Comparative Study on Spectrum Sensing and Modulation Techniques in Cognitive Radio Network

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***Abstract*—This paper conducts a comparative analysis of two prominent spectrum sensing methods, energy detection (ED) and matched filter detection (MFD), under different modulation schemes, specifically binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and 64-quadrature amplitude modulation (QAM), in an Additive White Gaussian Noise (AWGN) channel. The study evaluates the performance of ED and MFD in terms of probability of detection, false alarm, and sensitivity to signal-to-noise ratio (SNR). Simulation results indicate that 64-QAM is the preferred modulation scheme for achieving superior spectral efficiency. The analysis leverages receiver operating characteristic (ROC) curves to highlight the trade-offs between the probability of detection and probability of false alarm. These findings provide critical insights into the selection of appropriate spectrum sensing techniques, enhancing overall spectrum utilization in cognitive radio network.**

***Index Terms*—Cognitive Radio Network, Spectrum Sensing, Energy Detection, Matched Filter Detection, QPSK, BPSK, 64-QAM.**

I. Introduction

Effective communication technologies have been a vital part of our lives for decades, and their expansion in today's world has been remarkable [1]. Communication influences everyone's lives in some way. The emergence of computing and services everywhere has altered the mode of operation globally and continues to strain an already overburdened radio spectrum. The fixed allocation of radio spectrum resources results in inefficient use of the most valuable radio spectrum bands.

Numerous recent studies have indicated that spectrum utilization is very unbalanced on a global scale. The global system for mobile communications, cellular, and unlicensed Industrial, Scientific, and Medical (ISM) bands are extremely congested while most spectrum bands are underutilized or poorly utilized, such as in TV broadcasting systems [2]. Moreover, ISM bands are becoming increasingly popular and overcrowded due to the development of Wi-Fi, Bluetooth, and wireless phones during the past few decades. Cognitive radio (CR) is useful for addressing these difficulties [3].

CRs can be programmed and adjusted to use the best available wireless channels. It detects available channels in the spectrum and adjusts its transmission or reception parameters (such as frequency, power control, and modulation) accordingly. CR enables dynamic spectrum access (DSA), in which an unlicensed user (also known as secondary user (SU)) is granted temporary access to the spectrum when it is not being used by a licensed user (also known as primary user (PU)) [4].

Spectrum sensing is detecting and identifying radio frequency signals inside a specific frequency band or channel [5]. Cognitive radio networks (CRNs), which rely on the capacity to dynamically access available radio spectrum, require this component. It seeks to detect whether and to what extent a given frequency band or channel is currently used by other users. This information is crucial for preventing interference and optimizing spectrum utilization. Sensing can be carried out in various ways, depending on the discovered signals and the available sensing resources. Spectrum sensing is a crucial function in modern wireless communication networks, allowing for the efficient and dependable sharing of spectrum across various users [6]. The typical strategies are energy detection (ED) [7], matched filter detection (MFD) [8], cyclostationary detection, and cooperative spectrum sensing (CSS) [9].

In order to understand spectrum sensing better, we need to look at a few performance indicators that tell us about this concept in depth. Each sensing technique's performance is quantified in terms of probability of detection (P_d) and probability of false alarm (P_{fa}) [10]. The probability of detection refers to identifying the presence of PU when PU is present, whereas the probability of false alarm refers to detecting the presence of PU when PU is not present. A higher chance of detection provides better protection of PUs, whereas a lower probability of false alarms indicates more efficient spectrum utilization. Another important performance indicator in spectrum sensing is the probability of error (P_e), which is the sum of the false alarm probability and the probability of miss-detection ($1 - P_d$). A lesser probability of error value indicates better model performance.

Our end goal in spectrum sensing is to rightly detect whether a PU is present or not in the channel so that we can send the SU to transmit data. These PU's and SU's have a signal, which is what we use in our model calculations for the detections. These signals also include a noise parameter in order to be realistic hence, we have used Additive White Gaussian Noise (AWGN) channel along with the main signal [11]. To effectively evaluate the performance of detection techniques in the presence of noise, it is crucial to consider the influence of modulation schemes, which play a pivotal role

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in shaping the performance of communication systems [12]. The quality of service within a system is largely influenced by the appropriate selection of modulation techniques. Among the various modulation schemes, this study focuses on three commonly used methods in practical applications, which are discussed as follows:

- Binary phase shift keying (BPSK): It is one of the simplest forms of digital modulation, encoding data by shifting the phase of a carrier signal between two distinct values: one for binary '0' and another for binary '1'. This scheme is widely recognized for its robustness in noisy environments [13].
- Quadrature phase shift keying (QPSK): It enhances the data transmission rate of BPSK by utilizing four distinct phase shifts to encode two bits per symbol, effectively doubling the data rate while maintaining a balance between bandwidth efficiency and resilience to noise [14].
- Quadrature amplitude modulation (QAM): It combines both amplitude and phase modulation to significantly increase data transmission rates by encoding multiple bits per symbol. This makes QAM especially suitable for applications requiring high data delivery, such as digital telecommunication systems and cable modems [15].

The novelty of this research lies in its comprehensive evaluation of widely used spectrum sensing techniques across multiple modulation schemes. The study provides a deeper understanding of how different modulation types impact the performance of ED and MFD. The following key contributions underscore the distinctiveness of this work:

- *Comparison of Sensing Techniques*: The study conducts a detailed comparison of ED and MFD across different modulation schemes, including BPSK, QPSK, and QAM, to evaluate their performance under various conditions.
- *Performance Metrics*: Receiver operating characteristic (ROC) curves are used to analyze the trade-offs between detection probability and false alarm probability for each modulation scheme.
- *SNR Sensitivity*: The research offers insights into how varying SNR levels affect the performance of ED and MFD.

The structure of the paper is organized as follows: Section II provides the related work, and Section III outlines the models employed in the study. Section IV presents the numerical results, followed by the conclusion in Section V. Table I lists the abbreviations used throughout the paper.

TABLE I
LIST OF ABBREVIATIONS.

Abbreviation	Description
ISM	Industrial, Scientific, and Medical
CR	Cognitive radio
CRN	Cognitive radio network
DSA	Dynamic spectrum access
PU	Primary user
SU	Secondary user
SNR	Signal to noise ratio
AWGN	Additive white Gaussian noise
BPSK	Binary phase shift keying
QPSK	Quadrature phase shift keying
QAM	Quadrature amplitude modulation
ED	Energy detection
MFD	Matched filter detection
CSS	Cooperative spectrum sensing
ROC	Receiver operating characteristic curve

II. Related Work

This literature review provides an in-depth analysis of the key works in the field, highlighting the evolution of ED and MFD sensing approaches and their contributions to the advancement of CR technology. The ED method is frequently used due to its simplicity, minimal complexity, and ability to detect PU without any prior knowledge [16]. Contrary to this, MFD is one of the most effective techniques that relies on prior knowledge of the PU's signal. This sensing approach is considered optimal in scenarios where specific information about the PU's signal is already available at the SU's receiver [17]. In recent times, several varied ED techniques have been suggested to enhance the sensing capabilities while introducing a moderate rise in computing complexity.

The most common approach is the classical ED method, where the work done by [18] is one of the pioneering works in the application of ED for spectrum sensing in CRNs. This method employs a non-coherent technique in which the energy of the received signal is compared to a predetermined threshold. This method is suitable for real-time implementation due to its simplicity, but its efficacy is sensitive to noise and fading conditions. To address these limitations, a threshold adaptation scheme based on the observed noise power is proposed in [19]. This adaptive method enhances the robustness of ED in environments that are dynamic and chaotic.

Cooperative sensing entails the collaborative decision-making of multiple CR devices in order to improve detection reliability. The concept of CSS is introduced in [20]. The research investigates fusion strategies, including AND, OR, and majority voting, to combine individual sensory decisions. Cooperative sensing not only enhances detection performance but also strengthens the resilience of CRN in the presence of fading and shadowing effects.

The double threshold approach modifies conventional ED by incorporating two distinct decision-making thresholds. Research conducted by [21] is a notable contribution to this field. In their paper, they proposed a double-threshold ED method in which the thresholds are dynamically adjusted based on the present noise level. This adaptive double threshold scheme increases the resiliency of ED in CRN by minimizing the effect of variable noise conditions.

Significant progress has been made in the investigation of ED approaches for spectrum sensing in CRNs. The integration of double threshold and CSS will undoubtedly contribute to the evolution of spectrum sensing in CRNs as the field advances.

III. Model

In our work, model used by [22] have been considered using different modulation techniques for ED methods. Once we receive the modulated signal for input, we need to find its energy, which we compare with the threshold. This input signal after modulation is passed through an A/D converter then a squaring device followed by an integrator. We basically have to multiply the root value of SNR with the modulated BPSK/QPSK/QAM signal and then add AWGN to the signal. Once we receive this signal, we must find the absolute value of this signal and square it. A visual depiction of the ED process is presented in fig. 1.

In case of single threshold based ED, two hypothesis H_0 and H_1 are considered, in which H_0 shows the absence of PU and H_1 shows the presence of PU. After that final test statistic X is calculated by using the sum of absolute values of squared signals and compared with the threshold energy level whose value λ. The formula for calculating P_d and P_{fa} can be found in [22].

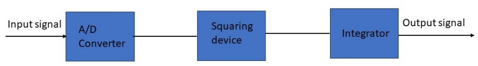


Fig. 1. ED process.

CSS method involves the contribution of various CRs and arrives at a final decision based on all their values. The final combination can be based on various logical rules such as the OR rule, AND rule or even MAJORITY rule but this paper specifically uses the OR rule. The probability of detection under the CSS scheme (Q_d) and the probability of false alarm under the CSS scheme (Q_{fa}) using the OR rule are given by

$$Q_d = 1 - \prod_{i=1}^{M} (1 - P_{di})$$
$$Q_{fa} = 1 - \prod_{i=1}^{M} (1 - P_{fai})$$

where M is the total number of CRs used for giving input signals, and P_{di}, P_{fai} are the contributions of detection probability and false alarm probability from the i^{th} SU of a particular CR.

A. Double threshold model

In double threshold model, two new threshold levels λ_1 and λ_2 are introduced, where $\lambda_1 < \lambda < \lambda_2$ such that a PU will be detected if the energy level of the signal is greater than λ_2 and PU will be absent if the signal energy level is lesser than λ_1. The formula for these new threshold levels is given by

$$\lambda_1 = (1 - \rho)\lambda$$
$$\lambda_2 = (1 + \rho)\lambda$$

where ρ is an uncertainty parameter and we have selected $\rho = 0.1$ for our simulations.

There is an obvious possibility of obtaining an energy level between $\lambda_1$and λ_2 (called confused region cases) in which case instead of making a decision we directly note its energy value and find the mean of all such cases and compare it with our original threshold value λ. If this mean value is greater than λ then the overall decision for these confused region cases is that PU is present and if it is lesser than λ then it indicates the absence of PU [22].

TABLE II
SIMULATION PARAMETERS.

Parameter	Value
Number of iteration	1000
Number of samples (N)	200 to 1000
SNR range	-15dB to -5dB
QAM bits (m)	64
Bit duration (T)	1 second
Uncertainty parameter (ρ)	0.1
Probability of false alarm (P_{fa}, when constant)	0.1
Number of CRs for CSS (M)	5
In-phase amplitude (Amf)	0.53945
Quadrature amplitude (AmQ)	0.53945

B. Matched filter detection

MFD method used in [23] is considered under different modulation techniques. It is one of the best filters that need knowledge about PU signals from the past. This sensing method is the best choice when the SU's sensor already knows something about the PU signal.

In this method, the final test statistic X_{MFD} used for comparing with threshold will be the sum of the absolute value of these squared signals is

$$X_{MFD} = \sum_{n=1}^{N} y(n)\ x_p^*(n)$$

where N is the total number of samples and x_p is the main user signal. We can calculate the threshold value using the formula.

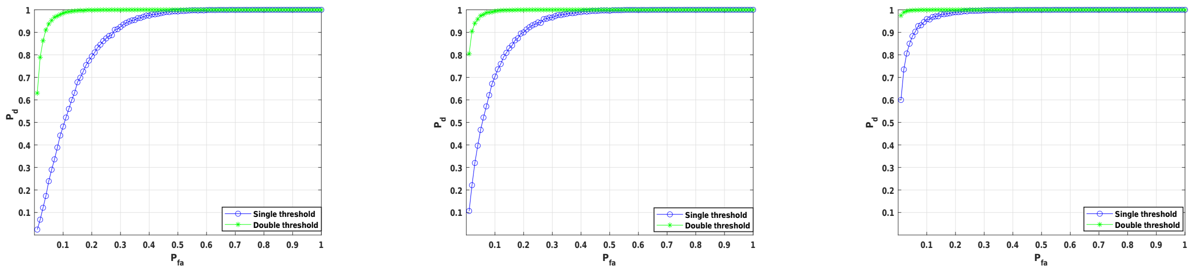
$$\lambda = Q^{-1}(P_{fa}) \times \sqrt{E\delta_w^2}$$

Here λ is the threshold energy level and δ_w^2 is the noise variance, and E denotes the signal energy of PU. In the case of a single threshold level, the formula for calculating P_d and P_{fa} can be found in [23].

We can also use the double threshold method on MFD scheme as we have all the parameters needed to find the upper and lower threshold levels and we have the test statistic as well. Moreover, we can apply CSS to this method using OR rule to get the aggregate results from multiple CRs.

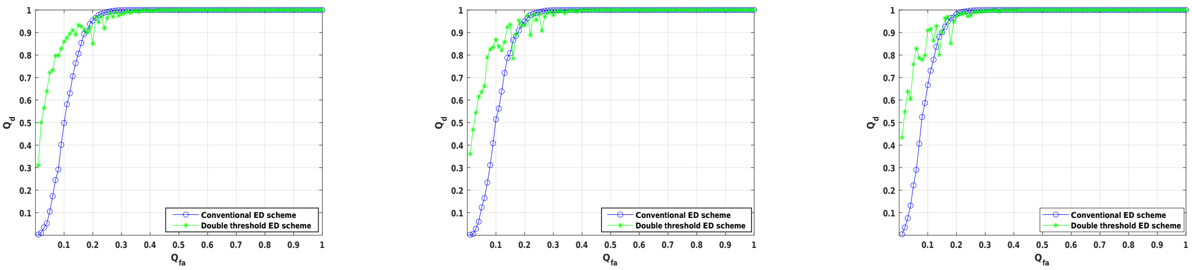
IV. RESULTS

This section provides the results of simulations that were performed using BPSK, QPSK, and QAM modulation techniques following the above algorithm for different scenarios. In this paper, the terms 64-QAM and QAM are used interchangeably to refer to 64-QAM modulation techniques. We will look at the performance comparison of these techniques amongst each other as well as for different spectrum sensing methods. The graphs are plotted between P_d and P_{fa}, which is also called the ROC curve. Table II provides a comprehensive



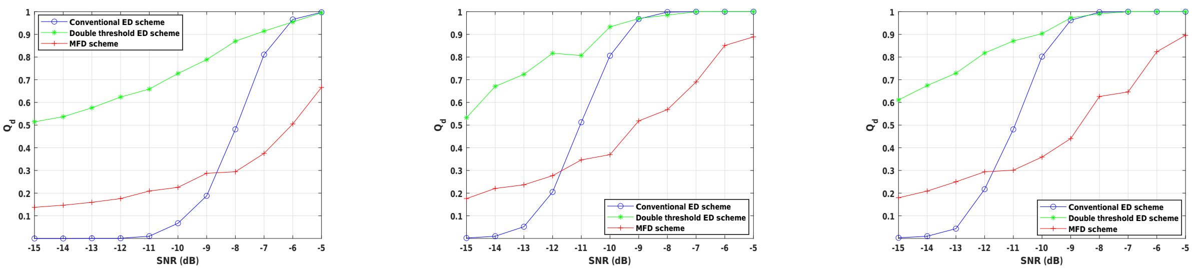
(a) (b) (c)

Fig. 2. ROC characteristics comparison for single and double threshold in BPSK (a), QPSK (b), and QAM (c) respectively.



(a) (b) (c)

Fig. 3. ROC characteristics comparison for single and double threshold using CSS in BPSK (a), QPSK (b), and QAM (c) respectively.



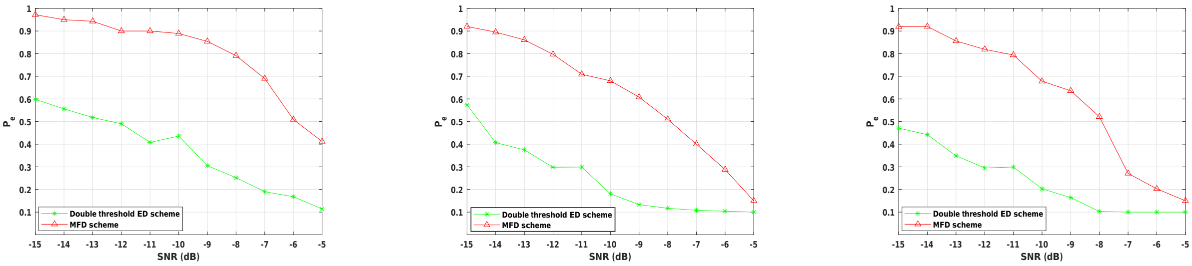
(a) (b) (c)

Fig. 4. Probability of detection comparison with SNR in BPSK (a), QPSK (b), and QAM (c) respectively.

overview of the simulation parameters utilized for generating the results.

1) ROC characteristics comparison for single and double threshold: In fig. 2, the ROC curves are plotted by incorporating double threshold method with an uncertainty parameter of 0.1 and results are compared with single threshold. Graphs are plotted for $N = 200$ samples and at -5 dB SNR value. We have ignored the confusion region for this particular plot. One clear observation from these graphs is that the detection probability is higher at the same false alarm probability level for the double threshold method than the single threshold method, implying that the double threshold method is very effective. We can also see that in the case of the double threshold method for 64-QAM, the detection probability is almost close to 1 throughout indicating that at the current level of SNR, this method has a very high accuracy.

2) ROC characteristics comparison for single and double threshold using CSS: The ROC graph was plotted using the CSS scheme for 100 samples at -8 dB SNR value, as shown in fig. 3. The total CRs considered for CSS is M = 5 CRs. This plot consists of curves that are of the conventional ED scheme of a single threshold and the double threshold ED in CSS. We can clearly see from the graph that the double threshold scheme outperforms the conventional scheme for most part of the probability of false alarm. At Q_{fa} of 0.1, for the 64-QAM model, the double threshold scheme has almost



(a) (b) (c)

Fig. 5. Probability of error comparison with SNR in BPSK (a), QPSK (b), and QAM (c) respectively.

an improvement of approximately 36% over the conventional scheme for the detection probability. We can also observe that 64-QAM has better results than BPSK and QPSK for the same values of false alarm probabilities thus implying this method is more accurate.

3) Detection probability comparison with SNR: This simulation was performed to analyze the relationship between the SNR value and probability of detection using CSS for conventional ED scheme, double threshold ED and MFD as seen in fig. 4. We fixed the probability of false alarm P_{fa} = 0.1. The SNR range is taken from -15dB to -5dB and the total number of samples $N = 200$. We have considered total CRs M = 5. We can clearly see that for low SNR values, the double threshold scheme has a much higher probability of detection than the conventional scheme and MFD. Moreover, we can observe that the 64-QAM plot has a higher detection probability at the same SNR value than the QPSK plots, which have a higher detection probability than the BPSK plot, indicating more accurate results for the QAM method. Subsequently, results show that in case of MFD, there is not much difference between the values of QAM and QPSK over the entire range of SNR values as opposed to the ED method where QAM clearly outperformed QPSK in every case.

4) Error probability comparison with SNR: We compared the probability of error and SNR values, keeping all the parameters the same as in the previous case. It is evident from fig. 5 that the probability of error is lesser for the double threshold ED scheme as compared to the MFD scheme. We can also observe that 64-QAM has a lesser probability of error as compared to the QPSK method which is lesser than the BPSK method at the same SNR values for example at -15dB, $P_e = 0.6$ for the proposed method using BPSK, 0.57 using QPSK and 0.48 for the proposed method using QAM and a similar trend is observed for all SNR values which suggest that 64-QAM is the better modulation technique amongst the three.

We can observe that the error values are much higher in case of MFD in comparison to ED under all modulation schemes, which clearly indicates that the latter should be preferred.

Fig. 6 shows the tabulated result comparison of P_e values between ED method and MFD method for different SNR values.

SNR Values	Energy Detection			Matched Filter Detection		
	BPSK	QPSK	QAM	BPSK	QPSK	QAM
-15	0.598	0.574	0.471	0.972	0.92	0.919
-14	0.556	0.407	0.442	0.95	0.895	0.92
-13	0.518	0.375	0.349	0.943	0.861	0.856
-12	0.49	0.298	0.295	0.91	0.797	0.819
-11	0.408	0.299	0.299	0.9	0.709	0.794
-10	0.436	0.181	0.203	0.889	0.68	0.678
-9	0.305	0.133	0.164	0.854	0.608	0.636
-8	0.252	0.117	0.103	0.791	0.51	0.521
-7	0.19	0.108	0.1	0.69	0.4	0.271
-6	0.168	0.104	0.1	0.509	0.288	0.203
-5	0.114	0.1001	0.1	0.412	0.15	0.15

Fig. 6. P_e values for different sensing methods at various SNR values.

V. Summary and Conclusions

This article has conducted a comparative study for spectrum sensing parameters using ED and MFD schemes where the input signal has been modulated using different techniques and passed through noise channel. The double threshold method using CSS is more effective than the single threshold method as it generally has a higher probability of detection for all the values of probabilities of false alarm, it has a higher detection probability at lower SNR values when compared to conventional methods and it also has a lower probability of error at low SNR values suggesting that it is the better method of the two studied.

64-QAM has proven to give better performance results than QPSK and followed by the BPSK model as it had higher detection probabilities for the same false alarm probabilities. It proved to have a higher detection probability than QPSK and BPSK at all SNR values and also had a lesser probability of error than QPSK and BPSK across all the SNR values which suggests that spectrum sensing using the 64-QAM method over QPSK and BPSK is the recommended method due to its better performance.

The order of P_d across various SNR values for different modulation techniques is QAM $>$ QPSK $>$ BPSK and similarly the order of P_e across various SNR values for different modulation techniques is QAM $<$ QPSK $<$ BPSK. These two points are sufficient evidence to conclude that QAM has the best performance overall amongst the techniques discussed in this study.

Due to its lower error probability and higher detection probabilities, the ED scheme produces better results than MFD scheme. These results are consistent across various modulation techniques and noise channel, so we can conclude that the ED spectrum sensing technique has superior performance overall.

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