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Enhancement of Spectrum Sensing Performance via Cooperative Cognitive Radio Networks at Low SNR

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Abstract

The inefficient use of spectrum is the key subject to overcome the upcoming spectrum crunch issue. This paper presents a study of performance of cooperative cognitive network via hard combining of decision fusion schemes. Simulation results presented different cooperative hard decision fusion schemes for cognitive network. The hard-decision fusion schemes provided different discriminations for detection levels. They also produced small values of Miss-Detection Probability at different values of Probability of False Alarm and adaptive threshold levels. The sensing performance was investigated under the influence of channel condition for proper operating conditions. An increase in the detection performance was achieved for cognitive users (secondary users) of the authorized unused dynamic spectrum holes (primary users) while operating in a very low signal-to-noise ratio with the proper condition of minimum total error rate.

Keywords: Cognitive Radio, Probability of Detection (Q_d), Probability of Miss-Detection (Q_{md}), Probability of False Alarm (Q_{fa}), Total Error Rate (Q_e) and threshold (T).

1. Introduction

Today's wireless networks are characterized by fixed spectrum assignment policy. There is a continuously increasing demand for frequency spectrum associated with limited resource availability. Additionally, the statistics of the Federal Communications Commission (FCC) stated that the temporal and geographical variations in the utilization of assigned spectrum have a range of 15 to 85 percent. Nowadays, it has become necessary to use the affordable spectrum more efficiently to upstay further growth of wireless communication. Therefore, the cognitive system is a revolutionary communication paradigm to treat the problem of inefficient use of underutilized spectrum and overcome the upcoming spectrum crunch issue. The underutilized spectrum holes, shown in Figure-1, develop to white spectrum holes. These frequency bands are assigned to specific system users called primary users (PU) or licensed users and the assigned frequency bands are called licensed bands. Cognitive users can be defined as unlicensed or secondary users (SU) who can find unused authorized spectrum holes dynamically for their own use without causing any confusion to primary users [1].

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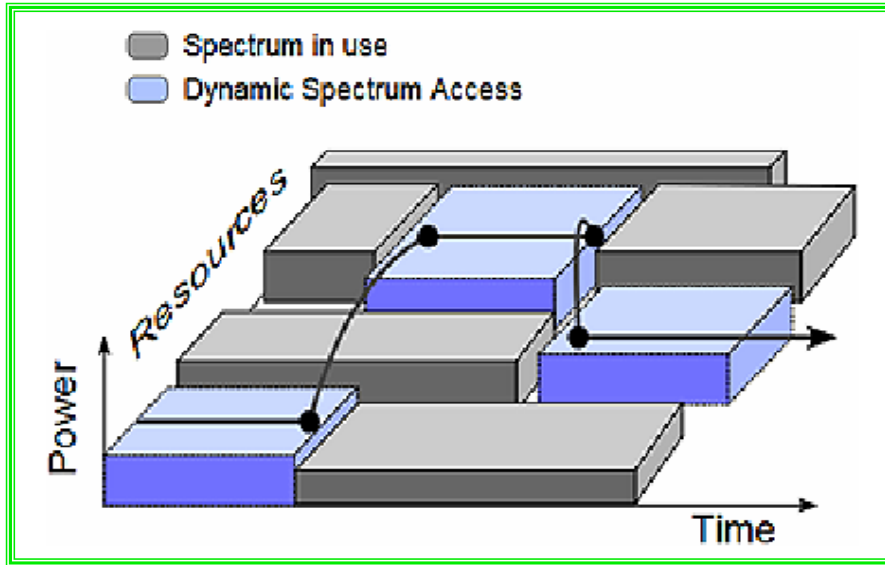


Figure 1- Underutilized spectrum holes concept

Hence, primary users can be defined as the users who have the authorized license to occupy a certain band of the spectrum. Secondary users can be defined as the users who have the conditional license and should not perform any confusion on the authorized spectrum when using the idle channel. The requirement of no interference is the key for developing cognitive systems and create fast and highly robust methods to make decisions about the idle and occupied frequency bands. Spectrum sensing will be the backbone of any autonomous cognitive radio.

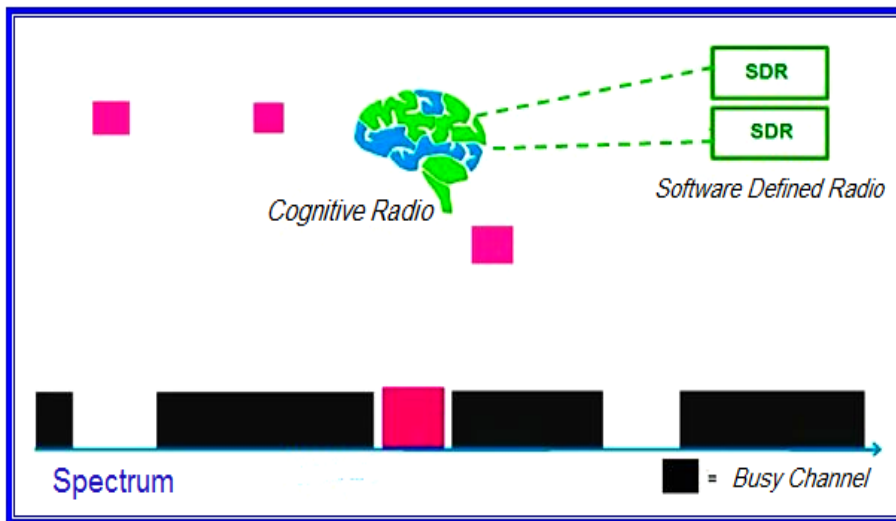


Figure 2- Cognitive radio mechanism for efficient use of the available frequency spectrum.

Therefore, simpler and more trustworthy spectrum detection techniques are needed. Energy detectors can confer simplicity and serve as a practical spectrum detection techniques. To enhance spectrum detection performance for cognitive network (CN), a cooperative spectrum detection methodology was proposed to overcome some spectrum sensing drawbacks, such as shadowing, fading, and receiver hidden node problems [2]. The cooperative spectrum detection aims to enhance cognitive radio detection performance by considering the advantage of cognitive users' spatial diversity to save the PU against interference and minimize the probability of false alarm and achieve an efficient usage of spectrum holes.

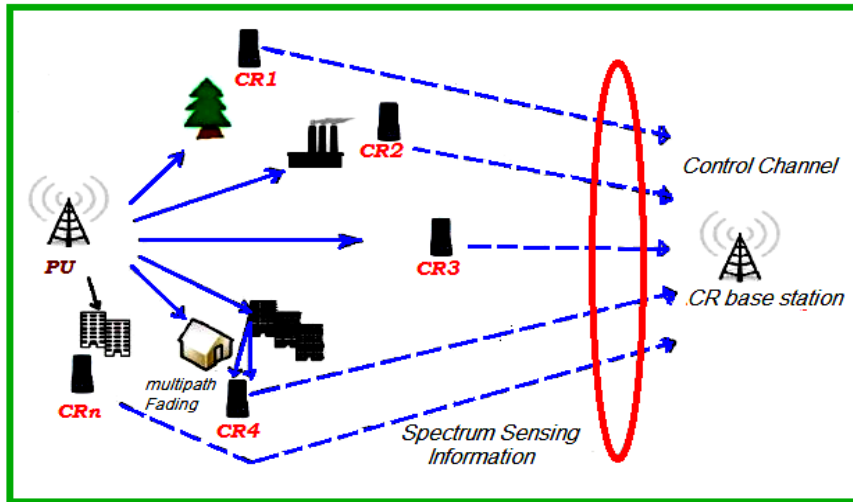


Figure 3- Cooperative Spectrum Sensing Technique

In a fading environment, the spectrum detection is sustained by uncertainty due to channel fading, i.e. the secondary user needs to differentiate between a white space, where the licensed signal is absent, and a deep fading, where the licensed signal is present. Thus, similar difficulties arise in the case of shadowing. To treat these issues, many different secondary users can cooperate to detect the presence of licensed signal. The advantage of diversity gains accomplished through cognitive users' cooperation to overcome fading, hidden nodes, and shadowing effects, and to perform high detection performance. CR users (Receivers) can measure the received signal properties and estimate what CR system (Transmitter) was meant to send. However, they should be also able to tell the transmitter about the way through which the waveform can be changed to avoid the interference. In other words, secondary users (receivers) should convert this information into a transmitted message and send it back to the CR system (Transmitter) [3- 8]. The basic cognitive radio cycle model is shown in Figure-4. The process is fulfilled through spectrum sensing, spectrum analysis, and spectrum decision states.

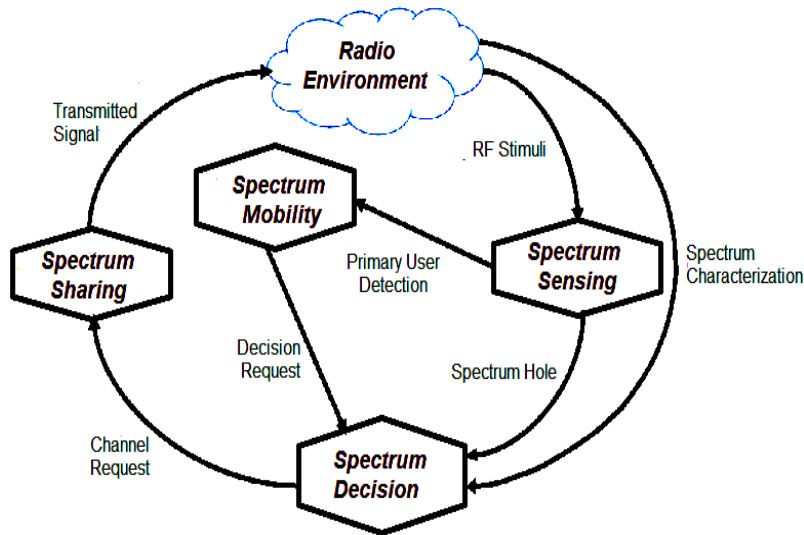


Figure 4-Cognitive Radio System Cycle Model

The cognitive system is a highly promising solution to the spectrum-scarcity problem. The most crucial activities in cognitive systems are the energy efficiency (EE) and spectrum efficiency (SE). Secondary users detect the spectrum to check the absence or presence of the primary signal depending on sensing parameters, such as signal-to-noise ratio (SNR), bandwidth, bit error probability, spectral efficiency, and throughput. The accuracy of sensing is a main requirement for accurate sensing, which provides a successful access operation of CRN. For known conditions, the energy detector (ED)

technique is the optimal method of sensing, through which the strength level of the detected signal energy is based on the threshold value of ED. For greater energy of the detected signal as compared to the threshold value, the presence of a primary signal is assumed; otherwise the physical channel is free. Spectrum sensing is applied to differentiate between two hypotheses; primary user presence hypothesis (H1) and primary user absence hypothesis (H0) [5, 6-13] as follows:

$$x(t) = \begin{cases} n(t) & , H_0 \\ h s(t) + n(t) & , H_1 \end{cases} \quad \text{---- (1)}$$

where $x(t)$ is the signal detected by CR users, $s(t)$ is the primary user's transmitted signal, $n(t)$ is the additive white Gaussian noise (AWGN), and h is the channel amplitude gain between the PU and the k^{th} CR user.

2. SYSTEM MODEL

Suppose a cognitive network with a number of cognitive users (K), referred to as $k = 1, 2, \dots, K$. Suppose that each CR performs local spectrum sensing autonomously by using N samples of received signal and that all cooperative CR users send their detected results (m_1, m_2, \dots, m_K) via the control channel. Consequently, the fusion center fuses the received local sensing information to make a final decision about the absence or presence of the primary signal. Thus, the secondary user who receives the signal can be defined as [7]:

$$x(t) = \begin{cases} n(t) & , H_0 \\ h_{pu} s_{pu}(t) + n(t) & , H_1 \end{cases} \quad \text{----- (2)}$$

and the ongoing SU received signal is defined as [4, 7]:

$$x_I(t) = \begin{cases} h_{su} s_{su}(t) + n(t) & , H_0 \\ h_{pu} s_{pu}(t) + h_{su} s_{su}(t) + n(t) & , H_1 \end{cases} \quad \text{----- (3)}$$

where $s_{pu}(t)$ is the PU transmitted signal, $s_{su}(t)$ is the leakage from the SU transmitted signal, h_{pu} is the PU channel gain, h_{su} is the SU leakage signal gain, and t is the time.

An energy detector is employed in our simulations to specify the state of the PU. The ED output statistic in each SU is given as [8]:

$$Y = \frac{1}{S} \sum_{i=1}^S |(\chi)|^2 \quad \text{---- (4)}$$

where S is the number of averaged samples.

The ED output for both hypotheses is expressed as [9]:

$$R_{H0} = |n|^2 \quad \text{----- (5)}$$

$$R_{H1} = |A+n|^2 \quad \text{----- (6)}$$

This paper is based on studying three different hard combining decision rules for Cooperative Spectrum Sensing (namely, OR, AND, and HV rules) and comparing them to the non-cooperative cognitive system, thus deducing the effects on the detection efficiency under specific conditions.

2.1 AND – Rule

The AND – rule takes the decision about the presence of the primary signal if *all* CR users detect it. The test that is using the cooperative AND rule can be defined as [10]

$$H_1 : \sum_{i=1}^K \Delta_k = K \quad \text{----- (7)}$$

$$H_0 : \text{Otherwise}$$

where K is the number of CR users and Δ is the final detection.

The probability of detection and the probability of false alarm are also defined as follows [8, 11]:

$$Q_{d,AND} = \prod_{i=1}^K P_{d,k} \quad \text{----- (8)}$$

$$Q_{f,AND} = \prod_{i=1}^K P_{f,k} \quad \text{---- (9)}$$

$$Q_{md,AND} = 1 - Q_{d,AND} = 1 - \prod_{i=1}^K P_{d,k} \quad \text{----- (10)}$$

2.2 OR_ Rule

The OR- rule takes the decision about the presence of the primary signal if *any* of cognitive users detect it. The test that is using the cooperative OR- rule can be defined as [10]:

$$H_1 : \sum_{i=1}^K \Delta_k \geq 1 \quad \text{---- (11)}$$

$$H_0 : \text{Otherwise}$$

where Δ is the final decision. The special case for the OR- rule being proportional to the case $M=1$ is defined as follows [8, 11]:

$$Q_{d,OR} = 1 - \prod_{i=1}^K (1 - P_{d,k}) \quad \text{---- (12)}$$

$$Q_{f,OR} = 1 - \prod_{i=1}^K (1 - P_{f,k}) \quad \text{---- (13)}$$

$$Q_{md,OR} = 1 - Q_{d,OR} \quad \text{---- (14)}$$

2.3 HV _ Rule

The Half-Voting, also called the majority rule, takes the decision about the presence of the primary signal if at least M of K secondary users have detected it, with $1 \leq M \leq K$, and is defined as [10]:

$$H_1 : \sum_{i=1}^K \Delta_k \geq M \quad \text{---- (15)}$$

$$H_0 : \text{Otherwise}$$

The majority decision special case takes place at $M = K/2$.

The probability of detection (Q_d) and false alarm probability (Q_f) are defined as [10] :

$$Q_{d,HV} = P_r \left\{ \Delta=1 \mid H_1 \right\} = P_r \left\{ \sum_{i=1}^k \Delta_k \geq M \mid H_1 \right\} \quad \text{----- (16)}$$

$$Q_{f,HV} = P_r \left\{ \Delta=1 \mid H_0 \right\} = P_r \left\{ \sum_{i=1}^k \Delta_k \geq M \mid H_0 \right\} \quad \text{----- (17)}$$

$$Q_{md,HV} = 1 - Q_{d,HV} \quad \text{----- (18)}$$

Thus, the CR spectrum sensing performance parameters are classified as follows:

- Signal to Noise Ratio (SNR)
- Probability of Correct Detections:
 - Q_d { decision , $Y = H_1 \mid H_1$ }
 - Q_d { decision , $Y = H_0 \mid H_0$ }
- Probability of False Alarm :
 - Q_{fa} { decision , $Y = H_1 \mid H_0$ }

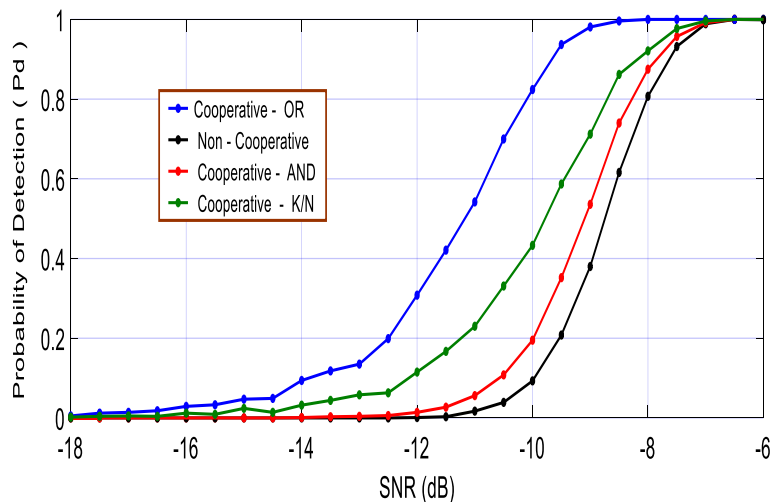


Figure 5-SNR (-18 dB to -6 dB) Vs Q_d at $Q_{fa} = 0.01$

- Probability of Miss-Detection :
 - Q_{md} { decision , $Y = H_0 \mid H_1$ }
- Total Error Rate:
 - $Q_e = Q_{fa} + Q_{md}$ [16]
- Threshold ($\bar{\gamma}$)
- Number of CR users

3. SIMULATION RESULTS

Hard combining cooperative decision rules were proposed in this paper to refine the CR detection efficiency and compared it to that of the non-cooperative cognitive system .

There are three cooperative sensing rules based on hard decision rules , namely :

- The OR rule gives the decision of H_1 if any of cognitive users detect the primary signal .
- The AND rule gives the decision of H_1 if all cognitive users send their detection status as bit_1, as a local detection of the primary signal.
- The HV- rule gives the decision of H_1 if at least half of the cognitive users send their local detection status as bit_1. Each CR user makes own decision about the absence or presence of the primary user and sends the one bit decision status (1 or 0) to the FC or the cooperative groups to make data fusion. The simulation was made for cognitive networks with seven cooperative cognitive secondary users with ($K = 7$ CR's). AWGN channel is also proposed for our simulations, with an SNR that ranges

from - 18 dB to - 6 dB , - 12 dB to 0 dB, and - 10 dB to 2 dB and with $Q_{fa} = 0.01$. Also, we SNR used ranges from -18 dB to -6 dB , -16 dB to -4 dB , -14 dB to -2 dB , -12 dB to 0 dB , and -10 dB to 2 dB . A QPSK modulation was also applied for the test, with modulation index $m = 6$, number of simulations $n = 2000$ for each value of SNR , and number of samples/signal $N = 1500$. Figures- 5 and 6 show the receiver operating characteristics (ROCs) for the hard combining cooperative decision rules (AND, OR, and HV) and a non-cooperative energy detector with Q_{fa} is 0.01 .

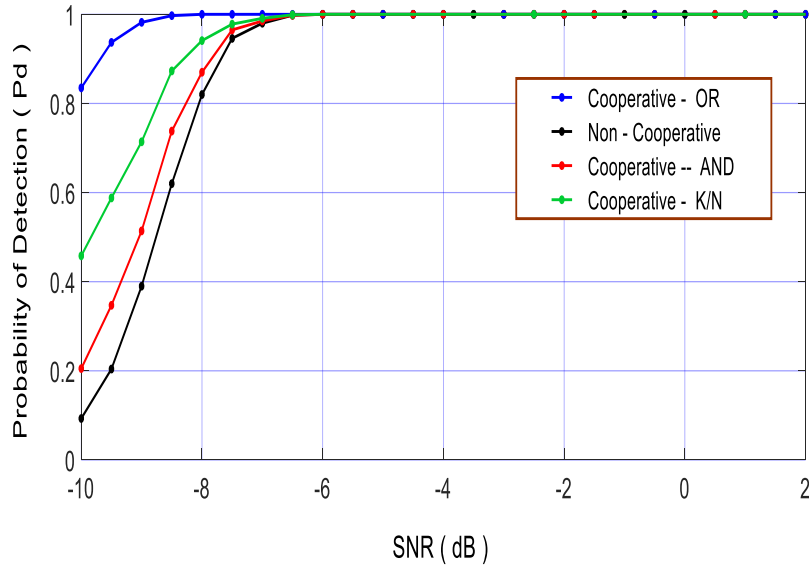


Figure 6- SNR (-10 dB to 2 dB) Vs Q_d at $Q_{fa} = 0.01$

The results in Figures- 5 and 6 indicate that the probability of detection increases as the SNR increases . In addition, the ROCs curves show that the OR-rule detection performance is the optimal for spectrum detection as compared to the other hard decision rules. Also, the HV or the majority hard decision rule has lower detection efficiency than the OR - rule, but it is higher than that of the AND - rule, while the value for the AND – rule is higher than that for the non-cooperative cognitive rule. These latter results indicate better detection performance when compared to those previously described [13- 20].

Therefore, we performed the same simulation at the same conditions, but with probability of false alarm Q_{fa} of 0.1, i.e. the Q_{fa} value was increased.

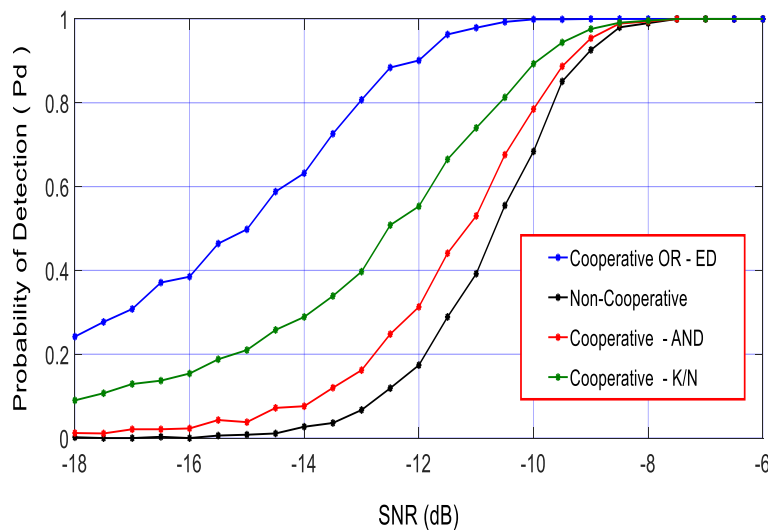


Figure 7- SNR (-18 dB to - 6 dB) Vs Q_d at $Q_{fa} = 0.1$

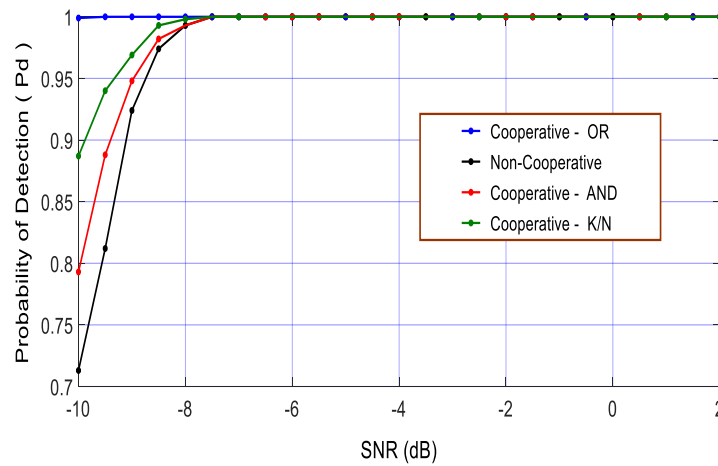


Figure 8- SNR (-10 dB to 2 dB) Vs Q_d at $Q_{fa} = 0.1$

It is clear from the ROCs response shown in Figures- 7 and 8 that the probability of the detection (Q_d) increases by increasing the false alarm probability (Q_{fa}), in parallel with the increase in SNR. It can be noted from the ROC curve in Figure- 5 that the SNR ranges -18 dB to -6 dB at the point of SNR = -10 dB, with $Q_{fa} = 0.01$, where :

$$Q_{d-OR} = 83\% \quad , \quad Q_{d-HV} = 44\% \quad , \quad Q_{d-AND} = 20\% \quad , \quad Q_{d-Non-cooperative} = 9\%$$

Also, the ROC curve in Figure- 7 shows the same SNR range (-18 dB to -6 dB) as that detailed in Figure-5, at the point of SNR = -10 dB, but with $Q_{fa} = 0.1$, where :

$$Q_{d-OR} = 99\% \quad , \quad Q_{d-HV} = 88\% \quad , \quad Q_{d-AND} = 77\% \quad , \quad Q_{d-Non-cooperative} = 68\%$$

Hence, it is obvious that the Q_d increases by increasing the Q_{fa} and SNR. Consequently, the OR - rule gives better efficiency of spectrum detection. These results indicate higher detection performance when compared to those of other studies [13, 14, 19, 20, 21, 22]. Also, these results confirmed that there is a relation between SNR, Q_d , and Q_{fa} , along with their effects on the detection efficiency of the spectrum. Also, there is a relation between Q_d and Q_{md} , as follows :

$$Q_{md} = 1 - Q_d \quad [18] , [13] \quad \text{---- (19)}$$

Generally, there exist two kinds of detection errors, namely the miss-detection error Q_{md} and false-alarm error Q_{fa} , which degrade the sensing performance. Therefore, the effect of the relation between Q_{fa} and Q_{md} will be simulated for the hard decision rules (OR , AND , and HV) and Non-cooperative CR network, and their effects on the spectrum detection efficiency will be determined. The analysis of spectrum detection efficiency under the target of probability of miss-detection and probability of false alarm, at $K = 7$ SU s, SNR = -10 dB, time bandwidth factor $U = 100$, and AWGN channel, was considered.

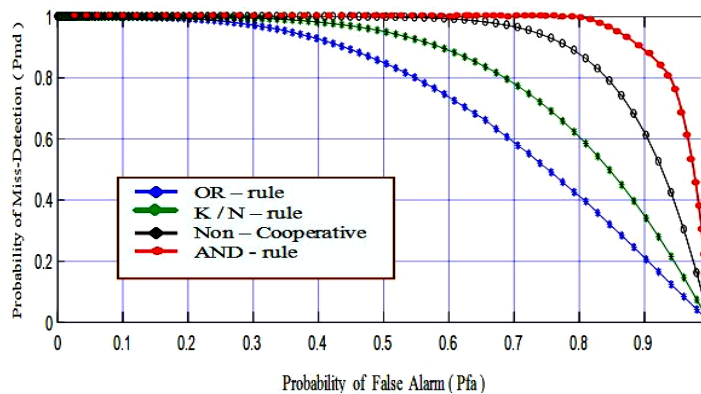


Figure 9- Q_{fa} Vs Q_{md} , at SNR = -10 dB

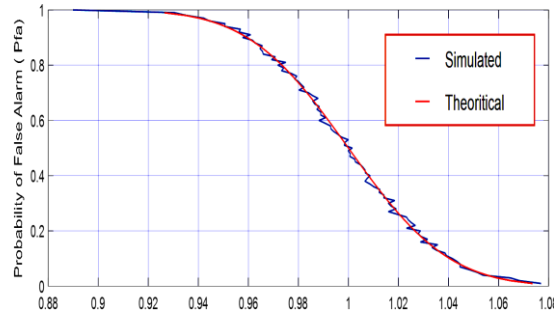


Figure 10- Threshold (T) Vs Q_{fa}

It is clear from the result in Figure- 9 that the OR rule gives minimum Q_{md} versus Q_{fa} values when compared to the other cooperative spectrum detection techniques (HV and AND rules). Thus, the OR rule is the optimal among the other hard combination data-fusion methods of cooperative spectrum detection. The obtained result show higher detection performance when compared to previous studies [12, 17, 19]. The aim of cooperative spectrum detection is to refine the detection performance and protect the primary user against interference resulting from large values of Q_{md} , which minimizes the false alarm probability of having an efficient usage of spectrum holes. Therefore, the aim is to keep the Q_{md} very low, hence the Q_{fa} increases and this would result in low spectrum utilization. This implies that a low probability of false alarms would result in high miss-detection probability, which increases the confusion to the primary users. Thus, this trade-off has to be considered. Then, the threshold is set to achieve a constant level of false alarm to perform the condition of minimum Q_{md} . Thereafter, the threshold level (T) is raised and lowered during detection to maintain acceptable level

Q_{fa} . Therefore, this meaning can be defined as an adaptive false alarm rate-adaptive threshold for detection (AFAR – ATD) [15], where:

$$Q_d = P(H1 / H1) = P(SNR > T / H1) \quad \text{----- (20)}$$

$$Q_f = P(H1 / H0) = P(SNR \geq T / H0) \quad \text{----- (21)}$$

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Threshold (T)

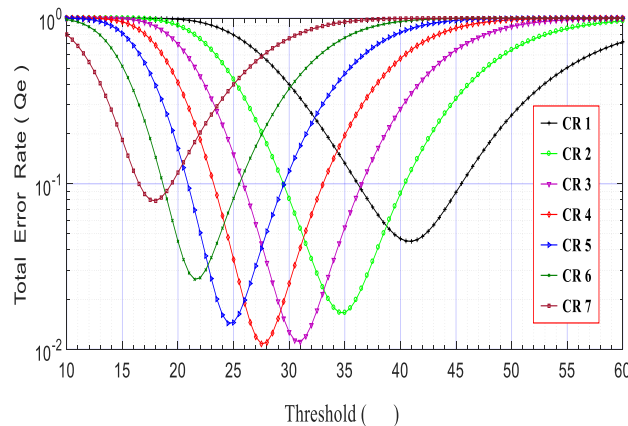


Figure 11- Total Probability of Error (Q_e) Vs Threshold (T) For AND ,OR , and HV fusion rules at, SNR = 10 db.

For a number of samples/signal $N = 1000$, only noise was received, i.e. the PU was absent, with $Q_{fa} = 0.01 : 0.01 : 1$. Thus, it is clear from the ROC value for T versus Q_{fa} that the Q_{fa} decreases as the T increases. Hence, the results satisfy the proper condition for designing cognitive networks with cooperative spectrum detection of high spectrum detection and minimum confusion, thus more

efficient spectrum utilization. Taking into consideration the total error rate (Q_e), which is the sum of probability of false alarm and probability of missed detection, the total error rate is given by :

$$Q_e = Q_{fa} + Q_{md} \quad \text{----- [22]}$$

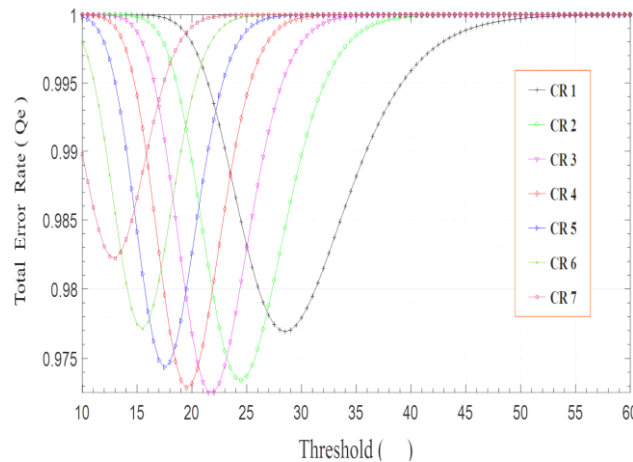


Figure 12- Total Probability of Error (Q_e) Vs Threshold (T) For AND , OR , and HV fusion rules , at SNR = - 10 db

From the results shown in Figures- 11 and 12, there a noticeable difference in the performance throughout the usage of $n = 1$ to 7 as $K=7$ cooperative fusion rule. For a fixed low threshold, the optimal hard decision fusion rule is the AND rule with a minimum error rate, i.e. $K = 7$. For a fixed high threshold, the optimal fusion rule is the OR rule with a minimum error rate, i.e. $n = 1$. Since the threshold is set to achieve a constant level of false alarm to perform the condition of minimum Q_e , thus the value of $n = 7$, which represents the AND fusion rule, gives a high total error when compared to the other curves .

Finally, we can note that the optimal hard decision fusion rule is the HV, i.e. the majority rule, with $n =4$ over all the range of threshold detection through the cooperative spectrum sensing scheme, which gives the minimum total errors at SNR = - 10 db. This is an appropriate value, while any increase or decrease would cause a large increase in the error rate significantly.

Finally, the results demonstrate a minimum Q_e at minimum SNR for the HV rule over all the range of threshold detection levels throughout the cooperative spectrum sensing scheme .

Table (1) Comparison between the total error rate of the three hard cooperative decision rules (AND OR, and HV) with two different levels of SNR.

4. Conclusions

In this paper, we presented a study of cognitive radio networks with various effective techniques of cooperative hard combining spectrum detection . A new approach was employed along with comparisons to the non-cooperative cognitive radio networks. Cooperative schemes (AND, OR, and HV) were employed and their performance was evaluated through SNR, Q_d , Q_{fa} , and Q_{md} . The simulation results verified that the combined hard cooperative spectrum detection techniques have better performance when compared to the non-cooperative approach, where the performance was enhance with the increase in SNR. The ROCs curves showed that the OR rule technique has the highest spectrum detection than the other two hard decision rules. The HV scheme had a lower detection efficiency than the OR rule, but it was higher than that of the AND rule. Consequently, the performance of all the cooperative CR schemes was better when compared to that of the non-cooperative cognitive schemes. In addition, it was obvious that the Q_d increases by increasing the Q_{fa} and SNR. Furthermore, seven cognitive users cooperated relatively in the system and the threshold was set to achieve a constant level of false alarm to perform the condition of minimum Q_{md} . Then, the operating threshold level was adjusted precisely during the detection to maintain an acceptable level of false alarm and achieve the optimal values of detection probability and total error rate.

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CONFLICT OF INTEREST

The authors confirm that this article content has no any potential conflict of interest.

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