Energy Detector with Adaptive Optimal Threshold for Enhancing Spectrum Sensing in Cognitive Radio Network

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Abstract: Cognitive radio (CR) is a promising solution to resolve the crisis of spectrum underutilization. Spectrum sensing is an indispensable aspect of CR network (CRN). Energy detection method is being recognized as a simple and reliable step for spectrum sensing. The significant factor of the energy detector (ED) is threshold, whose optimum value depends on signal to noise ratio (SNR). However, in a wireless environment, where the received signal is severely degraded due to the uncertain noise, reliable spectrum sensing is not guaranteed.

The key metrics of the CRN are total spectrum sensing error probability, throughput, and energy efficiency. For each SNR value, there exists an optimal threshold that minimizes total spectrum sensing error probability and maximizes throughput as well as energy efficiency. Therefore, the threshold of ED should be adaptive in CRN. This paper presents an optimal adaptive threshold by utilizing spectrum sensing errors for each metric in CRN.

Keywords: Cognitive radio, SNR, Optimal threshold, primary user, secondary user, spectrum sensing, throughput, energy efficiency.

I. Introduction

According to a Federal Communications Commission (FCC) survey, only 30% of assigned spectrum is utilized [1]. FCC recognized CR as the candidate to resolve the spectrum underutilization. The CRN includes the following essential functions [2]:

- Spectrum sensing: identify unused licensed spectrum
- Spectrum management: selecting the preeminent available spectrum band
- Spectrum sharing: coordinating the spectrum band with other users
- Spectrum mobility: quitting the spectrum band when a licensed user is detected and searching for other available user

CRN allows secondary users (SUs), who are using unlicensed spectrum, to utilize the licensed spectrum band assigned to the primary user (PU) when the spectrum band is provisionally not being used. Therefore, spectrum sensing is an imperative feature in CR network [3-5]. Spectrum sensing methods are divided in to synchronous detection and non-synchronous detection. The methods of synchronous detection are matched filter detection and cyclostationary feature detection [6].

Energy detection is a non-synchronous detection method. The more practical method for spectrum sensing is energy detection [7-11]. Authors in [7] presented an analysis of the ED method and the detection threshold is optimized to minimize the total error rate. The inappropriate choice of the threshold of the ED leads to a significant decline in the performance of CR. Authors in [8] explore this situation and presented optimal threshold values in ED. According to [12], the ED method is sensitive to noise uncertainty, and therefore this method requires an estimate of noise power, which is a challenging task [13].

The steps involved in ED are as follows:

Step 1: Filtering the received signal to select the preferred spectrum band

Step 2: Squaring the selected signal over the observation period

Step 3: Integrating the output of the squared signal

Step 4: Comparing the output of integrator with threshold of the ED to take decision on the status of PU

Threshold setting methods are based on either constant false alarm probability or constant missed detection probability. Increasing the threshold leads to an increase in the probability of missed detection, and decreasing the threshold leads to an increase in the probability of false alarm. Therefore, optimization of these two errors is contradictory goal. Further, since the data transmission time in CR is reduced due to sensing time, the throughput is reduced and energy consumption is increased. Total spectrum sensing error probability (sum of false alarm probability and missed detection probability), throughput, and energy efficiency (ratio of throughput and energy consumption) are three key metrics in a CRN. These key metrics are governed by false

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alarm and missed detection errors. In Industrial applications, where the effect of noise is severe, one should consider the total error as the key metric. One should consider throughput a key metric in decisive applications like health monitoring. In greenfield perspective, one should consider energy efficiency as the key metric. Therefore, the threshold of energy detection should be adaptive to the environment and application of the wireless communication.

Hence, designing a system with an adaptive threshold is a challenging issue in the communication environment. In this paper, we focus on presenting the optimal threshold values, which maximize the performance of each metric of CR under different SNR values.

The remainder of this paper is organized as follows. In section 2, spectrum sensing is reviewed. In section 3, minimization of the total spectrum sensing error probability is presented. In section 4, maximization of throughput and energy efficiency is presented. The results are presented in section 5, and finally conclusions are drawn in section 6.

Spectrum sensing Preliminaries

We consider a CR network with one PU and one SU with ED as illustrated in Figure 1. PU is utilizing a licensed spectrum band for transmitting data, and SU performs spectrum sensing to know the status of the PU. If the PU is absent (the channel is idle), the SU transmits the data in licensed spectrum band of the PU. If the PU is present (the channel is occupied), the sensing is being continued for every predetermined time slot until the SU finds an unutilized licensed band. The SU makes the final decision on the presence or absence of the PU using ED. In ED, the received signal, $y(t)$ is used to evaluate the energy $(\mathcal{E})$ of the signal. The energy is then compared to the threshold (λ^{ED}) to decide the status of the PU. Setting the proper threshold is a challenging task, as it has to differentiate between the signal and noise. If $\mathcal{E} < \lambda^{\mathrm{ED}}$, the channel is assumed to be idle, on the contrary, the PU is assumed to be occupied.

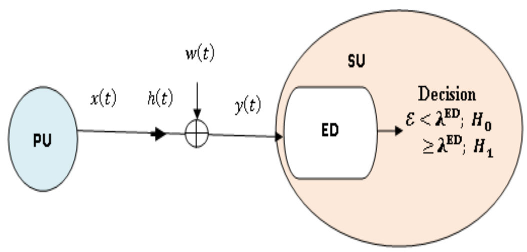

Fig. 1 Cognitive radio network

Analytically, signal detection can be formalized as a hypothesis test:

$$H_0 : y(t) = w(t) \text{ ; channel is idle} \quad (1)$$

$$H_1 : y(t) = h(t)x(t) + w(t) \text{ ; channel is occupied} \quad (2)$$

H_0 = hypothesis when channel is idle

H_1 = hypothesis when channel occupied by the PU

$x(t)$ = signal transmitting from the PU

$y(t)$ = signal received at the SU

$h(t)$ = complex channel gain of sensing channel between PU and SU

$w(t)$ = additive white Gaussian noise (AWGN)

In a binary hypothesis test, if H_1 is accepted when H_0 is true, it is called type I error. If H_0 is accepted when H_1 is true, it is called type II error. The probability of making a type I error, $P(H_1/H_0)$ is called the probability of false alarm $\left(P_f^{ED}(\lambda^{\mathrm{ED}})\right)$ and the probability of making a type II error, $P(H_0/H_1)$ is called the probability of missed detection$\left(P_m^{ED}(\lambda^{\mathrm{ED}},\gamma)\right)$. In AWGN channel, $P_f^{ED}(\lambda^{\mathrm{ED}})$ and $P_m^{ED}(\lambda^{\mathrm{ED}},\gamma)$ can be represented, respectively, as [14]

$$P_f^{ED}(\lambda^{\mathrm{ED}}) = \frac{\Gamma\left(u, \frac{\lambda^{\mathrm{ED}}}{2}\right)}{\Gamma(u)} \quad (3)$$

$$P_m^{ED}(\lambda^{\mathrm{ED}},\gamma) = 1 - P_d^{ED}(\lambda^{\mathrm{ED}},\gamma) = 1 - Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda^{\mathrm{ED}}}\right) \quad (4)$$

Where,

u = time-bandwidth product of the ED

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λ^{ED}= threshold of the ED

γ = SNR at SU

$P_d^{ED}(\lambda^{ED},\gamma)$ = probability of detection which is described as the probability that the detector states the presence of PU, when the PU is actually present

$\Gamma(\cdot,\cdot)$ = incomplete gamma function which is specified by

$$\Gamma(a,b) = \int_b^\infty t^{a-1}\, e^{-t} dt \quad (5)$$

$\Gamma(\cdot,0) = \Gamma(\cdot),$ = complete gamma function

$Q_u(\cdot,\cdot)$ = u th order generalized Marcum Q - function, which is specified by

$$Q_u(a,b) = \frac{1}{a^{u-1}} \int_b^\infty t^u\, e^{-\frac{(t^2+a^2)}{2}} I_{u-1}(at) dt \quad (6)$$

Where, $I_{u-1}(\cdot)$ is the $(u-1)th$ order modified Bessel function

Minimization of Total Spectrum Sensing Error Probability

Minimizing the false alarm errors to afford more spectrum access opportunities and minimize missed detection errors to afford more protection to PU are indispensable in spectrum sensing. In this section, we explore the minimization of the total spectrum sensing error probability. In Figures 2 and 3, $P_f^{ED}(\lambda^{ED})$ and $P_m^{ED}(\lambda^{ED},\gamma)$, respectively, versus λ^{ED}, are presented. From Eq. (3) and Figure 2, it can be observed that the performance of $P_f^{ED}(\lambda^{ED})$ is independent of SNR.

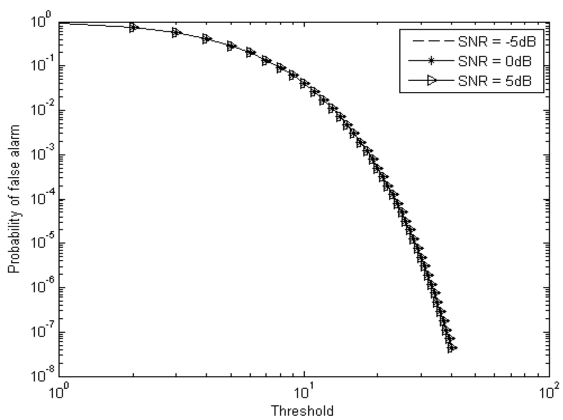

Fig. 2 False alarm probability vs. Threshold (SNR = -5 dB, 0 dB, 5 dB)

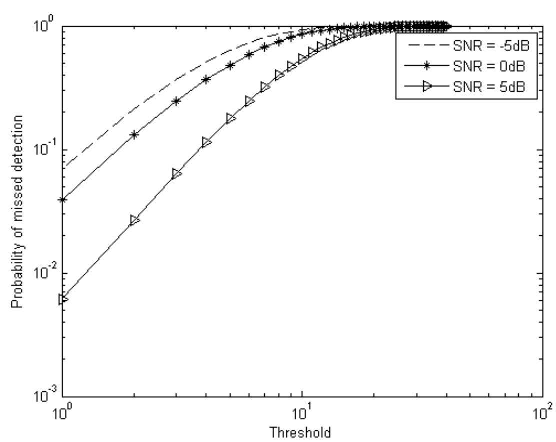

Fig. 3 Missed detection probability vs. Threshold (SNR = -5 dB, 0 dB, 5 dB)

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It is clear that, from false alarm stand point one should use high threshold, whereas from missed detection point, one should use low threshold. Hence, a careful trade-off is to be considered while setting the threshold.

In the present work, the total spectrum sensing error probability, which is formulated as the sum of $P_f^{ED}(\lambda^{\mathrm{ED}})$ and $P_m^{ED}(\lambda^{\mathrm{ED}},\gamma)$, is considered as one of the key metrics. In Figure 4, the total spectrum sensing error probability $\left(P_f^{ED}(\lambda^{\mathrm{ED}})+\ P_m^{ED}(\lambda^{\mathrm{ED}},\gamma)\right)$ is presented versus λ^{ED} in varying-SNR environment. It is perceived that there indeed exists a threshold to make $P_f^{ED}(\lambda^{\mathrm{ED}})+ P_m^{ED}(\lambda^{\mathrm{ED}},\gamma)$ minimum. The significance of selecting threshold is explained by dividing the each curve into two regions $(\lambda^{\mathrm{ED}} < \lambda_{opt}^{ED}\ and\ \lambda^{\mathrm{ED}} > \lambda_{opt}^{ED})$. When the threshold of the energy ED is taken

- in the left half of the λ_{opt}^{ED}, missed detection errors are minimum.
- in the right half of the λ_{opt}^{ED}, false alarm errors are minimum.
- at $\lambda^{\mathrm{ED}} = \lambda_{opt}^{ED}$, both missed detection errors and false alarm errors are minimum

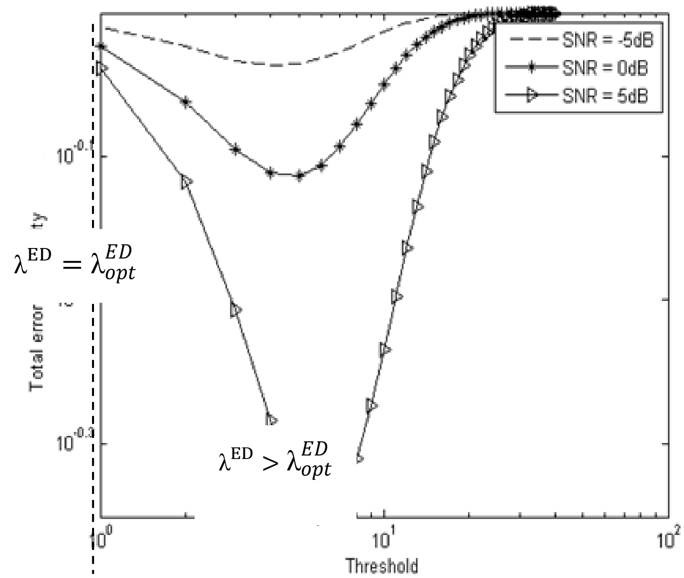

Fig. 4 Total error probability vs. Threshold (SNR = -5 dB, 0 dB, 5 dB)

Minimum missed detection and false alarm errors must be jointly sustained to optimize detection performance in SNR varying environment. It is perceived that there indeed exists a threshold to make $P_f^{ED}(\lambda^{\mathrm{ED}})+\ P_m^{ED}(\lambda^{\mathrm{ED}},\gamma)$ minimum.

Maximization of Throughput and Energy Efficiency

Refer to Table I for the main notation. In CRN, there are four possible scenarios between PU and SU. Throughput and energy consumption for each scenario are presented in Table II.

Table I Notations

Notation	Meaning
$\mathcal{T}_{pu}$	: PU's throughput when SU is absent
$\mathcal{T}_{su}$	: SU's throughput when PU is absent
$\mathcal{T}_{pu/su}$	: PU's throughput when SU is present
$\mathcal{T}_{su/pu}$	: SU's when PU is present
$\mathcal{E}_{sensing}$	: Energy consumed by SU to accomplish spectrum sensing
$\mathcal{E}_{pu}$	: Energy consumed by PU to transmit data
$\mathcal{E}_{su}$	: Energy consumed by SU to transmit data

Table II Throughput and Energy Consumption for Each Scenario

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Scenario	PU status	CR Decision	Channel occupancy	Through-put	Energy
1	Present	Present	only by PU	$\mathcal{T}_{pu}$	$\mathcal{E}_{sensing} + \mathcal{E}_{pu}$
2		Absent	Simultaneously by PU and SU	$\mathcal{T}_{pu/su} + \mathcal{T}_{su/pu}$	$\mathcal{E}_{sensing} + \mathcal{E}_{pu} + \mathcal{E}_{su}$
3	Absent	Absent	only by SU	$\mathcal{T}_{su}$	$\mathcal{E}_{sensing} + \mathcal{E}_{su}$
4		Present	neither by PU nor by SU	0	$\mathcal{E}_{sensing}$

Let us describe $P(H_0)$ as the probability for which the channel is idle and $P(H_1)$ as the probability for which the channel is occupied so that $P(H_0) + P(H_1)$. The average channel throughput $\left(\mathcal{T}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}}, \gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right)\right)$ is the sum of throughput of PU and SU. From Table II, $\mathcal{T}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}}, \gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right)$ can be delineated as

$$\mathcal{T}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}}, \gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right) = P(H_1)P_d^{ED}(\lambda^{\mathrm{ED}}, \gamma)\mathcal{T}_{pu} + P(H_1)\left(1 - P_d^{ED}(\lambda^{\mathrm{ED}}, \gamma)\right)\left(\mathcal{T}_{pu/su} + \mathcal{T}_{su/pu}\right) + P(H_0)\left(1 - P_f^{ED}(\lambda^{\mathrm{ED}})\right)\mathcal{T}_{su} \quad (7)$$

In CR network, each time frame contains a sensing slot (t_s) and a data transmission slot $(T - t_s)$, where T is the total time frame as illustrated in Figure 5.

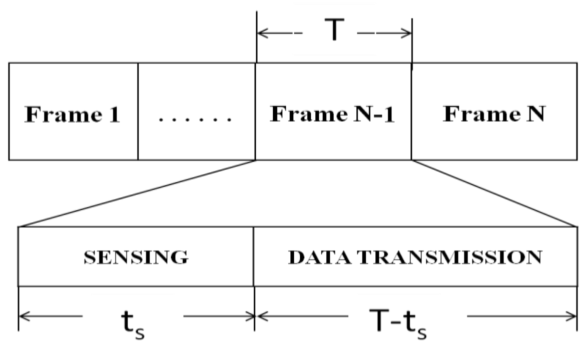

Fig. 5 Spectrum sensing frame of CR

The CR remains idle in the data transmission slot when PU is present and transmits data in the data transmission slot when it is absent. In a conventional system, the entire frame is used for data transmission; however, in CRN, a portion of the frame is reserved for sensing. Consequently, throughput is reduced and energy consumption is increased. Throughput of SU when PU is absent can be written as given below.

$$\mathcal{T}_{su} = \frac{T - t_s}{T} log_2(1 + SNR_{su}) \quad (8)$$

Throughput of SU when PU is present can be simplified to (under missed detection)

$$\mathcal{T}_{su/pu} = \frac{T - t_s}{T} log_2\left(1 + \frac{SNR_{su}}{SNR_{pu}}\right) \quad (9)$$

Where,

SNR_{su} = SNR of the SU

SNR_{pu} = SNR of the PU

Eq. (7) can be simplified to

$$\mathcal{T}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}}, \gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right) = \mathcal{T}_0 + P_d^{ED}(\lambda^{\mathrm{ED}}, \gamma)\mathcal{T}_1 - P_f^{ED}(\lambda^{\mathrm{ED}})\mathcal{T}_2 \quad (10)$$

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Where,

$\mathcal{T}_0 = P(H_0)\mathcal{T}_{su} + P(H_1)(\mathcal{T}_{pu/su} + \mathcal{T}_{su/pu}) > 0$

$\mathcal{T}_1 = P(H_1)(\mathcal{T}_{pu} - \mathcal{T}_{pu/su} - \mathcal{T}_{su/pu}) > 0,$ when $\mathcal{T}_{pu} > \mathcal{T}_{pu/su} + \mathcal{T}_{su/pu}$

$\mathcal{T}_2 = P(H_0)\mathcal{T}_{su} > 0$

The average energy consumption $\left(\mathcal{E}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}},\gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right)\right)$ is the sum of energy consumed by spectrum sensing, PU data transmission and SU data transmission. From Table II, $\mathcal{E}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}},\gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right)$ can be expressed as

$$\begin{aligned}\mathcal{E}_{average}&\left(P_d^{ED}(\lambda^{\mathrm{ED}},\gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right)\\ &= P(H_1)P_d^{ED}(\lambda^{\mathrm{ED}},\gamma)(\mathcal{E}_{sensing} + \mathcal{E}_{pu})\\ &+ P(H_1)(1 - P_d^{ED}(\lambda^{\mathrm{ED}},\gamma))(\mathcal{E}_{sensing} + \mathcal{E}_{pu} + \mathcal{E}_{su})\\ &+ P(H_0)\left(1 - P_f^{ED}(\lambda^{\mathrm{ED}})\right)(\mathcal{E}_{sensing} + \mathcal{E}_{su})\\ &+ P(H_0)P_f^{ED}(\lambda^{\mathrm{ED}})\mathcal{E}_{sensing} \qquad (11)\end{aligned}$$

The above Equation can be simplified to

$$\mathcal{E}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}},\gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right) = \mathcal{E}_0 - P_d^{ED}(\lambda^{\mathrm{ED}},\gamma)\,\mathcal{E}_1 - P_f^{ED}(\lambda^{\mathrm{ED}})\mathcal{E}_2 \qquad (11)$$

Where,

$\mathcal{E}_0 = P(H_1)\mathcal{E}_{pu} + \mathcal{E}_{sensing} + \mathcal{E}_{su} > 0$

$\mathcal{E}_1 = P(H_1)\mathcal{E}_{su} > 0$

$\mathcal{E}_2 = P(H_0)\mathcal{E}_{su} > 0$

From Eq (10) and Eq (11), Energy efficiency can be written as

$$\eta_{\mathcal{E}\mathcal{E}}\left(P_d^{ED}(\lambda^{\mathrm{ED}},\gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right) = \frac{\mathcal{T}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}},\gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right)}{\mathcal{E}_{average}\left(P_d^{ED}(\lambda^{\mathrm{ED}},\gamma), P_f^{ED}(\lambda^{\mathrm{ED}})\right)} = \frac{\mathcal{T}_0 + P_d^{ED}(\lambda^{\mathrm{ED}},\gamma)\mathcal{T}_1 - P_f^{ED}(\lambda^{\mathrm{ED}})\mathcal{T}_2}{\mathcal{E}_0 - P_d^{ED}(\lambda^{\mathrm{ED}},\gamma)\,\mathcal{E}_1 - P_f^{ED}(\lambda^{\mathrm{ED}})\mathcal{E}_2} \qquad (12)$$

The throughput and energy efficiency are key metrics of CRN. Throughput and energy efficiency versus the threshold are presented, respectively in Figures 6 and 7, for different SNR values. The simulation parameters are indexed in Table III.

Table III Simulation Parameters

Parameter	**Value**
u	10
$\mathcal{T}_{pu}$	20
$\mathcal{T}_{su}$	10
$\mathcal{T}_{pu/su} + \mathcal{T}_{su/pu}$	15
$\mathcal{E}_{sensing}$	0.15
$\mathcal{E}_{pu}$	40
$\mathcal{E}_{su}$	10
$P(H_0)$	0.5
$P(H_1)$	0.5

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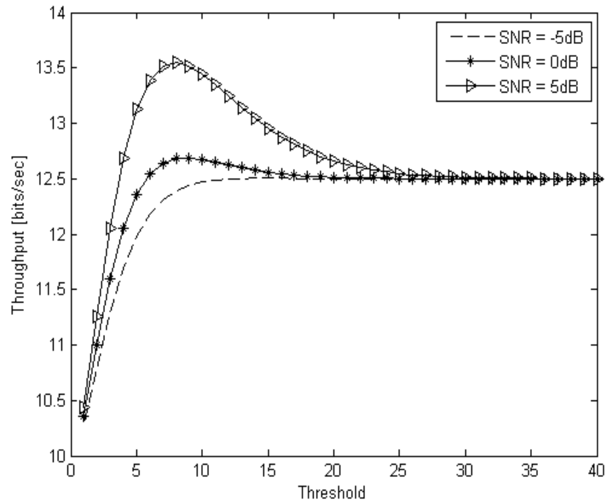

Fig. 6 Throughput vs. Threshold (SNR = -5 dB, 0 dB, 5 dB)

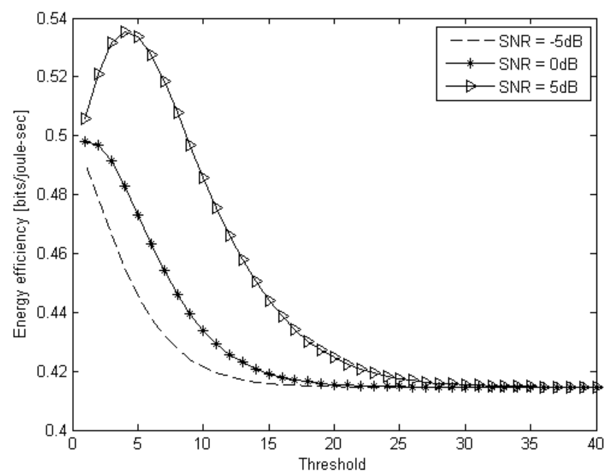

Fig. 7 Energy efficiency vs. Threshold (SNR = -5 dB, 0 dB, 5 dB)

It is clear from Figures 6 and 7 that if the threshold is fixed and the SNR increase, then throughput and efficiency also increases. Consequently, desired maximum throughput and maximum efficiency could be fixed; to do so, the threshold must be recalculated as a function of SNR. Spectrum and energy efficiency are primary resources in wireless environments [15-22]. In this context, the authors focus on optimizing threshold levels in CR systems to enhance these resources. The performance of the proposed work is discussed in the subsequent section.

II. Results and Discussion

It is clear from Figures 4 and 5 and 6 that there lies only one optimal threshold value for each metric. Table 4 shows the optimal threshold of each metric under different values of SNR.

Table IV Performance of Key Metrics of Cr

SNR	**Total spectrum sensing error**		**Throughput**		**% Efficiency**	
	Minimum value	λ_{opt}^{ED}	Maximum value	λ_{opt}^{ED}	Maximum value	λ_{opt}^{ED}
-5 dB	0.9189	4	12.55	16	49.07	1
0 dB	0.7693	5	12.68	8	49.79	1
5 dB	0.4455	6	13.55	8	53.55	4

From Table IV, it can be concluded that the larger the value of SNR, the lower the total spectrum sensing error probability and higher the maximum throughput as well as maximum energy efficiency. For instance, when SNR is 0 dB, the value of total

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spectrum sensing error probability is 0.7693 and decreases to 0.4455 when SNR increases to 5 dB. Moreover, when SNR rises from 0 dB to 5 dB, maximum throughput and maximum efficiency increase from 12.68 to 13.55 and 49.79% to 53.55%, respectively. It is clear that information of SNR is adequate for selection of an optimal threshold.

III. Conclusion and Future scope

In this paper, we presented optimal threshold values for total spectrum sensing error probability, throughput, and energy efficiency. As SNR value increases, the performance of the CR metrics is enhanced. For instance, when SNR increases from 0 dB to 5 dB, the total spectrum sensing error probability decreases from 0.7693 to 0.4455, the throughput increases from 12.68 to 13.55, and energy efficiency increases from 49.79% to 53.55%. Therefore, CR should adapt its operating parameters to the variations of the wireless communication environment.

Future research in CR networks could focus on advancing adaptive thresholding techniques for energy detection using deep learning models. This includes optimizing threshold adaptation algorithms based on real-time data.

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