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Proposed Two-Stage Detection Rules for Improving Throughput in Cognitive Radio Networks

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Abstract*—Cognitive Radio (CR) is a communication technology developed to solve the problem of spectrum scarcity. One way to improve the throughput of CR is the use of efficient decision rules of the fusion center to combine the collected information from cooperative sensors and produce the right final decision. For this purpose, hard decision rules like AND and OR and soft decision rules like Square Law Combination (SLC) and Maximum Ratio Combination (MRC) can be combined to optimize the throughput performance. In this paper, three decision rules, each consist of two decision stages (hard and soft) are proposed to improve the throughput of CR in cooperative scenario. The simulation results showed that the proposed rules enhance the throughput as compared with traditional ones. They demonstrated that the first proposed rule enhances the throughput by 106% and 58.9% at SNR equals -10 dB in Rayleigh fading channel over the classical OR-SLC and the AND-SLC rules, respectively. Under the same simulation conditions, the second proposed rule enhanced the throughput by 163% and 97.5%, while the third proposed method enhances throughput by 210% and 135%, respectively.*

Index Terms*—Cognitive radio, spectrum sensing, throughput, cooperative sensing, fusion center*

I. INTRODUCTION

Studies have shown that most of the licensed radio bands are underutilized which resulting in spectrum holes (white spaces) [1]. Spectrum scarcity occurred because of the following two reasons: fixed spectrum allocation policies do not allow unlicensed users for reusing the spectrum band allocated to licensed users, and the rapidly increasing demand for wireless services [2]. A new technology called Cognitive Radio (CR) is developed to address the spectrum scarcity by allowing the unlicensed users to access the white spaces in spectrum bands which are already assigned to the Primary Users (PUs) when the PUs are inactive [3-5]. The first step in CR cycle is spectrum sensing, which monitors the usage of licensed spectrum. Before using the licensed spectrum band,the CR users need to know if the licensed user occupied the band [6-8]. The most important challenge is to use the licensed spectrum by the CR user without interfering with the licensed users [9]. The decision rules can be either hard or soft. In a hard fusion scheme, every cognitive radio user makes the local binary decision independently on the presence or absence of PU. All decisions of the CR users are then sent to the Fusion Center (FC), where the global decision is made [10], while in soft fusion,the CR users send their sensing information to the fusion center without making local decisions. The decision is made at FC by using one of the combining rules [11]. The use of mixed types of decision rules can improve the decision credibility and the throughput as a result. Throughput is affected by fusion rules that make the global decisions. However, using an appropriate fusion rule in cooperative spectrum sensing scheme causing increase the throughput in cognitive radio.

In this paper, the performances of existing two - stage detection methods are evaluated and three proposed rules are presented to optimize the throughput of the CR network. The rest of the paper is organized as follows. Section II, shows the described system model. In Section III, the introduction to

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the proposed decision rules is demonstrated. Simulation results are given in Section IV. The conclusion is explained in Section V.

II. THE MODEL OF COOPERATIVE SENSING

Two hypotheses are available in the cooperative sensing, as follows:

$$H_0: \ r(n) = w(n)$$
$$H_1: \ r(n) = h\, s(n) + w(n) \tag{1}$$

where r(n) is the signal received from PU, h is the channel gain, s(n) is the signal transmitted by primary user and w(n) is the additive white Gaussian noise (AWGN). In cognitive radio, SUs must be able to detect the signal from the primary user. For individual spectrum sensing, this is difficult since the fundamental characteristics of wireless channels such as multipath fading, shadowing, can degrade the signal [12]. To overcome these issues of individual spectrum sensing, cooperative spectrum sensing is used, where SUs send their local sensing information to fusion center FC to make the final decision [13]. According to the nature of decisions taken, cooperative spectrum sensing schemes can be categorized into: soft combination schemes, hard combination schemes and two-stage combination schemes [14].

A. Soft combination schemes:

In this scheme, SUs send their sensing information to FC without making any decisions. The main rules in this detection techniques are square law combination (SLC), maximum ratio combination (MRC) and double threshold soft decision (DTSD) rule.

- Square law combination (SLC): in this rule the energies at each secondary user are sent to the fusion center where they are added and a comparison with predefined threshold is applied to decide the presence or absence of PU. The overall energy of this rule is [15]:

$$E_{SLC} = \sum_{i=1}^{\mathrm{Nu}} E_i \tag{2}$$

  where E_i are the energies from ith CR user, and Nu is the number of secondary users.

- Maximum Ratio Combination (MRC): The energies of CR users are multiplied with a normalized weight and then added. The overall energy for this rule is:

$$E_{MRC} = \sum_{i=1}^{M} w_i E_i \tag{3}$$

  MRC soft combination scheme defines weight coefficients as [16]

$$w_i = \sum_{i=1}^{\mathrm{Nu}} \frac{E_i}{\sqrt{\sum_{j=1}^{\mathrm{Nu}} {E_j}^2}} \tag{4}$$

- Double Threshold Soft Decision Rule (DTSD): This method uses two thresholds for energy comparison purposes. The mechanism of its operation is as follows: all the secondary users send their sensing information (energies) to the fusion center. At the fusion center, all energies are, compared individually with the first threshold λ_1. Then the energies that fall below this threshold are excluded to reduce the probability of false alarm. Finally, the rest of energies are added together and compared with the second threshold λ_2. The test statistic for this proposed rule is [17]:

$$E_{DTSD} = \sum_{E_i > \lambda 1} E_i \tag{5}$$

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B. Hard combination schemes:

Hard combination scheme: In this scheme, SUs performs local decisions and send one binary decision bit to FC. The existing rules are as follows:

- AND rule: In this rule, the final decision made by the FC depends on all of the local decisions sent to FC. The false alarm probability is calculated from [18]:

$$P_{FA,\,AND} = (P_{FA,\,i})^{Nu} \tag{6}$$

- OR rule
  In this rule, the final decision made by the FC depends on any one of the local decisions sent to the fusion center. The false alarm probability is calculated from [18]

$$P_{FA,\,OR} = 1-(1-P_{FA,\,i})^{N} \tag{7}$$

- Majority rule
  In this rule, the final decision made by the FC depends on half or more of the local decisions sent to FC. The false alarm probability is calculated from [18]:

$$P_{FA,MAJORITY} = \begin{cases} \sum_{ceil\left(\frac{N_u}{2}\right)}^{N_u} \binom{N_u}{ceil\left(\frac{N_u}{2}\right)} (P_{FA,I})^{ceil(Nu/2)} (1-P_{FA,i})^{Nu-(ceil(Nu/2)}, & N_u \text{ is odd} \\ \sum_{N_u/2}^{N_u} \binom{N_u}{N_u/2} (P_{FA,i})^{Nu/2} (1-P_{FA,i})^{Nu-(Nu/2)}, & N_u \text{ is even} \end{cases} \tag{8}$$

where ceil (x) rounds the elements of $N_u/2$ to the nearest integers greater than or equal to x.

- Majority Plus One (MPO) rule
  We recently proposed this rule [19]. With this rule, the final decision made by the FC is depending on half plus one or more of the local decisions sent to the FC. The false alarm probability of this rule is given by:

$$P_{FA,MPO} = \begin{cases} \sum_{ceil\left(\frac{N_u}{2}\right)+1}^{N_u} \binom{N_u}{ceil\left(\frac{N_u}{2}\right)+1} (P_{FA,\,I})^{ceil(Nu/2)+1} (1-P_{FA,\,i})^{Nu-(ceil(Nu/2)+1)}, & N_u \text{ is odd} \\ \sum_{\left(\frac{N_u}{2}\right)+1}^{N_u} \binom{N_u}{\left(\frac{N_u}{2}\right)+1} (P_{FA,\,i})^{(Nu/2)+1} (1-P_{FA,\,i})^{Nu-((Nu/2)+1)}, & N_u \text{ is even} \end{cases} \tag{9}$$

C. Two- stage detection schemes:

This scheme uses two- stage of rule decisions. At the first stage, the hard combining is used by CR. If the global decision on the presence of the primary user is 0, the CR steps into the second detection stage by requesting the sensors to provide soft information to perform the soft combining [20]. This method enhances the probability of detection and decreases the probability of false alarm which lead to increase the throughput. The throughput for the secondary network is defined as:

$$Throughput = \left(1-\frac{\tau}{T}\right)(1-P_{FA}) \tag{10}$$

where T is the frame duration and τ is the sensing time. This equation clearly shows that the throughput increases as the probability of false alarm decreases.

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III. THE PROPOSED DECISION RULES

Three decision rules are proposed in this paper to improve the throughput of CR. The proposed rules are of different types. Each one of them consists of the hard decision rule followed by soft one to improve the throughput. When the hard decision rule is applied, if the detection probability is less than 0.5, the process is terminated and 0 is sent to FC. Else, the CR steps to the second stage to apply the soft decision rule. The proposed rules are described as below:

A. The first proposed rule (MPO-SLC)

In this rule, the hard decision stage is represented by the first proposed rule MPO and the soft decision stage is represented by the traditional soft decision rule SLC. The flow chart for this rule is shown in Fig. 1. After generating primary user signal using QPSK modulation over fading channel, the spectrum sensing process overall secondary users is initiated using energy detection. The computed energy in each sensing node is compared with corresponding threshold λ_h, where h stands for hard decision. The hard decisions of all nodes are then sent to FC which uses MPO rule to produce final decision about signal presence. The false alarm probabilities of all nodes are stored and the overall PFA is computed using (9) to estimate the throughput. If the probability of detection of resulting decision (obtained statistically depending on SNR, threshold and P_{FA}) is less than 0.5, the sensing process is terminated in order not to spend further time for verification using soft rule. Otherwise the sensing energies from all nodes are applied to SLC rule. The threshold used in this case is λ_s where s stands for soft decision threshold. The false alarm and throughput are computed in similar way.

B. The second proposed rule (AND-DTSD)

In this rule, the hard decision stage is represented by the traditional decision rule AND while the second proposed decision rule DTSD is used to achieve the soft decision stage. Fig.2 can also act as the design flow for this combining rule with the following differences: MPO rule is replaced by AND rule, so (6) is used instead of (9) to calculate the false alarm probability. The soft rule used here is DSTD which uses two soft thresholds λ_{s1} and λ_{s2} , so the flow between points 4 and 5 in Fig.1 will be as shown in Fig.2.

C. The third proposed rule (MPO-DTSD)

In this rule, the hard decision stage is done using the first proposed rule MPO. The soft decision stage is represented by the second proposed decision rule DTSD. The flow chart for this rule is demonstrated in Fig.1, with the right side replaced by Fig.2.

IV. SIMULATION RESULTS

The simulation parameters that are used is as follows: the total frame duration is 0.1 sec. including the sensing and transmission time. The number of sensing nodes is 9. The PU signal is a random data modulated using QPSK modulation. AWGN and Rayleigh multipath channels are used as transmission and reporting channels. For AWGN channel, SNR is changed from -20 to -2 dB while for multipath fading ITU indoor channel model is used. The probability of false alarm versus signal to noise ratio is presented in Fig.3. According to Fig.3, it is obvious that MPO-SLC rule achieves improved performance over OR-SLC and AND-SLC rules. For example, at SNR equals -4 dB, the MPO reduces P_{FA} of OR-SLC and AND-SLC by 45.8% and 38.4 % respectively.

The throughput versus SNR for the OR-SLC and AND-SLC rules and the proposed MPO-SLC rule is presented in Fig.4. The figure shows that MPO-SLC significantly improves the throughput as compared with OR-SLC and AND-SLC. For instance, when SNR equals -10dB, the proposed method enhances the throughput of OR-SLC and AND-SLC rules by 106% and 58.9% respectively.

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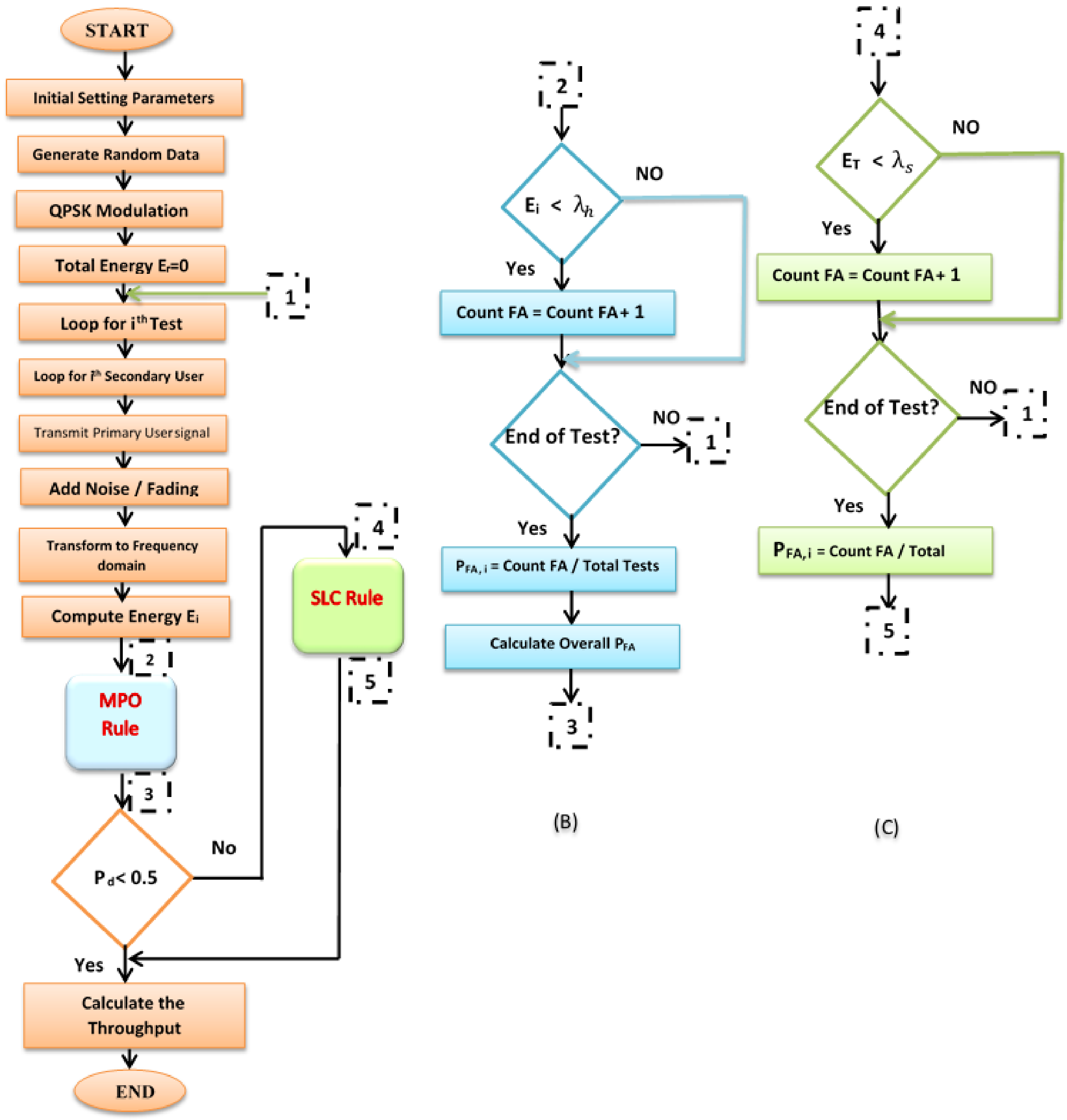

FIG. 1. THE FLOWCHART OF THE PROPOSED MPO-SLC RULE
(A) THE MAIN FLOWCHART FOR THE PROPOSED APPROACH
(B) THE FLOWCHART FOR THE MPO RULE
(C) THE FLOWCHART FOR THE SLC RULE

Fig.5 presents the probability of false alarm versus signal to noise ratio over Rayleigh fading channel. As it is clear in this figure, AND-DTSD rule achieves higher performance than OR-SLC and AND-SLC rules especially when SNR decreases. For instance, when SNR equals -10 dB the proposed rule reduces P_{FA} to 0.2 while the corresponding values of P_{FA} for OR-SLC and AND-SLC rules are 0.69 and 0.6 respectively. Fig.6 presents the throughput versus SNR for the OR-SLC and AND-SLC methods and the proposed one. It is clear in this figure that the throughput increases when SNR increase. Thereby, when SNR= -10 dB, the enhancement in throughput using the proposed method over OR-SLC and AND-SLC rules are 163% and 97.5%, respectively.

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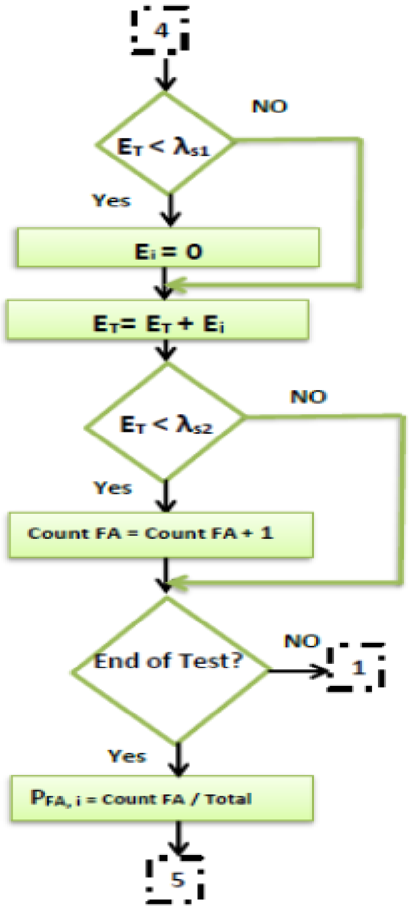

FIG. 2. THE FLOWCHART OF DTSD SOFT COMBINATION RULE

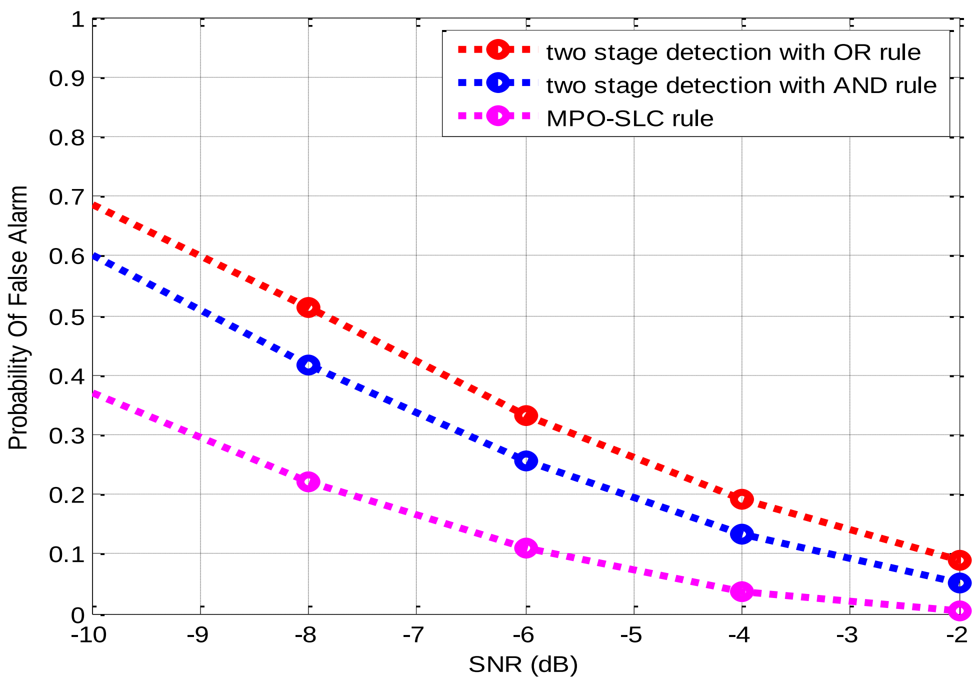

FIG. 3. TWO STAGE DETECTION, SNR VERSUS PROBABILITY OF FALSE ALARM OVER RAYLEIGH FADING CHANNEL

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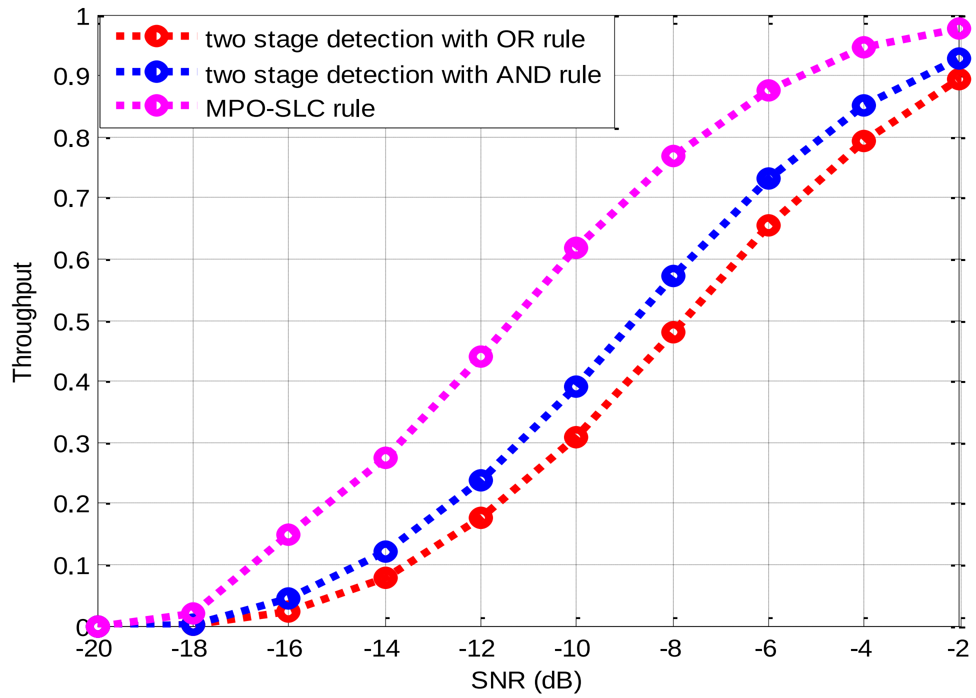

FIG. 4. TWO STAGE DETECTION, SNR VERSUS THROUGHPUT OVER RAYLEIGH FADING CHANNEL

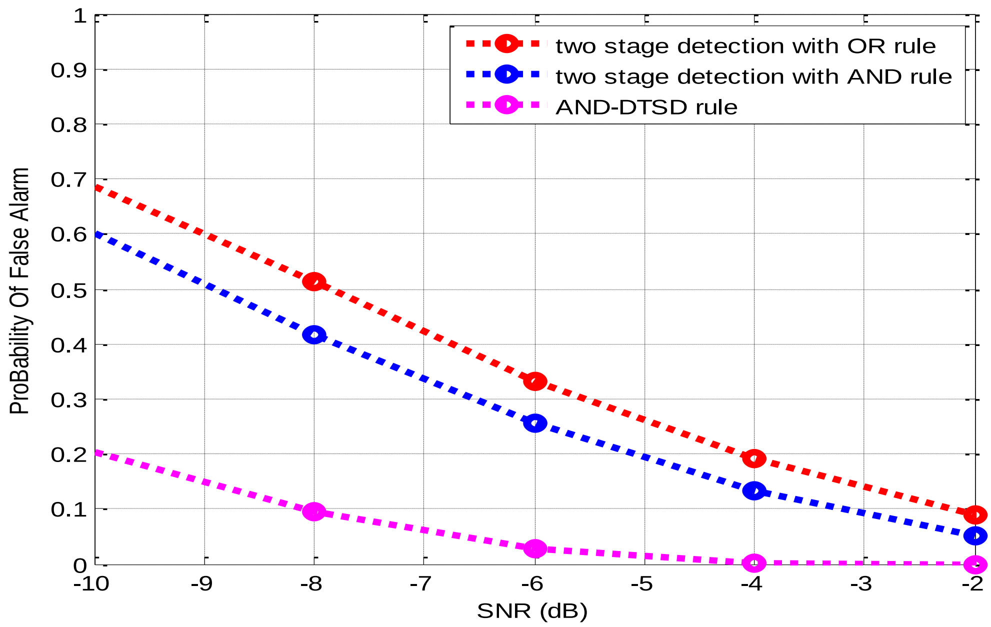

FIG. 5. TWO STAGE DETECTION, SNR VERSUS PROBABILITY OF FALSE ALARM OVER RAYLEIGH FADING CHANNEL

Fig.7 depicts the probability of false alarm versus signal to noise ratio over Rayleigh fading channel. As it clear in this figure, MPO-DTSD rule achieves better performance than OR-SLC and AND-SLC rules. The proposed rule significantly enhances the probability of false alarm over OR-SLC and AND-SLC rules. It offers practical operation values of P_{FA} in a very small values of SNR. For example at -10 dB the proposed rule is 5×10^{-2} while for OR-SLC and AND-SLC are 0.69 and 0.6 in respectively.

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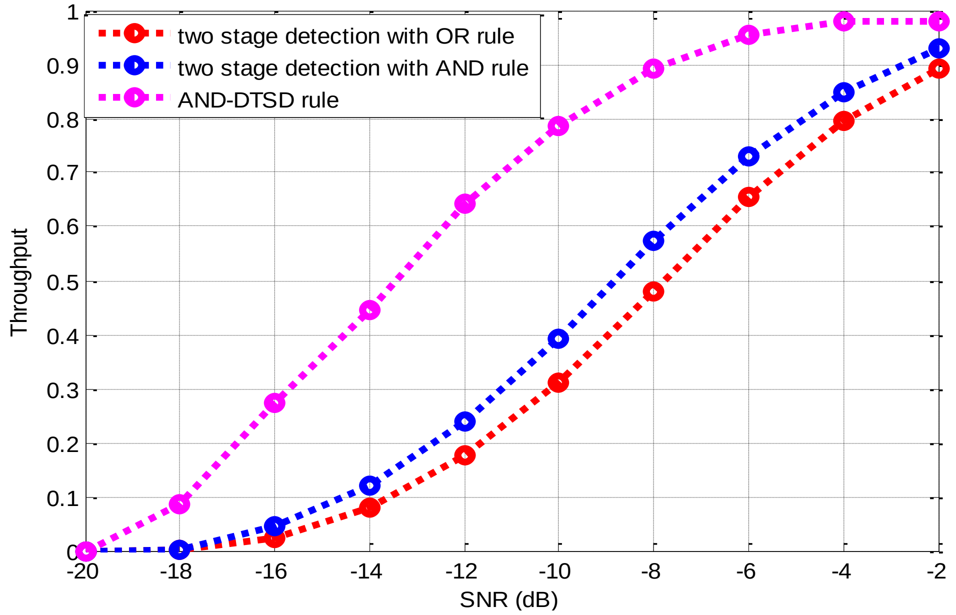

FIG. 6. TWO STAGE DETECTION, SNR VERSUS THROUGHPUT OVER RAYLEIGH FADING CHANNEL

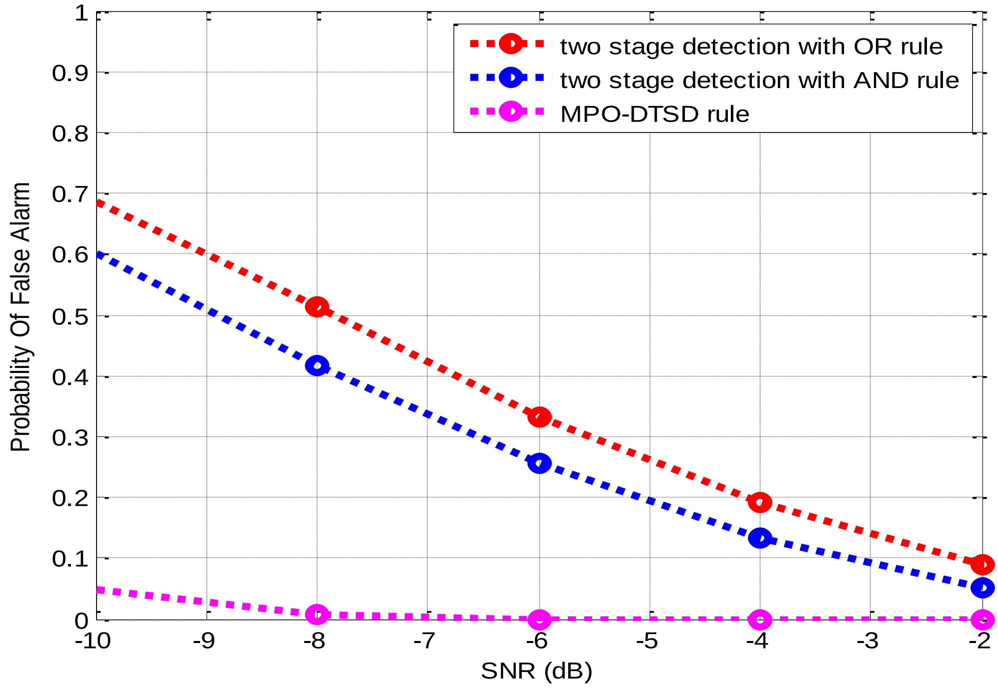

FIG. 7. TWO STAGE DETECTION, SNR VERSUS PROBABILITY OF FALSE ALARM OVER RAYLEIGH FADING CHANNEL

Fig.8 presents the throughput versus SNR for the OR-SLC and AND-SLC methods and the proposed one. It is clear in this figure that the proposed method has superior throughput as compared with OR-SLC and AND-SLC methods. It can be also noticed that the achievable throughput improvement occurs at very severe noisy conditions (SNR less than -18 dB). For example when SNR= -10 dB the enhancement of throughput for proposed method over OR-SLC and AND-SLC rules by 210% and 135% respectively. Table I summarizes the enhancement of the proposed rules as compared with traditional rules in the two stage decision. It is clear that the processing time for MPO-SLC rule is smaller than the processing time in AND-DTSD and MPO-DTSD rules. And MPO-DTSD rule achieve higher throughput enhancement.

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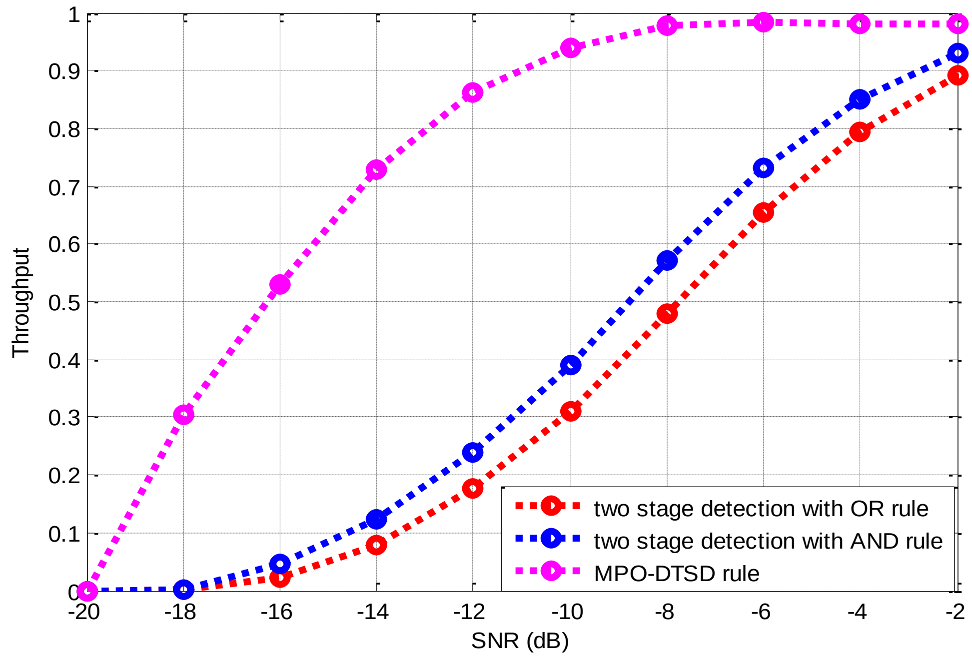

FIG. 8. TWO STAGE DETECTION, SNR VERSUS THROUGHPUT OVER RAYLEIGH FADING CHANNEL

TABLE I SUMMARY OF THE ENHANCEMENT OF THE PROPOSED RULES IN TWO STAGE DECISIONS

Method	Compared with	SNR (dB)	Throughput Enhancement Ratio	Processing Time (sec.)
MPO-SLC	OR-SLC	-10	106%	105.89
		-6	33.6%	
		-4	19%	
	AND-SLC	-10	58.9%	
		-6	19.8%	
		-4	11.1%	
AND-DTSD	OR-SLC	-10	163%	122.91
		-6	45.8%	
		-4	23.5%	
	AND-SLC	-10	97.5%	
		-6	30.7%	
		-4	15.4%	
MPO-DTSD	OR-SLC	-10	210%	108.22
		-6	50%	
		-4	23.6%	
	AND-SLC	-10	135%	
		-6	34.5%	
		-4	15.5%	

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V. CONCLUSIONS

Increasing the number of cognitive users and using suitable global decision rule can reduce the probability of false alarm and increase the throughput as well. The decision rules can be are either hard or soft. The use of mixed types of decision rules can improve the decision credibility and the throughput as a result. Three modified mixed-types of decision rules have been proposed and their performance have been investigated and compared to other mixed rules available in the literature over noisy and Rayleigh multipath channels. The proposed rules are not only mixing the hard and hard rule but they set a special criterion to save computations based on the value of detection probability. The results have showed that all the three proposed decisions improve the throughput and enhance the performance over traditional mixed-types rules with different percentages. Among these rules, the third proposed rule which combines MPO hard rule and DSTD soft rule offers the best improvement.

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