysis." They observed improved spectrum sensing performance with optimized threshold selection, although there was room to enhance detection time. Kumar et al. (2019) evaluated false alarm and detection probabilities using energy detection in their study, "Analysis of Optimal Threshold Selection for Spectrum Sensing in a Cognitive Radio Network: An Energy Detection Approach" (Wireless Networks). They proposed an optimal threshold to boost throughput compared to traditional detection probability methods, but channel noise was not considered in the analysis.

In a subsequent study, Kumar et al. (2021**)**, *"*Threshold Selection Analysis of Spectrum Sensing for Cognitive Radio Network with Censoring-Based Imperfect Reporting Channels,*"* investigated threshold optimization under both perfect and imperfect reporting conditions across different channels, examining censoring and non-censoring techniques. They highlighted the need for further improvement in error probability and throughput in these scenarios.

Toma and López-Benítez (2021) presented a novel method in "Cooperative Spectrum Sensing: A New Approach for Minimum Interference and Maximum Utilization." This strategy employed collision and missed opportunity ratios to enhance spectrum utilization while minimizing interference using spectrum sensing parameters.

Finally**,** Yu, Wang, and Du (2021**)** introduced a cooperation-based energy detection method in their work, "Cooperative Spectrum Sensing Algorithm to Overcome Noise Fluctuation Based on Energy Detection in Sensing System." This approach aimed to mitigate noise uncertainty in conventional energy detection systems and improve spectrum sensing capacity. However, detection performance decreased at low SNR levels, and sensitivity was impacted by increased power fluctuations due to noise.

3. System Design

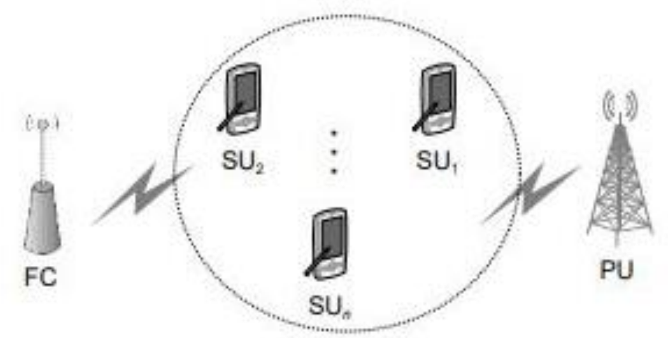

Figure 1: Proposed System model

In the proposed system model, we have use single licensed user or the primary user (PU), n secondary users (SU) or cognitive user (CU), single transmitter and receiver and a fusion centre (FC) which is shown in Figure 1. Here, every SU employees energy detection spectrum sensing techniques and transfer the sensed spectrum to the FC. The sensing results may be affected due to fading channel such as Rayleigh or Nakagami-m or AWGN.

Let us consider PU activity as idle denoted by P(H0) or as busy denoted by P(H1). The licensed user or the primary user continuously moves between inactive and active states simultaneously, and the SU performs the spectrum sensing of primary spectrum and takes the advantage to transmit the data periodically. The throughput for the proposed PU activity comes under two cases -
Case-1: Absence of PU and false-alarm by the CU.
Case-2: Presence of PU but not detected by the CU.

However, considering periodical spectrum sensing scheme in which the particular time frame comprises of detecting and transmitting and redo after T units of time as describe in Figure 3.

Let us considered P frames, in which each frame comprises of sensing and reporting (Ts) and data transmission (T - Ts). Considering the signal transmitted and noise of primary user is free and same as random variables. The received signal X(n) at CU is represented in eqn (1).

$$X(n) = \begin{cases} W(n) & : H0 \\ h.S(n) + W(n) & : H1 \end{cases} \quad (1)$$

Where W(n) - Additive noise, S(n) – signal transmitted, and h- gain coefficient. The energy (E) is measure with a threshold (λ) value to make decision about the primary user (PU) is occupied or not. If E >λ, then H1 hypothesis exist i.e. PU is present and if E < λ, H0 hypothesis exist i.e. PU is absent.

The test statistics T(x) for EDSS is given in eqn (2):

$$T(x) = \frac{1}{N} \sum_{N=0}^{N-1} |X(n)|^2 \quad (2)$$

Where N-total number of samples and for a sufficient high number of samples N > (256).

The probability of false-alarm (Pf) and probability of detection (Pd) is given below [2]:

$$P_f = \frac{1}{2} Erfc\left(\frac{ƛ - N\sigma_n^2}{\sqrt{2N\sigma_n^4}}\right) \quad (3)$$

$$P_d = \frac{1}{2} Erfc\left(\frac{ƛ - N\sigma_n^2(1+\gamma_p}{\sqrt{2N\sigma_n^4(1+\gamma_p)^2}}\right) \quad (4)$$

$$P_m = 1 - P_d \quad (5)$$

$$P_e = P_f + P_m \quad (6)$$

where ƛ- threshold value, N- number of samples, ϒ-SNR and Erfc (.) -error function.

3.1 Calculation of detection probability for various fading channels

The spectrum sensing of cognitive radio network is analyse by using false alarm and detection probability. Computation of average detection probability ($\overleftarrow{Pd}$) for different fading channel is given in eqn (7):

$$\overline{P_d} = \int_0^\infty P_d\, f(\gamma) d_\gamma \quad (7)$$

where f(ɣ) is the SNR distribution function over fading channel. And the average probability of misdetection (Pm) over various channel is determine by taking the average of the probability of misdetection. The average misdetection $(\overleftarrow{P_m})$ of AWGN and Nakagami is depicted in eqn (8) and (9):

$$\overleftarrow{P_m^{AWGN}} = \frac{1}{2}\left[Erfc\left(\frac{N\sigma_n^2 - ƛ}{\sqrt{2N\sigma_n^2}}\right) - \left(e^{\left(\frac{\frac{1}{\gamma^2} + \frac{4}{\gamma}\left(\frac{N\sigma_n^2 - ƛ}{\sqrt{2N\sigma_n^2}}\right)\sqrt{\frac{N}{2}}}{2N}\right)} Erfc\left(\frac{N\sigma_n^2 - ƛ}{\sqrt{2N\sigma_n^2}} + \frac{1}{\gamma\sqrt{2N}}\right)\right)\right]$$

(8)

$$\overleftarrow{P_m^{Naka}} = \frac{\left(\frac{m}{\gamma}\right)^m}{2\Gamma(m)} \int_0^\infty (x^{m-1})\left(e^{-\frac{mx}{\gamma}}\right) Erfc\left(\sqrt{\frac{N}{2}}x + \frac{N\sigma_n^2 - ƛ}{\sqrt{2N\sigma_n^2}}\right) dx$$

(9)

where Γ (.)- Gamma function, m- parameter shape and ϒ-SNR average. The false-alarm probability does not depend on the value of the SNR as the false-alarm probability is calculated under the hypothesis H0. Where the value of false alarm remains same for all the channels whether it might be fading or non-fading.

3.2. Threshold Selection Model

A threshold is selected, to check the presence or absence of primary user. The sensing process of detection of the target signal is measured according to the performance of Pd over different fading channels. In energy detector technique balance between Pf and Pm should be considered to determine the threshold. And Pf should be minimized, while Pd should be maximized, which is the constant false alarm rate (CFAR) approach. In this, the value of Pm or Pf can be reduced to a minimum by fixing maximum Pd. In general, threshold value is normally chosen to meet a certain value of Pf, in this kind of situation the values which has to be known is the noise power. Determining of Pd and Pf, ƛ for a certain Pf value is derived in eqn (10):

$$ƛ = Q^{-1}(\text{Pf})\sqrt{2N} + (\text{N})\sigma n \quad (10)$$

Where Q^{-1} (.) is the inverse of the distribution function.
Where Q-function Q(x) can be expressed in eqn (11):

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty exp\left(-\frac{y^2}{2}\right) dy \quad (11)$$

When the threshold is calculated at low SNR, the performance of detection is greatly reduced. To improve performance at low SNR, we can refer to Equation (6), which states that the total error probability is the sum of Pf and Pm The threshold can be determined by applying the error probability Pe, which depends on Pf and Pm, and must satisfy the following conditions [10]

$$\frac{\partial P_f}{\partial ƛ} + \frac{\partial P_m}{\partial ƛ} = 0 \quad (12)$$

$$\frac{\partial^2 P_m}{\partial ƛ^2} < 0 \quad (13)$$

From eqn (3) and eqn (5) by differentiating Pf and Pm, it is define as follows:

$$\frac{\partial P_f}{\partial ƛ} = -\frac{1}{\sqrt{2\pi}\sigma_0} e^{-\left(\frac{(ƛ - \mu_0)^2}{\sqrt{2}\sigma_0}\right)} \quad (14)$$

(14)

$$\frac{\partial P_m}{\partial ƛ} = -\frac{1}{\sqrt{2\pi}\sigma_1} e^{-\left(\frac{(ƛ - \mu_1)^2}{\sqrt{2}\sigma_1}\right)} \quad (15)$$

(15)

where:

$\mu_0 = N\sigma_n$
$\mu_1 = N\sigma_n^2(\gamma + 1)^2$
$\sigma_0^2 = 2N\sigma_n^4$
$\sigma_1^2 = 2N\sigma_n^4(\gamma + 1)^2$

Using eqn (12), (13), (14) and (15) the threshold can be redefined as follows:

$$ƛ = \frac{-b + \sqrt{b^2 - ac}}{a}$$

where:
a=$\sigma_1^2 - \sigma_0^2$
b=$\sigma_0^2\mu_1 - \sigma_1^2\mu_0$
c=$\sigma_1^2\mu_0 - \sigma_0^2\mu_1 - \frac{2\sigma_1^2\sigma_0^2}{ln\frac{\sigma_1}{\sigma_0}}$

3.4 Optimal Threshold Condition

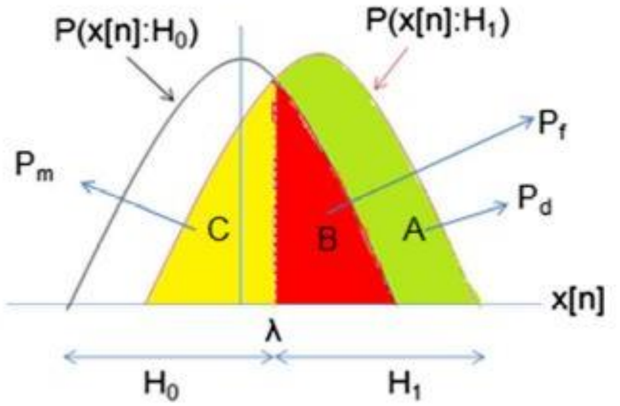

Figure 2: Threshold selection in hypothesis model

In cognitive radio network, the detection performance relies in the selection of accurate threshold. Noise and primary user signals are aimed to fully distinguished when spectrum sensing is developed. And the actual performance can be analysed by using generated estimated values. Here, new threshold definition is presented to improve the spectrum sensing performance to detect the primary user. The hypothesis testing H0 and H1 that depends on the threshold selection is define for the spectrum sensing. Which is shown in Fig. 2. Expected distribution of two groups H0 and H1 is shown here. Here, it is clear that if we increase the Pf we reduce the Pm and vice versa, which varies H0 and H1 causing the Pe to change. The balance between the probability of false alarm and probability of miss detection is very critical. To support this balance between the two probabilities, optimal thresholds (ג) are determined. Then, with the help of the equation the most appropriate threshold is selected.

4. Results and Discussion

In Cooperative Spectrum Sensing in the proposed system model in which the FC employed the majority cooperative rule and implies the Energy Detection Technique. The results for detection and miss detection probability have been simulated at different values of SNR. And also the graphs of calculated and theoretical threshold value have been simulated. Table 1 shows the parameters used for the simulation to obtain the output.

Table 1: List of parameters

Parameter	Value	Parameter	Value
SNR	<10dB	T	100 sec
Tsr	0.25sec	Fading channel	AWGN, Nakagami

Figure 3 (a) and (b) shows the miss detection vs false alarm probability under different fading channel i.e. AWGN and Nakagami channel. It is observe that miss detection decreases as the value of false alarm is increased. And it tends to remains constant for the lower value of SNR.

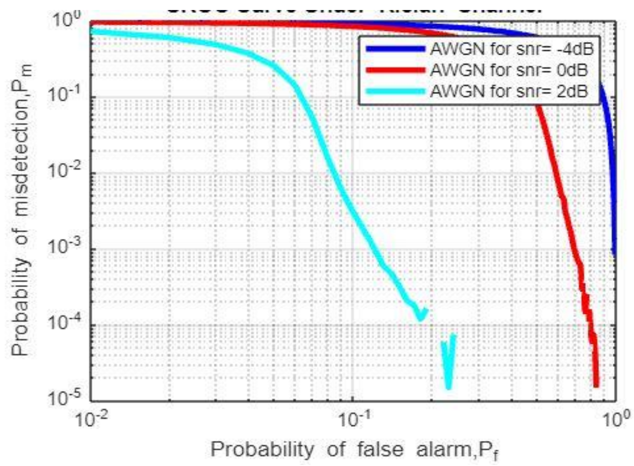

Figure 3(a): Curve under AWGN fading channel

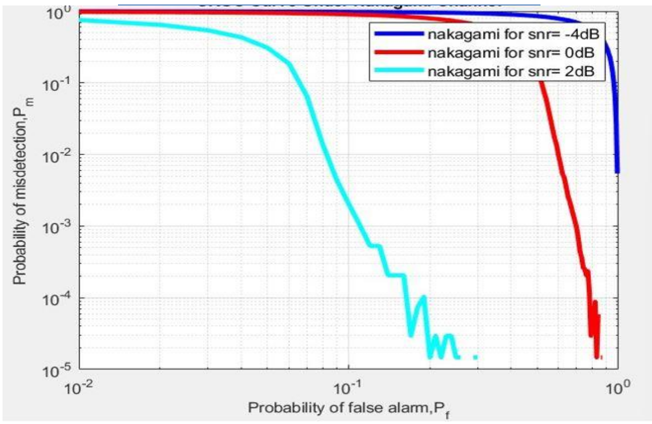

Figure 3(b): Curve under Nakagami channel

Figure 4 (a) and (b) shows the detection vs false alarm probability at different fading channel is shown. Here it is observe that detection increase with the false alarm probability. Figure 4also shows how probability of misdetection varies for the higher values of SNR. From figure 3 and figure 4 we can observe probability of miss detection is exactly the reciprocal of probability of detection. We can also analyse that pf ≥ pm as mention in above optimal threshold condition. Hence it may also note that at low SNR total spectrum sensing error probability have better performance but for higher SNR probability of false alarm provides better spectrum sensing.

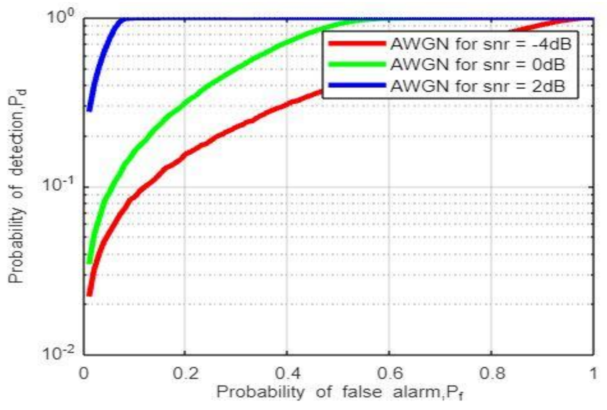

Figure 4(a): Curve under AWGN fading channel

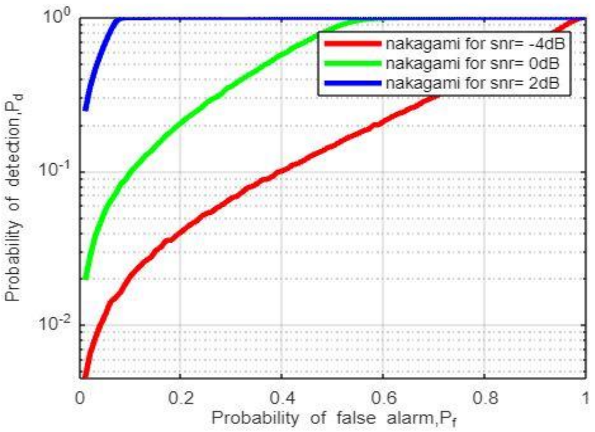

Figure 4(b): Curve under Nakagami channel

Figure 5 shows the theoretical and the calculated value of threshold vs probability of false alarm. Here, the false alarm probability is maximum when value of threshold is small. So to get the optimize value of probability of detection the value of threshold should be set as small as possible.

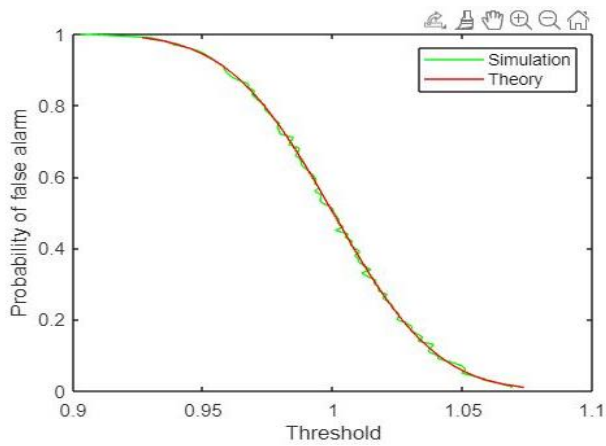

Figure 5: Theoretical and the calculated value of probability of false alarm vs threshold

Figure 6 shows the theoretical and the calculated value of probability of detection vs SNR for fixed Pf. It can be observe that probability of detection is maximum when value of SNR increases which can also be seen in figure 3(a) and (b).

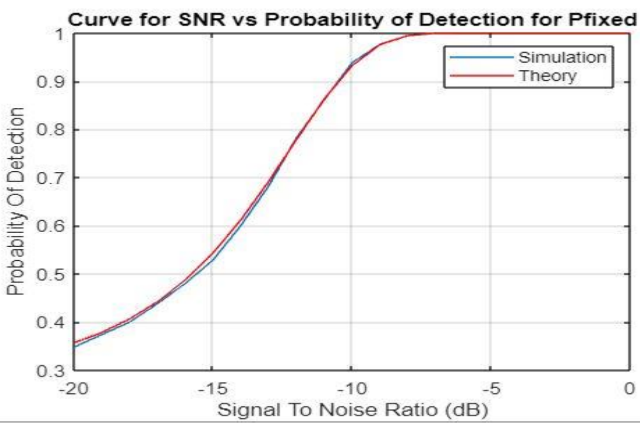

Figure 6: Theoretical and the calculated value of probability of detection vs SNR for fixed Pf

5. Conclusion and Future Work

This paper explores the determination of thresholds using false alarm and miss detection probabilities across various fading channels, simulated in MATLAB. By employing energy detector techniques for spectrum sensing, the optimal conditions for variable SNR values and appropriate threshold values can be examined through the simultaneous analysis of Pf and Pm. The suggested approach meets the EDSS optimality requirements for low SNR environments since it exhibits higher Pm and lower Pf at low SNR. Additionally, this approach allows for threshold verification at high SNR values, with the potential for future work to focus on primary user detection. Furthermore, diverse sensing approaches can be implemented in contemporary wireless technologies. To improve spectrum sensing outcomes in cognitive radio networks, there is a lot of room for research on diverse parameters using a range of methodologies.

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Author's contribution: Champa Tanga Conceptualization, investigation, writing- original draft. Tage Kunya: visualization and methodology, review, validation.

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