

## Adaptive Double Threshold based Spectrum Sensing for Cognitive Radio Networks

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### Abstract

Rapid growth of wireless communication and limited spectrum availability to support the applications and services, has led to the development of cognitive radio as promising solution to address the problem of spectrum scarcity. Spectrum sensing is one of the fundamental functions towards the implementation of the cognitive radio concept in wireless communication. In this paper, we present an adaptive double threshold based spectrum sensing utilizing fuzzy logic. It is shown that the proposed scheme achieves enhanced detection performance under noise uncertainty at a given  $P_f$  and also overcomes the problem of spectrum sensing failure. In this scheme, fuzzy logic is implemented at individual CR and the implementation of fusion center for decision making is done away with. Hence, overheads are reduced as compared to existing techniques. Probability of detection, probability of false alarm, and SNR are used as performance metrics. Simulation results shows that proposed scheme outperforms conventional and Cooperative sensing with single threshold, schemes by 33% and 16% at  $-5$  dB SNR, respectively

We have further implemented cooperative sensing along with the proposed scheme using fusion center and compared with recent techniques. It is further found that CSS with proposed scheme provides 8% , 33.3% and 16% improvement in detection as compared to that for cooperative CED with MRC and OR scheme and Hierarchical scheme at  $-8$ dB SNR, respectively. Since, in proposed scheme, only one bit decision is sent by each CR to fusion centre, hence communications overheads are also reduced as compared to MRC and Hierarchical scheme.

**Keywords:** Spectrum sensing techniques, Energy detector, Adaptive double threshold, Cooperative spectrum sensing

### 1. Introduction

During the last few decades, rapid growth of wireless services has increased the demand for radio spectrum dramatically and this trend is expected to continue in coming years with the emergence of new wireless devices and applications. In the conventional approach of spectrum allocation, a certain frequency band of spectrum is licensed or assigned exclusively to specific operators called primary users. Most of the useful spectrum is either licensed or already in use. Even license-exempt band such as Industrial, Scientific and Medical band (2.4 GHz ISM band) has also become overcrowded. Thus it is becoming very difficult to find vacant frequency bands to either deploy new services or enhance existing ones. On the other hand, a FCC report shows that a large portion of the assigned spectrum remains underutilized [1]. Usage of spectrum ranges from 15-85% depending upon temporal and geographical variations. This inefficient use of the scarce natural resource-radio spectrum necessitates a new paradigm for the flexible use of the most suitable and available bands.

Cognitive radio is a novel technology paradigm towards efficient use of spectrum. The main idea of this technology is to properly sense the spectral conditions over a wide bandwidth, identify the presence or absence of licensed user and use the licensed spectrum without any interference to any licensed user [2]. In basic terminology, licensed users are known as primary users (PU) and cognitive radios are low preference secondary users (SU) which use spectrum only after ensuring the non interference to primary users. Key to successful operation of cognitive radio is to reliably identify unused frequency bands and this task is performed by spectrum sensing techniques. There are many spectrum sensing techniques available in the literature. Some of them are Energy Detection, Cyclostationary based detection, Matched Filter and Covariance based detection [3].

Energy detection (ED) is quite popular due to its simple implementation, fast sensing speed and no requirement of priori information about primary user [4, 5]. However, performance of ED is limited by noise uncertainty since perfect noise variance information is required in this scheme. Further, multipath fading, shadowing and hidden node problems also degrade the performance of single user spectrum techniques [5]. One possible solution to overcome these problems is Cooperative spectrum sensing (CSS) [6, 7]. In this technique, sensing information available at different locations are used collaboratively for determining the decision of spectrum availability, thus provides the diversity gain and improves accuracy [8-10]. However, this performance improvement is achieved at the cost of increased overhead. Various techniques are proposed in literature to remove noise uncertainty problem [11-14]. Double threshold based sensing mitigates noise uncertainty problem. But, when all measured values lie between two thresholds then it causes Spectrum sensing failure problem [15-17].

Recently research on applying fuzzy logic to cognitive radio networks is emerged since this technique can provide a tool for building a framework for the systems where target problems are difficult to model because of vagueness and ambiguity. Fuzzy theory also helps dealing with noise uncertainty or uncertain conditions in case of fast changing RF environment. This technology is applied to many areas of cognitive radio network including cross layer optimization, spectrum access, and spectrum handoff [17, 18]. However, there is large scope for utilizing the potential of fuzzy logic towards improving the spectrum sensing techniques. In this paper, we investigate spectrum sensing problem with the objective of achieving enhanced detection accuracy in the presence of noise uncertainty and to overcome spectrum sensing failure problem. In the proposed scheme, the implementation of fusion center for decision making is done away with and fuzzy logic is implemented at individual CR. performance metrics used are probability of detection ( $P_d$ ), probability of false alarm ( $P_f$ ), and SNR.

The rest of the paper is structured as follows: Section 2 highlights the related work on energy detection, double threshold based spectrum sensing and spectrum sensing failure problem, Section 3 describes the system modeling for energy detection based spectrum sensing technique. In Section, proposed spectrum sensing techniques has been presented. Section 5 gives the idea about cooperative detection with proposed scheme. Numerical results are presented and analyzed in Section 6. Finally conclusions are drawn in Section 7.

## 2. Related Study

Energy detection (ED) is widely used for spectrum sensing due to its low sensing period, low complexity, low computational and implementation cost. Moreover, ED has been a preferred approach because of its ability to work even when any prior information about the signal is not available. Conventional energy detector (CED) uses one threshold [4]. For reliable spectrum sensing it is desirable to set optimum threshold level since sensing performance depends on the threshold level. Due to noise uncertainty, it is difficult to set optimum threshold hence reliability degrades.

Moreover, at low SNR this uncertainty about the noise distribution leads to an SNR Wall which is the SNR below which robust detection is impossible for the given detector [4].

Several ideas have been proposed in literature to mitigate noise uncertainty in cooperative CR systems [11-14]. In [11] a cooperative sensing based on ED with three thresholds is proposed to deal with noise uncertainty. Covariance and eigenvalue based cooperative detection technique is proposed in [12]. In [11, 12], sensing decisions taken by individual users are forwarded to fusion centre through reporting channels. Hence more bandwidth of control channel is occupied and overheads are increased. A censoring based double threshold method is discussed for reducing the overhead at the cost of performance loss [13]. The authors in [14] have shown the increased performance using 'n ratio based logic with two thresholds. But when all detected values lie between two thresholds, then no value is sent to fusion centre which causes spectrum sensing failure. Spectrum sensing failure problem is solved by sending detected values between two thresholds to fusion centre [15]. This scheme increases system hardware requirement as fusion centre is needed to take final decision. In [16], spectrum sensing failure problem is solved by individual user taking only the difference of measured energy and threshold value into consideration. But this is not sufficient to quantify the reliability of each secondary user in confused region which lies between two thresholds. It indicates that more parameters are required to quantify the reliability of each SU.

In [18], a new combining scheme is proposed for cognitive spectrum sensing based on fuzzy logic. This approach provides good sensing performance and high the flexibility for decision fusion. However, in most of papers, fuzzy logic is implemented at fusion centre. If fuzzy logic is implemented at node level, it can further improve the performance by improving local sensing results. In our proposed scheme, fuzzy logic is applied at individual CR to take final sensing decision in confused region. Hence, no fusion centre is needed to resolve spectrum sensing failure problem. Moreover, Cooperative sensing using fusion centre with proposed scheme further increase the performance.

### 3. System Modeling

Spectrum sensing can be classified as decision making problem which involves estimation at first stage followed by a decision stage. The secondary network needs to make a decision between two hypotheses deciding if the band is vacant or occupied.

We assume that  $x(t)$  is the signal transmitted by the primary user,  $h(t)$  is the impulse response of channel,  $w(t)$  is additive white Gaussian noise (AWGN) with mean zero and variance  $\sigma_n^2$  and  $y(t)$  is a signal received by user that consists of signal plus noise.

For detecting a primary user signal at  $n$ th time instant, secondary user needs to discriminate between the following two hypotheses:

$$y(n) = \begin{cases} w(n) & H_0 \\ x(n)h(n) + w(n) & H_1 \end{cases} \quad (1)$$

$H_0$  is the null hypothesis which indicates that primary user does not communicate and  $H_1$  is the alternative hypothesis that indicates the existence of the primary user.

Spectrum sensing with Energy Detection is described in the next section:

#### 3.1. Energy Detector with Single Threshold

Energy detection is a simplest and optimal way to detect PU when no priori information of the PU is available to SU. In this technique, energy of the received signal

is measured over a specified observation time [4,6] . Output of the energy detector can be given in time domain as follows:

$$E = \sum_{n=1}^N |y(n)|^2 \quad (2)$$

Where N is number of samples.

This energy is compared with a threshold  $\lambda$  for deciding the presence or absence of the PU as illustrated in Figure 1. We consider a signal of bandwidth W. According to the Sampling Theorem, in order to represent the energy of infinite number of terms over a duration T, we need approximately  $2u$  sample where  $u = TW$ , defined as time bandwidth product [4].

For hypothesis  $H_0$ , primary signal is not transmitted and only noise is present. In this case, Test statistic  $Y$  is the sum of the squares of  $2u$  Gaussian variables with zero mean and  $\sigma_n^2$  variance. Therefore, statistic  $E$  follows a central chi-square ( $\chi^2$ ) distribution with  $2u$  degrees of freedom. For hypothesis  $H_1$ , received signal is the sum of signal and noise. Here, the decision statistic  $E$  will follow a non-central  $\chi^2$  distribution with  $2u$  degrees of freedom and a non-centrality parameter  $2\gamma$  [4].

$$E \sim \begin{cases} \chi_{2u}^2, & H_0 \\ \chi_{2u}^2(2\gamma), & H_1 \end{cases} \quad (3)$$

Therefore, with a given decision threshold  $\lambda$ , the  $P_d$  can be expressed as [4]

$$P_d = P(E > \lambda | H_1) = \int_{\lambda}^{\infty} Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) f(\gamma) dx \quad (4)$$

Where  $Q_u$  is the generalized Marcum Q-function,  $\gamma$  is the SNR and

$$f(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right), \gamma \geq 0 \quad (5)$$

is the probability density function (PDF) of the channel effect with the average SNR  $\bar{\gamma}$ . Probability of false alarm can be computed by

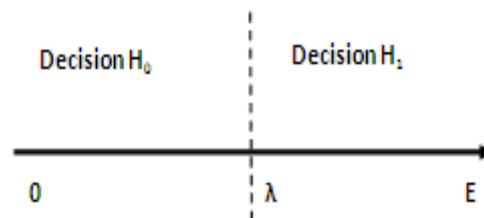
$$P_f = P(E > \lambda | H_0) = \int_{\lambda}^{\infty} f_{\chi^2}(y) dy = \frac{\Gamma(u, \lambda/2\sigma_n^2)}{\Gamma(u)} \quad (6)$$

where  $\gamma$  is the SNR.  $\Gamma(\cdot)$  and  $\Gamma(\cdot, \cdot)$  are complete and incomplete gamma functions [4].

For a given  $P_f$ , the threshold  $\lambda$  can be computed as

$$\lambda = 2\sigma_n^2 \Gamma^{-1}(u, P_f \Gamma(u)) \quad (7)$$

where  $\Gamma^{-1}(\cdot, \cdot)$  is the inverse of the incomplete gamma function.



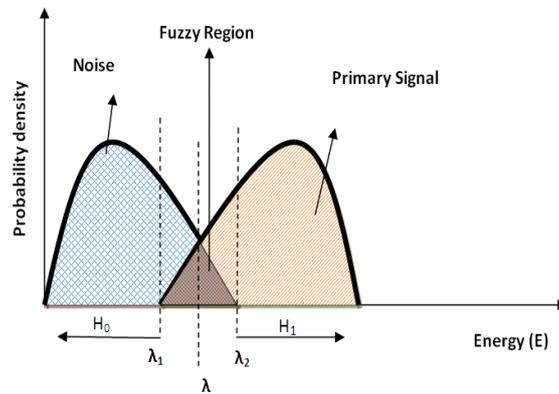
**Figure 1. Single Threshold Energy Detection**

This technique has low complexity, ease of implementation and faster decision making capability. But in case of noise uncertainty it is difficult to set this threshold optimally.

### 3.2. Energy Detector with Double Thresholds

To overcome noise uncertainty problem, two thresholds are used in [11-16]. However, the use of two thresholds causes the problem of confused or fuzzy region. This is the region that lies between two thresholds. If detected values lie outside the fuzzy region, it will generate 0 or 1 depending upon the presence or absence of PU signal. However, if test statistics falls in this fuzzy region, either this information is ignored for reducing overhead purpose or detection decision is taken in cooperative manner. In case, the information is ignored, then accuracy of spectrum sensing is compromised. Moreover, if all detected values lie in fuzzy region, then no information is available for taking decision which causes spectrum sensing failure problem [14].

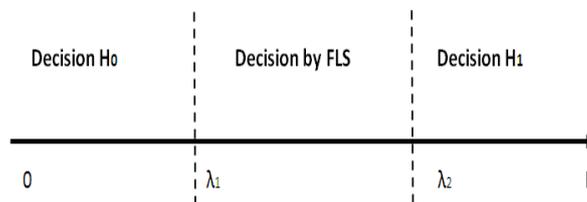
If the decision is taken in cooperative manner, multiple CRs with fusion centre is required, which increases system requirement [15]. In [16], decision is taken by single user but it considers only difference between measured value and threshold.



**Figure 2. Energy Distribution of Noise and Primary User Signal**

In the proposed scheme, each CR user detects PU signal and makes final decisions individually. It implements the decision through fuzzy logic and does not require FC, finally resulting in increased detection accuracy.

The novelty of our work lies in the fact that if Test statistics lies within confused region, the final decision will be taken fuzzy logic system as shown in figure 2 with two parameters. The two parameters are credibility of individual user, and SNR of individual user. In present context, credibility is defined as closeness of test statistics to higher threshold. In the related available literature to the best of our knowledge, fuzzy logic is implemented at fusion centre for spectrum sensing purpose. In the proposed scheme fuzzy logic is implemented at individual user for taking decision.



**Figure 3. Double Threshold ED with FLS**

To represent noise uncertainty, the estimated noise variance is assumed on the interval  $[(1-\rho)\sigma_n^2, (1+\rho)\sigma_n^2]$  where  $0 < \rho < 1$  is a parameter that quantifies the noise power

uncertainty. In this paper, the lower threshold  $\lambda_1$  is chosen in accordance with the lower limit of noise variance, and the upper threshold  $\lambda_2$  is chosen in accordance with to the upper limit of noise variance.

Hence,

$$\lambda_1 = 2(1 - \rho)\sigma_n^2\Gamma^{-1}(u, P_f \Gamma(u)) \quad (8)$$

$$\lambda_2 = 2(1 + \rho)\sigma_n^2\Gamma^{-1}(u, P_f \Gamma(u)) \quad (9)$$

Decision by Energy Detector is determined as the following rule:

$$D = \begin{cases} 1 & \text{if } E > \lambda_2, H_1 \text{ declared : channel occupied} \\ F & \text{if } \lambda_1 < E < \lambda_2, \text{ Fuzzy decision} \\ 0 & \text{if } E < \lambda_1, H_0 \text{ declared : channel vacant} \end{cases} \quad (10)$$

where  $E$  is test statistics for ED.

$F$  is decision taken by fuzzy logic system as follows:

$$F = \begin{cases} 1 & \text{if } P > \lambda_F, H_1 \text{ declared : channel occupied} \\ 0 & \text{if } P < \lambda_F, H_0 \text{ declared : channel vacant} \end{cases} \quad (11)$$

Here,  $P$  is output of fuzzy logic system defined as possibility of presence of primary user and  $\lambda_F$  is threshold set for taking decision by fuzzy logic system. In our case, we set  $\lambda_F = 0.5$ . Final decision will be:

$$O = D + F \quad (12)$$

$$O = \begin{cases} D + F > 0, H_1 \text{ declared : channel occupied} \\ \text{else , } H_0 \text{ declared : channel vacant} \end{cases} \quad (13)$$

where  $D$  and  $F$  are mutually exclusive events.

#### 4. Proposed Spectrum Sensing Using Fuzzy Logic with Double Thresholds

Figure 4 shows the proposed scheme for signal embedded with noise in Rayleigh channel.

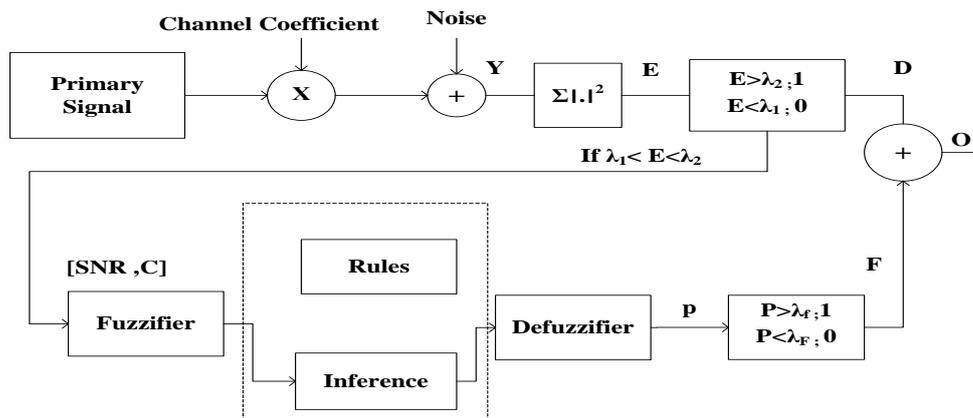


Figure 4. Block Diagram of Proposed Scheme

The square law device detects the signal and gives energy  $E$ . If this energy  $E$  is greater than  $\lambda_2$ , then  $H_1$  is declared or if less than  $\lambda_1$ , then  $H_0$  declared.

However, if  $E$  lies between  $\lambda_1$  and  $\lambda_2$  then fuzzy logic system is invoked to take decision in confused region. Fuzzy being a multi-valued logic may consider multiple input parameters for decision making.

In the proposed system, decision is taken on the basis of following two antecedents

Antecedent 1: Credibility

Antecedent 2: SNR at secondary user

There is one consequent i.e. output of fuzzy logic as follows:

Consequent: Possibility of presence of primary user.

It is denoted by  $P$ .

In CED, only comparison between measured energy and threshold is considered. However, if measured energy is less than threshold but difference of both is very less, then there may be the possibility of the presence of signal. We have considered this difference in terms of credibility. If  $E$  lies between  $\lambda_1$  and  $\lambda_2$  then credibility  $C$  is defined as

$$C = \frac{(E - \lambda_1)}{(\lambda_2 - \lambda_1)} \quad (14)$$

If  $C$  is large, it implies that,  $E$  is close to higher threshold. In view of this, the credibility reflects the measure of closeness of decision to  $H_1$  or  $H_0$ . If credibility is high, it means decision is closed to  $H_1$ . If credibility is low, then decision is close to  $H_0$ .

SNR of SU is again important parameter for PU detection. In Soft combination scheme like MRC, Optimal soft combining scheme, optimal cooperative sensing, and each user is required to send its SNR measurement to fusion centre along with raw data or normalized energy [17], which requires extra bandwidth. In proposed scheme, SNR is used at sensing node itself for taking appropriate decision in confused region. It thus saves bandwidth and improves the detection performance at local level.

SNR at  $k$ th Cognitive user is given as

$$Y_k = \frac{\sigma_{s,k}^2}{\sigma_{n,k}^2} \quad (15)$$

where  $\sigma_{s,k}^2$  signal power is received and  $\sigma_{n,k}^2$  is noise power received at SU.

The linguistic variances used to represent the Credibility, SNR are divided into three levels: low, moderate, and high. The consequence  $P$  is divided into five levels: very low, low, medium, high and very high. Membership functions (MFs) used to represent antecedent and consequent variables are shown in Figure 5. The inference method used is Max- Product and Centroid method is used as defuzzification method.

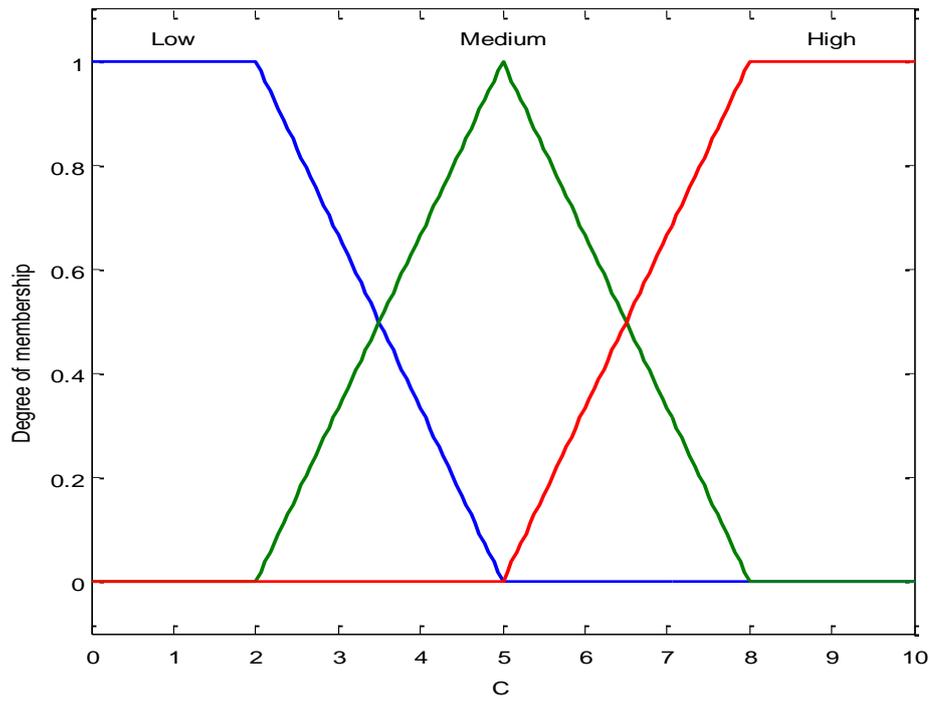


Figure 5(a). MF of Antecedent 1 (Credibility)

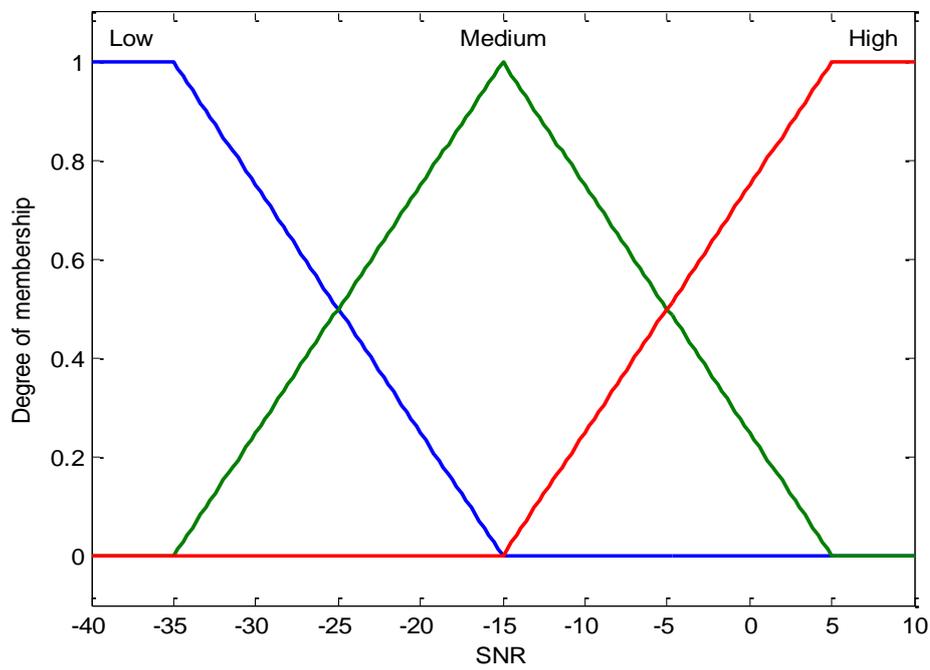
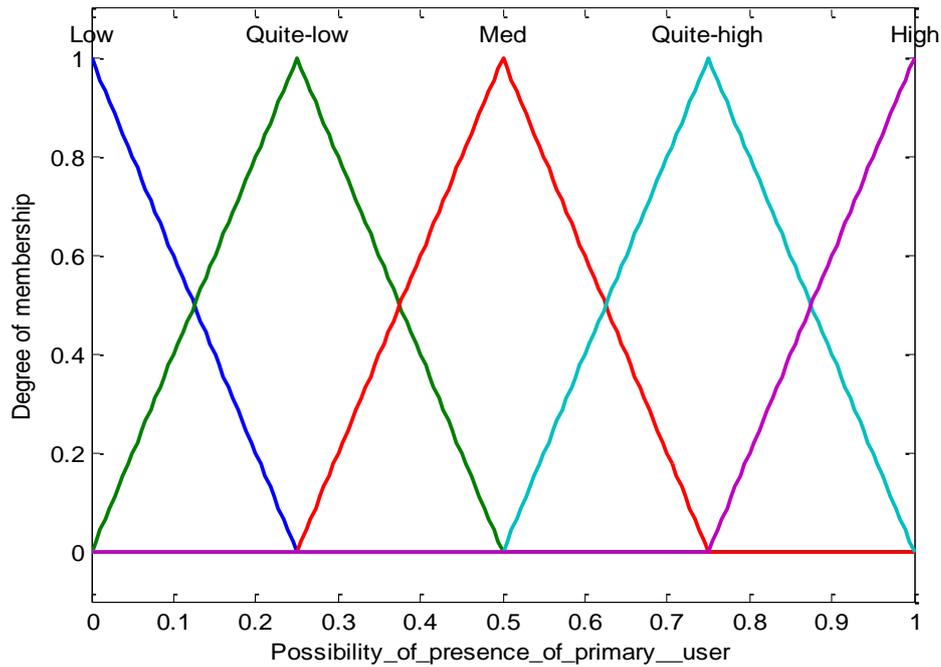


Figure 5(b). MF of Antecedent 2 (SNR)



**Figure 5(c). MF of Consequent (Possibility of presence of Primary User)**

As there are 2 antecedents and 3 fuzzy subsets, we need set up  $2^3 = 8$  rules are formulated. Rule base is shown in Table 1.

**Table 1. Rule Base for the Proposed FLS**

Antecedent 1 (Credibility)	Antecedent 2 (SNR)	Consequent (Possibility of Presence of Primary user)
Low	Low	Low
Low	Medium	Quite Low
Low	High	Medium
Medium	Low	Quite Low
Medium	Medium	Medium
Medium	High	Quite High
High	Low	Medium
High	Medium	Quite High
High	High	High

**Algorithm**

**Proposed ED with Adaptive double threshold and fuzzy scheme**

1. Given N samples of signal  $\{x_1, x_2, x_3 \dots x_N\}$
2. Calculate  $\lambda_1$  and  $\lambda_2$  according to  $P_f$ , minimum and maximum noise variance.
3. Calculate Test statistic  $E(x)$  ← Energy of the signal
4. If  $E(x) \geq \lambda_2$ 
  - D ←  $H_1$
  - else if  $E(x) \leq \lambda_1$ 
    - D ←  $H_0$
  - else  $\lambda_1 < E(x) < \lambda_2$ 
    - i) Calculate credibility of user as  $(E - \lambda_1) / (\lambda_2 - \lambda_1)$
    - ii) Estimate SNR ( $\gamma$ ) of the link.
    - iii) Give inputs [ Credibility, SNR] to fuzzy logic based scheme and calculate Test Statistic P ← Possibility of presence of Primary user
    - iv) If  $P > \lambda_F = 0.5$ 
      - F ←  $H_1$
      - else
        - F ←  $H_0$

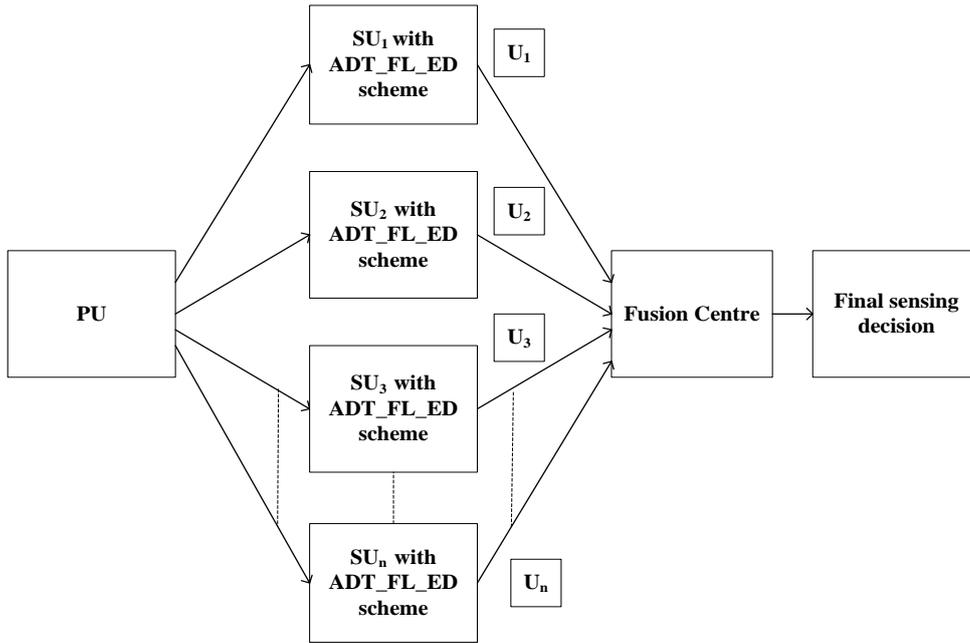
end if

5. Final decision  $O = D + F$

**5. Cooperative Detection with Proposed ADT\_FL\_ED Scheme**

The concept of cooperative sensing is to use multiple\_sensors and combine their measurements to take final decision to improve the performance [8-11]. The final decision making process can be categorized as soft combination or data fusion and hard combination or decision fusion. In data fusion, complete information from all cooperative users is sent to fusion centre where all information is combined according to some rule *e.g.* SNR based weight or equal weight etc. in MRC or EGC scheme respectively. Since complete data is transmitted to fusion centre, this scheme requires large bandwidth. In decision fusion or hard combination, decision is taken by cooperative secondary users at local level and one bit decision is transmitted to fusion centre where final decision is taken by combining all decisions according to AND, OR, and MAJORITY rule. AND rule declares the presence of primary signal when all the users indicate that signal is present. OR rule declares the presence of primary signal when at least one user indicates the signal is present. MAJORITY rule declares signal presence when more than half of users indicate that signal is present. Hard combination requires only one bit of overhead and low bandwidth control channel. But performance of decision fusion is poor in comparison to data fusion.

In this paper, we improved the performance of cooperative sensing with decision fusion using Adaptive threshold and fuzzy logic based Energy detector at each secondary user. We propose a new CSS technique utilizing adaptive threshold and fuzzy logic based ED at individual SU.



**Figure 6. Proposed CSS Scheme with ADT\_FL\_ED**

Assuming uncorrelated decision, probability of detection [14] for decision fusion is given by

$$P_{d,Coop} = \sum_{i=k}^n \binom{n}{i} P_d^i (1 - P_d)^{n-i} \quad (17)$$

Where  $P_d$  is probability of detection of individual user and  $n$  is total number of cooperative nodes. Performance of cooperation can be evaluated using OR rule by setting  $n=1$  in equation (18)

$$P_{d,OR} = 1 - (1 - p_d)^n \quad (18)$$

## 6. Results and Discussion

In this section, performance of our proposed scheme is evaluated and compared with CED through simulation and numerical results. Primary signal is QPSK with carrier frequency 1MHz. The sampling frequency is fixed at 50 MHz. Rayleigh channel with delay vector = [0, 4, 8, 12] microseconds, gain Vector = [0, -3, -6, -9] and Doppler shift of 4 Hz is used. In order to achieve the convergence, 1000 simulation runs were performed.

Membership function of credibility, SNR and possibility of presence of primary user is shown in Figure 5. Performance metrics are  $P_d$ ,  $P_f$  and SNR.

As shown in Figure 7 probability of detection is plotted as a function of SNR for CED, and proposed Adaptive threshold with fuzzy logic based detector for  $P_f=0.1$ . Proposed Scheme shows better result than conventional scheme. At SNR= -5 dB,  $P_d$  for CED is 0.6 while it is 0.9 for proposed scheme which is the spectrum sensing requirement of IEEE 802.22. Figure 8 shows the performance of proposed scheme at different  $P_f = 0.001, 0.05, 0.01$  and  $0.1$ . Performance depends upon required false alarm probability. Low value of  $P_f$  is desirable but it reduces  $P_d$  also. Proposed scheme gives  $P_d=0.9$  for  $P_f=0.001$  at SNR = -3dB.

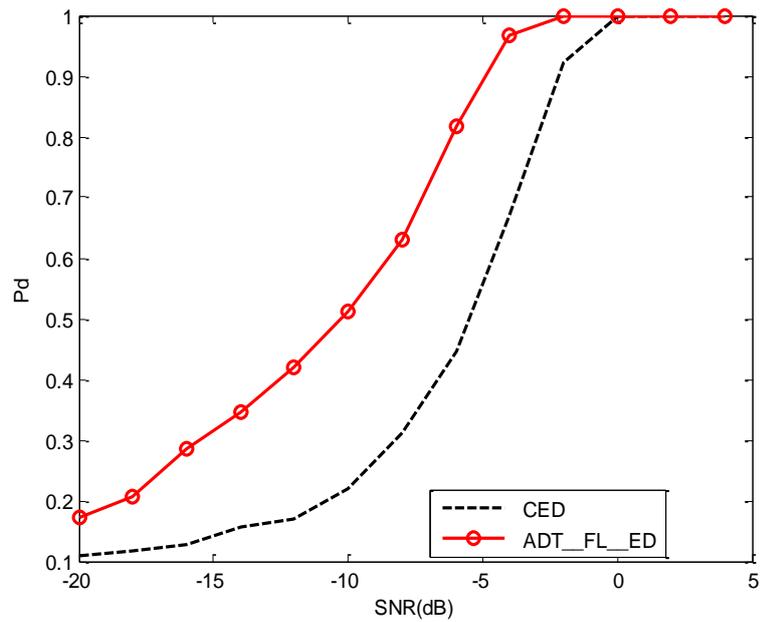


Figure 7.  $P_d$  versus SNR at  $P_f = 0.1$

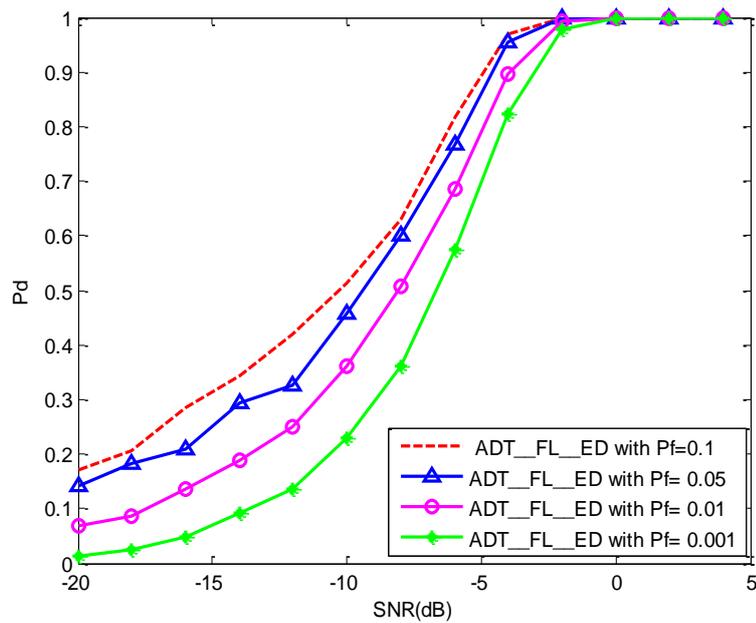
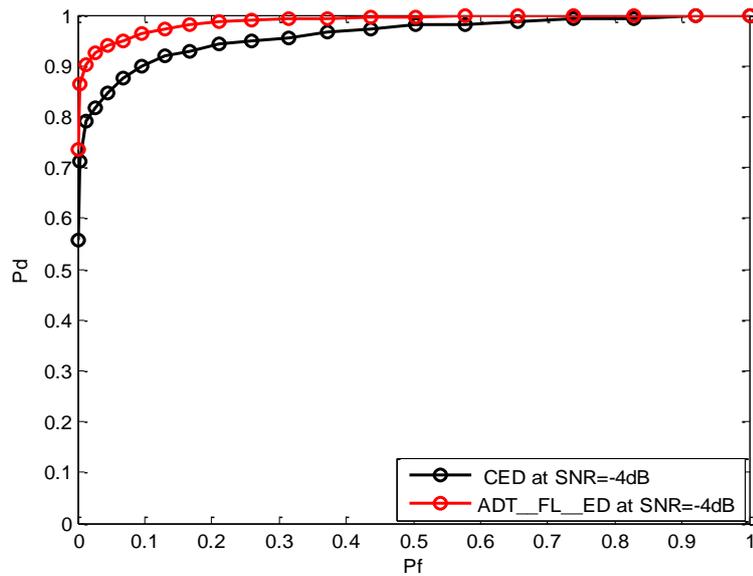
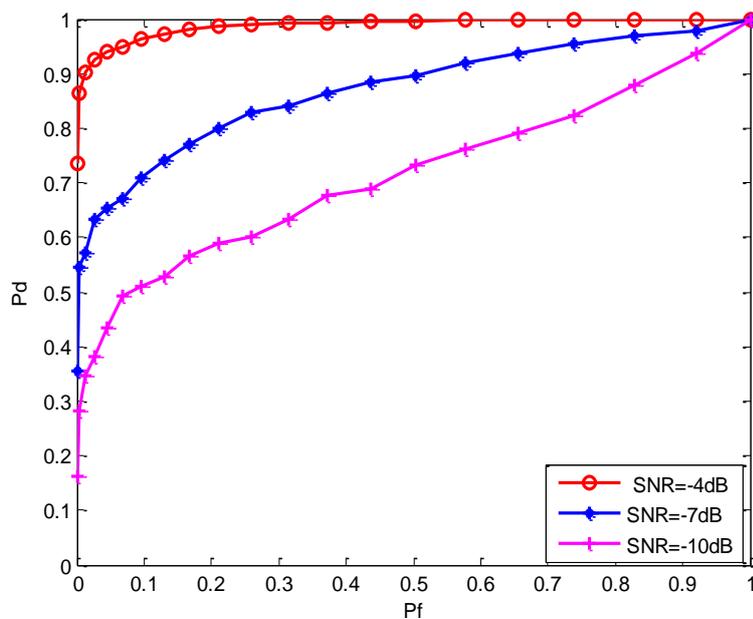


Figure 8.  $P_d$  versus SNR at  $P_f=0.1, 0.05, 0.01$  and  $0.001$

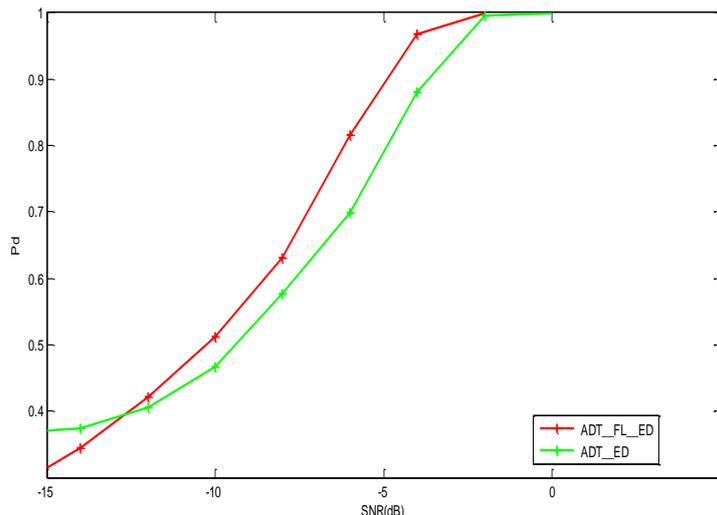


**Figure 9. ROC Curves of CED and ADT\_FL\_ED at SNR=-4 dB**

Figures 9 and 10 show the Receiver Operating Characteristics (ROC) curves depicting the relationship between  $P_f$  and  $P_d$  at a specific SNR value. Low value of  $P_f$  is desirable for increasing spectrum efficiency. From Figure 9 it is found that desired  $P_d = 0.9$  is available at  $P_f=0.001$  at SNR= -4 dB for proposed scheme while for CED, required  $P_f$  is 0.15 is for same desired  $P_d$  at same SNR. Fig 10 shows ROC curves at different settings of SNR for the proposed scheme. Figure 11 shows that in a given environment our proposed scheme outperforms the ADT\_ED scheme discussed in [16 ] after -12 dB. ADT\_FL\_ED gives desired  $P_d$  of 0.9 at -5 dB whereas ADT\_ED scheme gives same desired  $P_d$  at SNR= -3.7 dB.

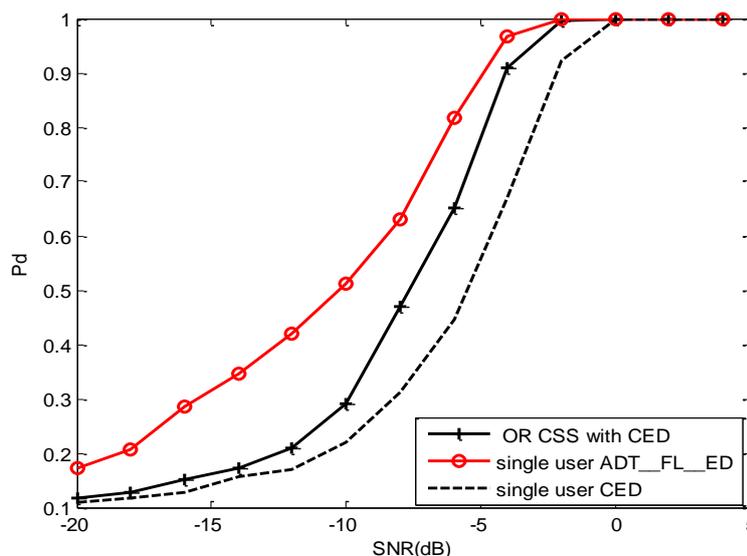


**Figure 10. ROC Curves for Proposed ADT\_EL\_FD at Different SNR**

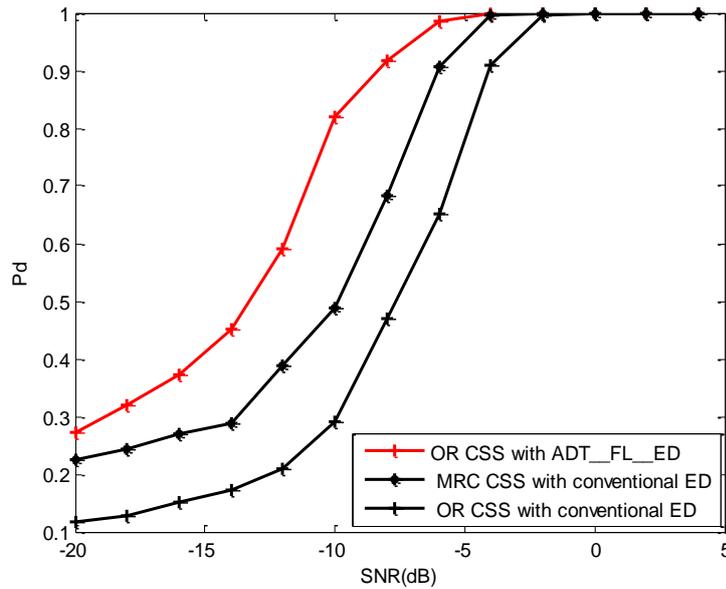


**Figure 11.  $P_d$  Vs SNR Curve for ADT\_FL\_ED and ADT\_ED Scheme for  $P_f=0.1$**

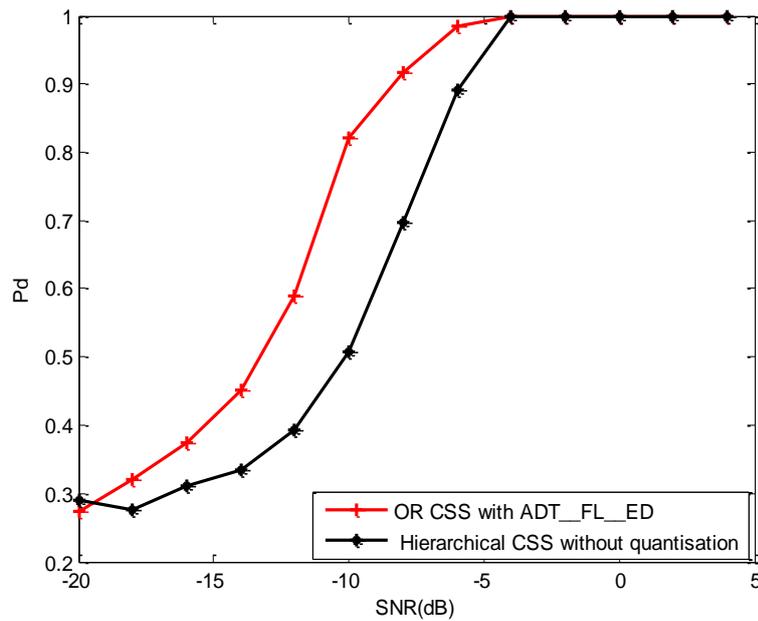
Figures 12, 13 and 14 depict result for cooperative detection. Only three CR users are considered for cooperation. Figure 11 shows that single user ADT\_FL\_ED gives better performance than cooperative CED with OR Hard combination scheme. It gives improvement of 16% and 33% as compared to CSS-CED and single threshold CED at  $-5$ dB SNR respectively. Figure 12 shows that Cooperative ADT\_FL\_ED with OR hard combination scheme outperforms Cooperative CED with MRC soft combination scheme and OR Hard Combination scheme by 8% and 33.6% at  $-8$  dB SNR, respectively. Figure 14 shows that in a given environment CSS with ADT\_FL\_ED outperforms the Hierarchical scheme discussed in [20] by 16% at  $-8$ dB. Moreover, The communications overheads are also reduced in the proposed scheme as compared to the MRC and Hierarchical scheme for given value of  $P_d$  as only one bit for local decision is sent to fusion centre.



**Figure 12.  $P_d$  versus SNR for CSS with CED at  $P_f = 0.1$ , Total Numbers of Cooperative CR Users  $k = 3$**



**Figure 13.  $P_d$  versus SNR at  $P_f = 0.1$  for CSS with ADT\_FL\_ED and CED, Total Numbers of Cooperative CR users  $k = 3$**



**Figure 14.  $P_d$  versus SNR at  $P_f = 0.1$  for CSS with ADT\_FL\_ED and Hierarchical, Total Numbers of Cooperative CR Users  $k = 3$**

## 7. Conclusion

In this paper, we have proposed an adaptive double-threshold and fuzzy logic based energy detection scheme for spectrum sensing. The sensing failure problem in confused region is solved using fuzzy logic without implementing the fusion center. Numerical results show that proposed ADT\_FL\_ED scheme outperforms CED and CSS with single threshold, schemes by 33% and 16% at  $-5$  dB SNR, respectively. We have further implemented ADT\_FL\_ED with decision fusion based cooperative sensing. In this

strategy, decision of each CR is reported to FC to make the final decision about the primary user signal detection. It further shows 8%, 33.3% and 16% improvement in detection as compared to that for cooperative CED with MRC and OR scheme and Hierarchical scheme at  $-8\text{dB}$  SNR, respectively. Communications overheads are also reduced as compared to MRC and Hierarchical scheme. Our results also indicate that the proposed scheme helps in mitigating the effect of noise uncertainty and achieves better detection performance.

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