Spectrum Sensing Using Cooperative Matched Filter Detector in Cognitive Radio

Ayoob Aziz[1], Ghaith Khalil[2]* and Zozan Ayoub[3]

[1]Information and Telecommunication public (ITPC), Ministry of Communication, Nineveh, Iraq; ayoobazeez@yahoo.com

[2]Faculty of Engineering and Information Technology, University of Melbourne, VIC, Australia; ghkhalil1976@gmail.com

[3]Computer Engineering Department, College of Engineering, University of Mosul, Iraq; zozanazeez1@gmail.com

*Corresponding Author: ghkhalil1976@gmail.com

Abstract: The vast rise in the number of internet-connected devices necessitates a more accessible spectrum. As a result, Cognitive Radio was already proposed as a solution to the problem of restricted spectrum resources by utilizing available spectrum which is assigned to primary users. This method allows the secondary user to utilize the spectrum whenever the primary user is not using it, and it does so without intruding with the primary user. Whenever the secondary user detects the spectrum, it faces many issues, such as complexity in sensing, leading to a lack of noise value, and the primary user is hidden to all secondary users. In order to tackle these challenges, many spectrum sensing frameworks were introduced in the literature. In this paper, an adaptive threshold matched filter detector and a cooperative matched filter detector frameworks are utilized to detect the spectrum and resolve the issues above. The probability of detection (Pd), probability of miss detection (Pm), and probability of false alarm (Pf) are the metrics used to assess sensing accuracy. To simulate suggested detectors results and proficiency, the MATLAB R2020a software was utilized. In comparison to earlier studies, the simulation conclusions reveal that the detection process starts with lower SNR values compared to previous work.

Keywords: Cognitive Radio; MATLAB; WSN; Spectrum Sensing; Radio Frequency; Cooperative Matched Filter Detector

1. Introduction

In the last decades there was a revolution in wireless communication technology between a large variety of devices. The technology targeted the speed and reliability and made the communication between these devices more reliable, fast, and secure. This affects the speed of sending and receiving data and productivity due to many devices connected together at the same time. Cognitive radio on the other hand is a technology that takes advantage of unused spectrum that is already owned by primary user (PU) and solves the problem of spectrum scarcity.

In other words, Cognitive Radio (CR) is an intelligent wireless communication technology that recognizes which communication channels are used so the transceiver can instantly move into a different and a free channel to avoid the occupied ones. It is improving the use of the spectrum and reducing its scarcity. This happens when enabling a secondary user (SU) to use the idle spectrum that is unused by PU [1]. Please see figure (1).

The Cognitive Radio is known to be reliable, low in cost, has a simple network architecture, it improves link reliability, easy in configuration, easy to upgrade, uses advanced network topologies and it offers better spectrum utilization and efficiency [17].

As seen in Figure (2), the primary functions of CR are spectrum sensing, spectrum sharing, spectrum mobility and spectrum management. Spectrum sensing involves performing a spectrum scanner to determine whether there are parts of the spectrum that are unused by PU so that they can be reused by SUs. This should be done conditionally, whereas PU is not affected [2,3].

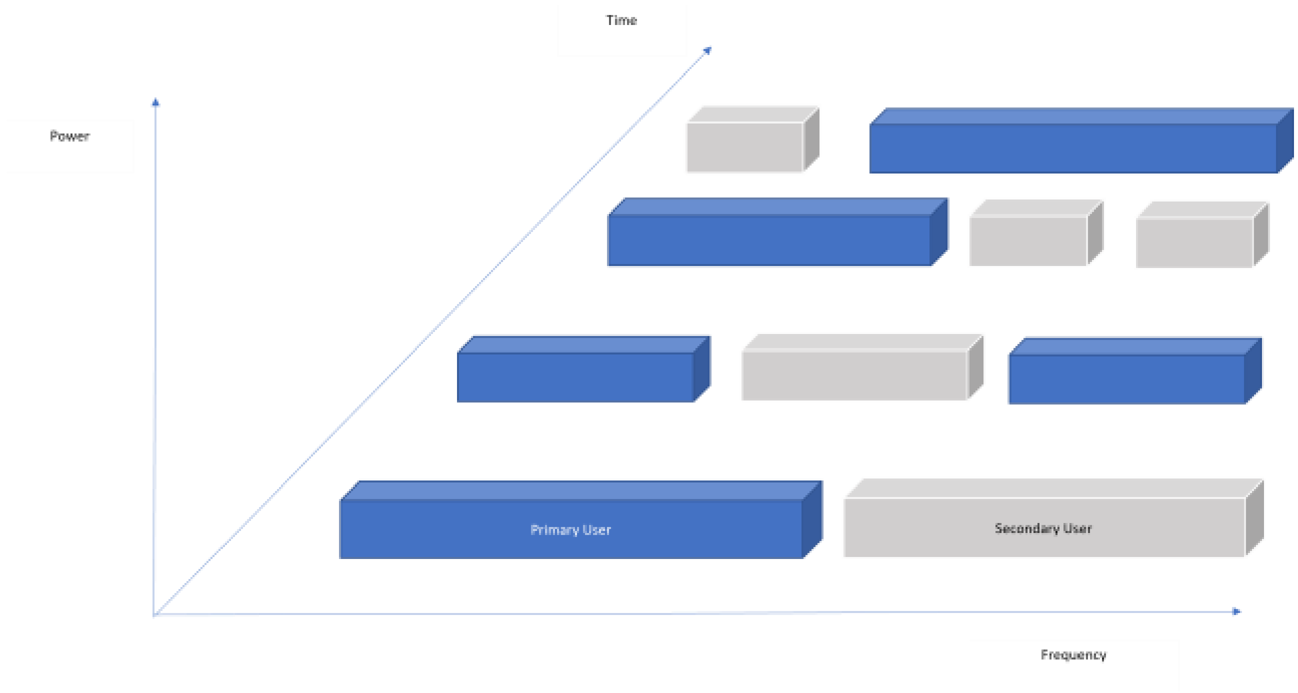

Figure (1): The cognitive radio behavior

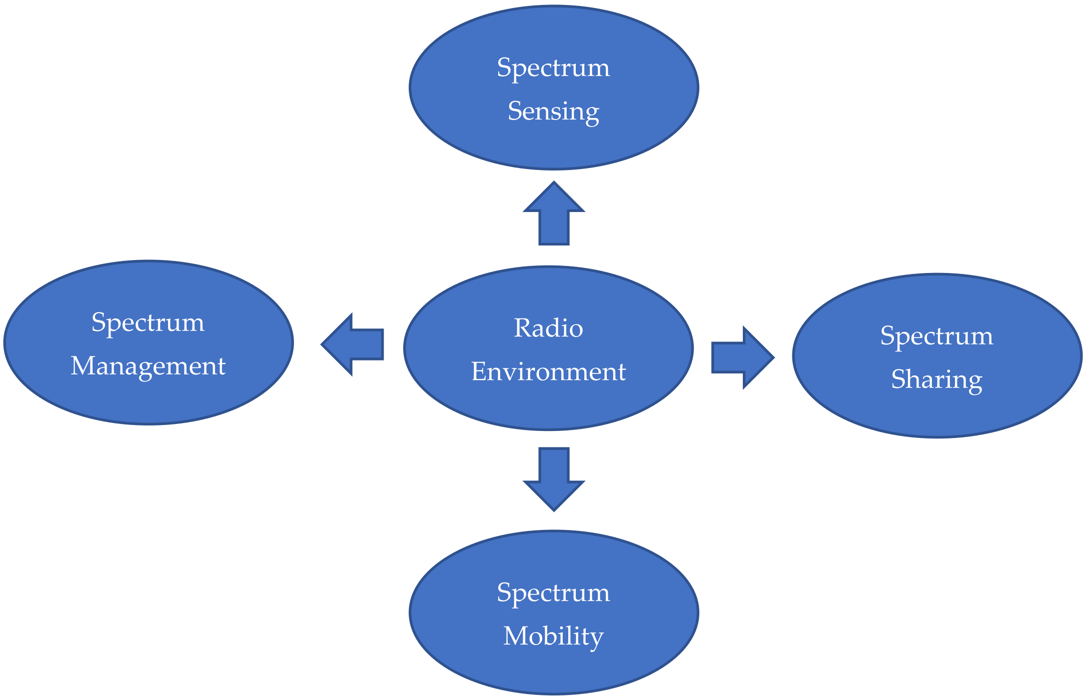

Figure 2. Functions of cognitive radio

Spectrum sharing is the process whereby the holes in the spectrum are reasonably distributed to the unlicensed user. If many unlicensed users try to access the spectrum, then access to the CR network should be coordinated to prevent multiple users from colliding in overlapping portions of the spectrum. Not similar to spectrum sensing, which is used in the physical layer, and spectrum management, which is closely associated with upper-layer services. Spectrum sharing is identical to multi-user multi-access and resource allocation techniques in the MAC layer of current communication systems [4,5].

Spectrum mobility is responsible for maintaining continuous communication during SU movement from one channel to another. When a spectrum hole is detected and then allocated to SU, it can keep using this idle channel till PU starts transmitting again. At this point, SU must vacate the channel and move to another vacant channel.

Spectrum management is a procedure for spectrum analysis and judgment based on the spectrum sensor results, i.e., it is responsible for selecting the optimum channel from all spectrum sensing holes detected according to the Quality of Service (QoS) for communication that best meets the user's requirements [6]. In the CR system, the spectrum holes detected may disseminate in a wide band that may include both licensed bands and unlicensed bands [7].

The main objectives of this research are to solve two problems that inherited in CR and spectrum sensing techniques, these problems are:

Difficulty in the detection process due to the lack and uncertainty of the noise value. This leads to an increase in the probability of false alarm and probability of miss detection.

2- PU is invisible to all SUs (Hidden Node Problem), so it cannot be detected accurately. Where some SUs may declare that the channel is unoccupied by PU while the others are not, and this leads to a decrease in the probability of detection.

In this paper we will introduce a work based on a matched filter detector method (MFD) as it's the most effective in our opinion and the most accurate before giving a brief introduction and comparison between other spectrum sensing methods used in CR. Also, to handle the challenges of secondary users in detecting the spectrum issues, this paper employs an adaptive threshold matched filter detector and a cooperative matched filter detector to detect the spectrum as we will see in section four. In section three we will explain more on the use of MFD and its effectiveness before introducing our proposed scheme where we will adopt two solutions the first is Matched Filter Detector algorithm using an adaptive Threshold and a cooperative Matched Filter Detector algorithm using an adaptive threshold. In section four we will explain those two solutions supported by diagrams before we head to the discussions and results supported by graphs and tables in section 5, and finally we will conclude the paper in section 6. The next section will be discussing the related work conducted by other researchers in the same field.

2. Related Works

The matched filter detector was demonstrated in numerous studies from diverse angles. In [8], the authors proposed an Adaptive Threshold scheme for Matched Filter-based Detection over an Additive White Gaussian Noise channel to maximize the Probability of Detection for a given Probability of False Alarm in varying environmental conditions by implementing artificial neural networks. Observe that as the SNR increases, the probability of detection also increases for a fixed SNR equal to 30 dB.

In [9], the authors proposed spectrum sensing based on matched filter detection in CR networks which demonstrated good performance then a simulation is carried out to measure the performance of the matched filter to detect primary users over the AWGN channel. A higher probability of detection is obtained with a SNR of 25 dB. As the probability of false alarm increased, threshold values decreased. For a 0 dB SNR, the lower threshold is achieved for the probability of false alarm of 0.1. If the signal characteristics are known, the matched filter gives a better probability of detection.

In [10], the authors used a dynamic selection of the sensing threshold by measuring the power of noise present in the received signal using a blind technique in order to improve the detection performance. The proposed model was implemented and tested using GNU Radio software and USRP units. The signal was detected at an SNR of -10 dB when the probability of false alarm is 0.01 and at an SNR of -14 dB when the probability of false alarm is 0.02. The probability of detection corresponding to the sensing technique with a dynamic threshold reaches 100% for a value of SNR = −2 dB.

In [11], the authors used new multiple antenna elements (MAE) and matched filtering (MF) based spectrum sensing technique named MAE/MF, which is proposed for detection capability enhancement. Multiple antenna elements' utilization improves the received signal-to-noise ratio, which is proportional to the achieved antenna array gain. The likelihood ratio test is used to decide the presence or absence of the PU signal. Simulation results showed that the proposed MAE/MF technique outperforms the single antenna element based matched filter (SAE/MF) and other existing techniques in the state-of-the-art, especially at extremely low signal to noise ratios and with a limited number of received signal samples. At SNR = 6 dB, it becomes a probability of detection.

In [24] different primary radio user activity models were presented along with their classification. The paper also discussed those approaches which performed real implementation for spectrum occupancy along with spectrum bands on which the implementation was performed and location where implementation was carried out. Same in [25], were the authors highlighted some of the recent information theoretic limits, models, and designs of these networks.

In a different approach than our work in [26] the authors provided a systematic overview on CR networking and communications. They investigated the key functions of the physical (PHY), medium access control (MAC), and network layers involved in a CR design. Then they addressed the signal processing techniques for spectrum sensing in PHY layer, as well as cooperative spectrum sensing, and transceiver design for cognitive spectrum access.
Similar work was presented in [27], where the authors explained the fundamental signal-processing aspects involved in developing a fully functional cognitive radio network, including spectrum sensing and spectrum sculpting.
In [28], the authors introduced basic concepts of game theory, then explained how these concepts can be used in designing spectrum sharing protocols, with an emphasis on state-of-the-art research contributions in cognitive radio networking. In [29].

An important comparison between Energy Detection (ED) and Matched Filter Detection (MFD) was mentioned in [29] and [30] can be found in Table 1 below. The comparison will demonstrate which method is more reliable and which one is more feasible to be used based on the need of the designers, technology and based on the function that its used for.

Table 1 A comparison between Energy Detection (ED) and Matched Filter Detection (MFD).

Energy Detection (ED)		Matched Filter Detection (MFD)
1	Low operating cost	High operating cost
2	No prior knowledge is needed for PU.	Prior knowledge is needed for PU.
3	Uncomplicated and easy to implement	Complicated and not easy to implement
4	Low sensing accuracy. the sensing is not good with high noise and PUs cannot be detected with low SNR	High sensing accuracy, the sensing with high noise and PUs can be detected with low SNR
5	The time needed for sensing is long	The time needed for sensing is short
6	It is practically used	Not always practically used because PUs signals sometimes do not know in advance
7	It cannot distinguish between other SUs uses the channel and the PU	It can distinguish between other SUs uses the channel and the PU

3. Spectrum Sensing techniques and Important Terminologies

The Spectrum sensing techniques for cognitive radio can be classified based on the bandwidth of the spectrum of interest for sensing [31]. Below we will focus firstly on the detection methods used and we will name several techniques before we select the most efficient detection method in our opinion to concentrate on.

3.1 Detection Methods for Narrowband Sensing and Wideband Sensing

The spectrum sensing techniques can be classified into two types: narrowband and wideband [32] and [33]. The narrowband sensing analyses one simultaneous frequency channel while the wideband sensing analyses a number of frequencies at a time [34], the wideband sensing is not feasible for our work as it consumes more power and energy opposite to the narrowband sensing techniques. Some of the detection methods for wideband sensing are: FFT-based detector, Wavelet-based detector, Multi-coset sensing, Compressive sensing, and Filter-based detector. On the other hand, we can see many narrowband sensing techniques such as: Energy detection (ED), Matched filter detection (MFD), Cyclisationary feature detection and Eigenvalue base detection. In the next section we will focus on the narrowband practically the (MFD) for the reasons which we mentioned before.

3.3 Matched Filter Detector (MFD)

The Matched filter detector Method (MFD) is the most complex type of spectrum sensing technique and the most accurate. The sensing can give good results with high noise (low SNR) and PUs can be detected easily because the sensing time is short. It maximizes the signal-to-noise ratio at the output of the detector. However, it needs advanced knowledge of the primary user signal [12]. The MFD strategy can only be used when the prerequisite knowledge, such as: pilot carrier, modulation type, spreading codes, and pulse shape, is known. It can tell the difference between other SU uses of the channel and the primary user [13]. The MFD statistical test is given [14]:

$$A_{matched}[k] = h[k-n] * x[n], \tag{1}$$

Where x is the received signal, * is the convolution and h is the impulse response.
The mathematical equation that is used for calculating the adaptive threshold (AT) level for the MFD is given in Equation (2) [15]:

$$\mathrm{AT_{matched}} = \mathrm{Q}^{-1}(\mathrm{P_f})\sqrt{\mathrm{E}\sigma^2}, \quad (2)$$

Where E is the PU signal energy and σ^2 is the variance [15].
The mathematical equation that is used for calculating P_d of the matched filter detector is given in Equation (3) [15]:

$$\mathrm{P_{d,theoretical}} = \mathrm{Q}\left(\frac{(\mathrm{T}-\mathrm{E})}{\sqrt{\mathrm{E}\sigma^2}}\right), \quad (3)$$

Where Q is the function, T is the sensing threshold level.
To calculate Pd in Simulink, the Equation (4) is used:

$$\mathrm{P_{d,Simulation}} = {}^{\mathrm{N_d}}\!/_{\mathrm{N}}, \quad (4)$$

Where N_d represents the number of detections, N represents the number of samples. The theoretical and simulation equations for the Pm of matched filter detector are as follows [16]:

$$P_{m,theoretical} = 1- P_{d,theoretical}, \quad (5)$$

$$P_{m,Simulation} = {}^{N_m}\!/_{N}, \quad (6)$$

Where N_m represents the number of miss detection, N represents the number of samples. The mathematics equation that is used for calculating P_f of the MFD is given in Equation (7) [15]:

$$P_{f,theoretical} = Q\left(\frac{T}{\sqrt{E\sigma^2}}\right), \quad (7)$$

To calculate Pf in Simulink, the Equation (8) is used:

$$P_{f,Simulation} = {}^{N_f}\!/_{N} \quad (8)$$

Where N_f represents the number of miss detections, N represents the number of samples.

3.3 Energy Detector (ED) method

It is a preferred method for spectrum sensing, because of its simplicity of operation, time-and frequency-applicability, does not require any prior knowledge about PU, low computational and implementation costs. The detection of PU signal depends on the energy level in the channel [35], [36] and [37]. The energy detector statistical test is given inequation (9):

$$ED = \sum |x(n)| N 2 n=1 \quad (9)$$

Where N is the number of samples, $x(n)$ is the received signal simulated in this work.

3.4 Threshold Level (T)

Threshold Level (T) The threshold level T is decided whether the target signal is absent or present. This threshold level determines all performance metricsPd, Pm and Pf. The Adaptive threshold level (AT) measures the noise signal according to estimated noise variance. This done based on the information calculated from the received signal. It increases Pd and decreases Pf compared to energy detection in a static threshold manner [38].

There are number of advantages for using adaptive threshold in the PUs detection process, they can be summarized in:

Decrease the error probability (Pm, Pf) in the SS.

Increase the detection probability (Pd).

Increase the accuracy of the SS detection.

The mathematics equation that used for calculating the AT level for the ED is given in equation (10) [39]:

$$ATenergy = \sqrt{2Nv\ 4}Q -1\ (Pf) + Nv\ 2 \quad (10)$$

Where $ATenergy$ is the Adapted threshold of ED, v is the noise energy per sample, which is considered as (1/SNR), $Q -1$ is the Inverse function for Pf.

The value of this threshold is calculated based on a constant value of SNR and number of samples, while (Pf = 0.01) [39].

The mathematical equation that is used for calculating the AT level for the MF is given in equation (11) [40]:

$$ATmatched = Q -1\ (Pf\ )\sqrt{E\sigma\ 2} \quad (11)$$

Where E is the PU signal energy and σ 2 is the variance [40]

4. Proposed Methods

Two solutions are presented to handle the problem of not understanding the value of the noise and the PU being unseen to all Sus. Those solutions are the matched filter detector algorithm using adaptive threshold and the cooperative matched filter detector algorithm using an adaptive threshold. We will explain them below after highlighting the advantages of cooperative spectrum sensing.

4.1. Advantages of Cooperative Spectrum Sensing

There are many advantages of using cooperative sensing than individual sensing, they can be summarized in these points:

The cooperation technique among SUs can improve the performance of the spectrum detection in CR.

Increase the accuracy by increasing Pd.

To overcome the problems of fading, shadowing and hidden node that are inherited in SS.

Interference mitigation/avoidance between PUs-SUs and SUs-Sus

4.2. Matched Filter Detector Algorithm Using an Adaptive Threshold

A matched filter detector (MFD) algorithm is proposed using the adaptive threshold (AT) level to solve the problem of lack of noise value. As shown in Figure (2) which demonstrates the overall work and the preliminary parameters of some variables, such as the number of samples, SNR, probability of false alarm (Pf), and the input signal simulated as Binary Phase-shift keying (BPSK). The MFD level is calculated using Equation (1) after adding AWGN, and the AT level for MFD is calculated depending on Equation (2). later, the value of AT is compared with the value of MFD so that the probability of detection (Pd)and probability of miss detection (Pm) can be calculated. This process is continued and repeated until the last number of samples with different SNR range values is completed. Please see figure 3 and Table 2.

So as per figure 3, the process will be as follows:

The parameters will be initialized as Nd=0, Nm=0 and SNR=Start, Pf=0.01

Transmitted signal (s(n)) will be received by the modulation BPSK then add the noise of AWGN then calculate both the power of AT and the power of the matched filter detector (MFD) then compare it the value of MFD was greater or smaller than AT then go to the next step.

Otherwise, the transmitted signal (s(n)) will have an impulsive response then calculate the power of the MFD or the matched filter detector if the MFD greater than AT then PU present (H1) and Nd=Nd+1 then calculate Pd=Nd/N, otherwise the PU is absent or (H0) and Nm=Nm+1, then calculate Pm=Nm/N

After that the SNR will be checked if it has ended then (End), otherwise the SNRnew= SNRold+step and repeats the steps from add the noise of AWGN until the noise is ended.

4.3. Cooperative Matched Filter Detector Algorithm Using an Adaptive Threshold

In this section we will be using an adaptive threshold to establish an algorithm for cooperative matched filter detector. The idea here is to use as many (SUs) as possible in order to sense the same spectrum. This method employs the following procedures:

Using many SUs to sense the same spectrum.

Each SU has different circumstances (noise and gain).

Every SU follows the MFD algorithm mentioned in section 4.2.

The result of the comparison between MFD and AT should be transferred to the FC.

The results come from the comparison. Apply either the OR fusion rule or the AND fusion rule.

The steps are repeated until the number of samples and SNR values are completed.

A flowchart for a cooperative matched filter detection algorithm using an adaptive threshold is given in Figure (4).

Table 2 Algorithms notations.

Algorithms notations	
N	The number of Samples
SNR	Signals to noise ratio
Nd	The number of detections
Nm	The number of miss detections
Pd	Probability of detections
Pm	Probability of miss detections
PBSK	Binary phase-shift keying
AT	Adaptive threshold
MFD	Matched filter detector
AWGN	A Channel Proposed by [9]

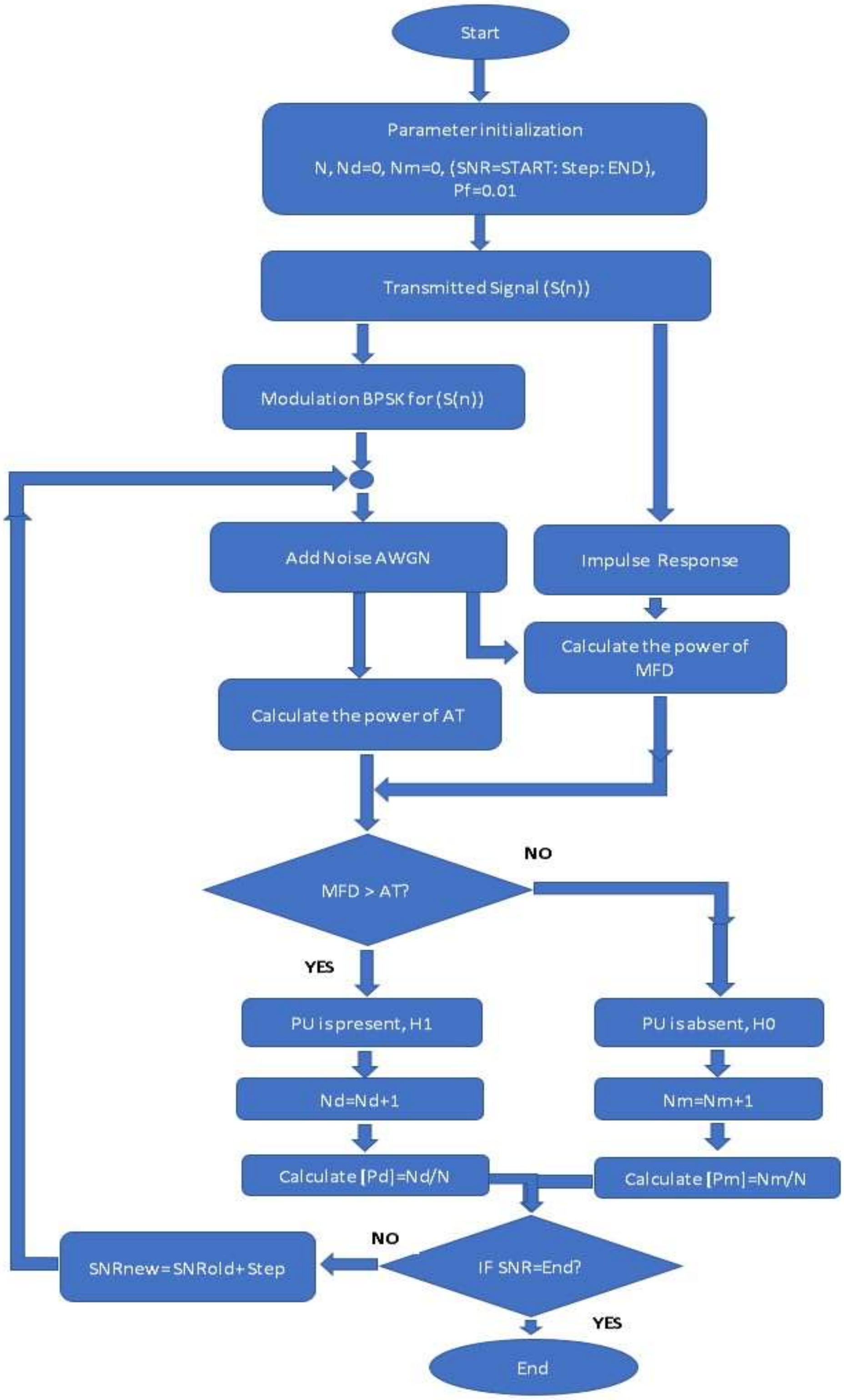

Figure 3. A Flowchart for A Matched Filter Detector Algorithm Using An Adaptive Threshold.

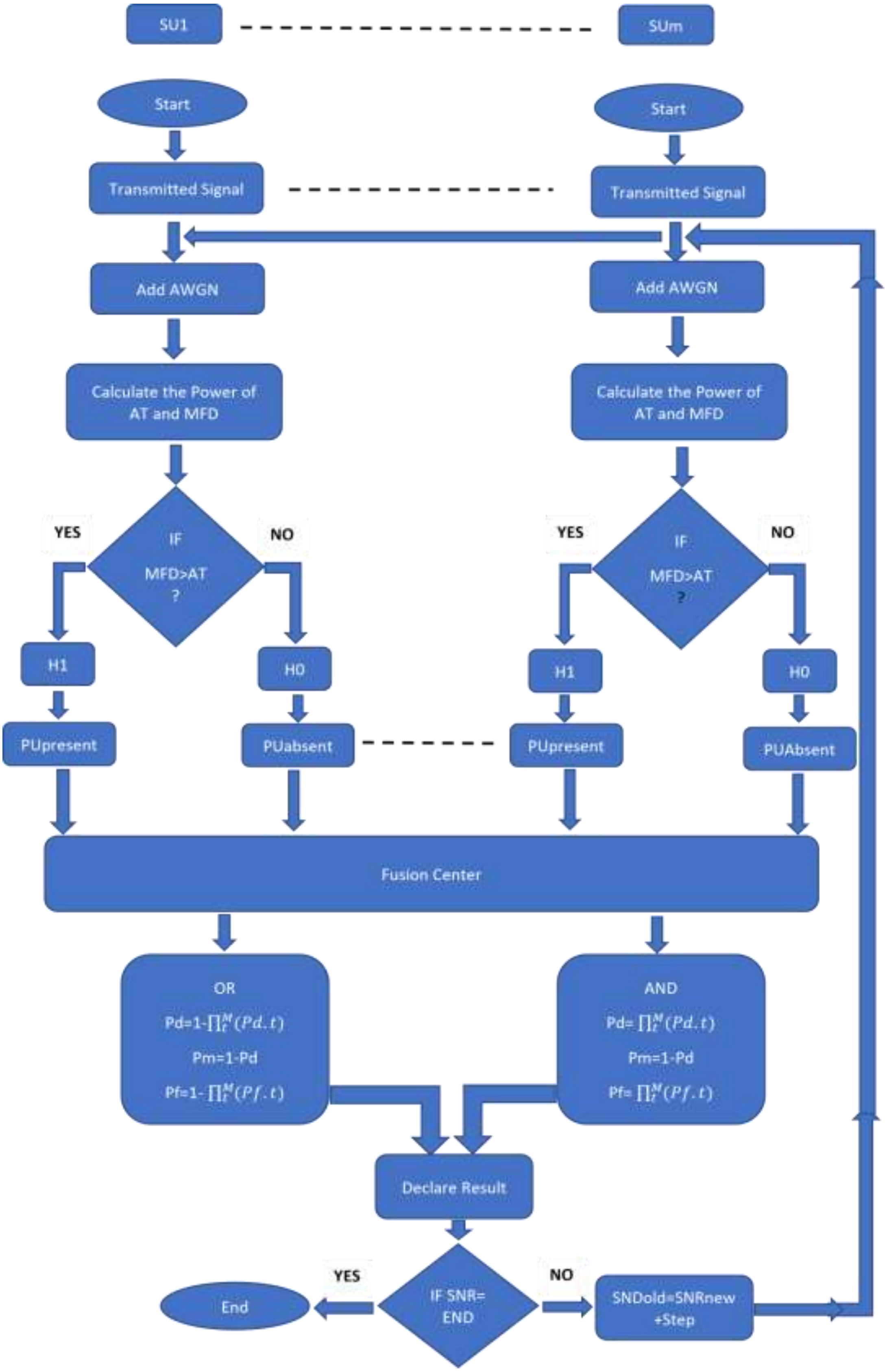

Figure 4. A Flowchart For A Cooperative Matched Filter Detection Algorithm Using An Adaptive Thresold.

4. Results and Discussion

Matlab program is used to simulate and assess the effects of a suggested system design. The initial settings used in the simulation are as follows: N =100 samples, Pf = 0.01, and SNR is changed between -20 and 20 dB.

Figure (5) shows the probability of detection for a matched filter detector (Pd) and the SNR for the two cases, theoretical and simulation. The SNR value is varied in steps from -20 dB to 20 dB. In the simulation case, it is seen that the Pd value is small (about 0.044) at a small value of SNR till -20dB, and it rises to be 1 at SNR equals 0 dB up to 20 dB. In the theoretical case, the figure seems to be very close to the simulation case.

Figure (6) shows the relation between the probability of miss detection for matched filter detectors (Pm) and SNR for both theoretical and simulation cases. In the simulation case, Pm value (about 0.956) at SNR equals-20dB, and they decrease to 0 at SNR equals 0 dB, up to 20 dB. In the theoretical case, Pm value (about 0.95) at SNR equals -20 dB, and they decrease to 1 dB at SNR equals-1 dB, up to 20 dB.

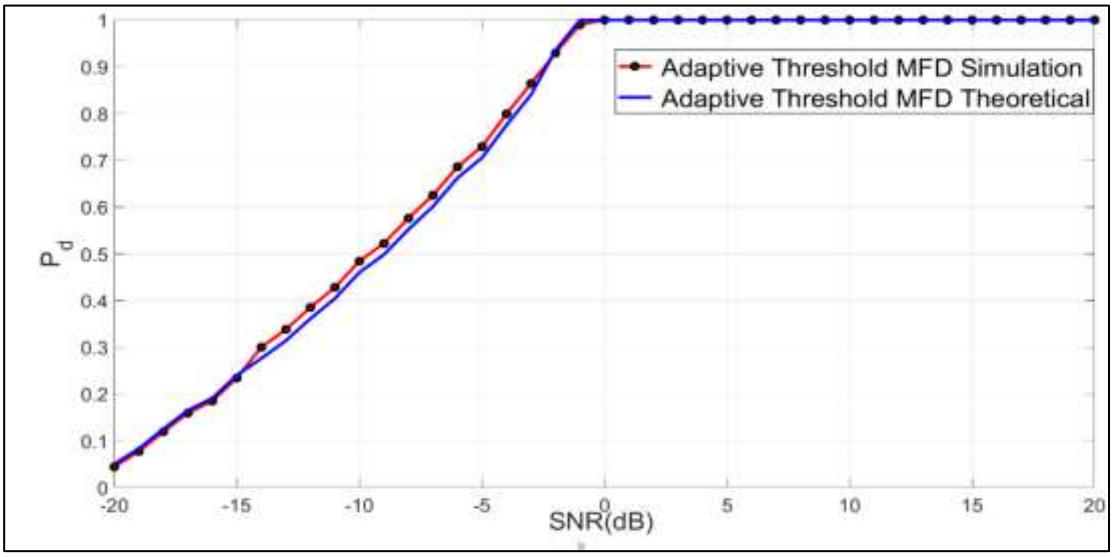

Figure 5. Theoretical and simulation Pd for the MFD case vs. SNR

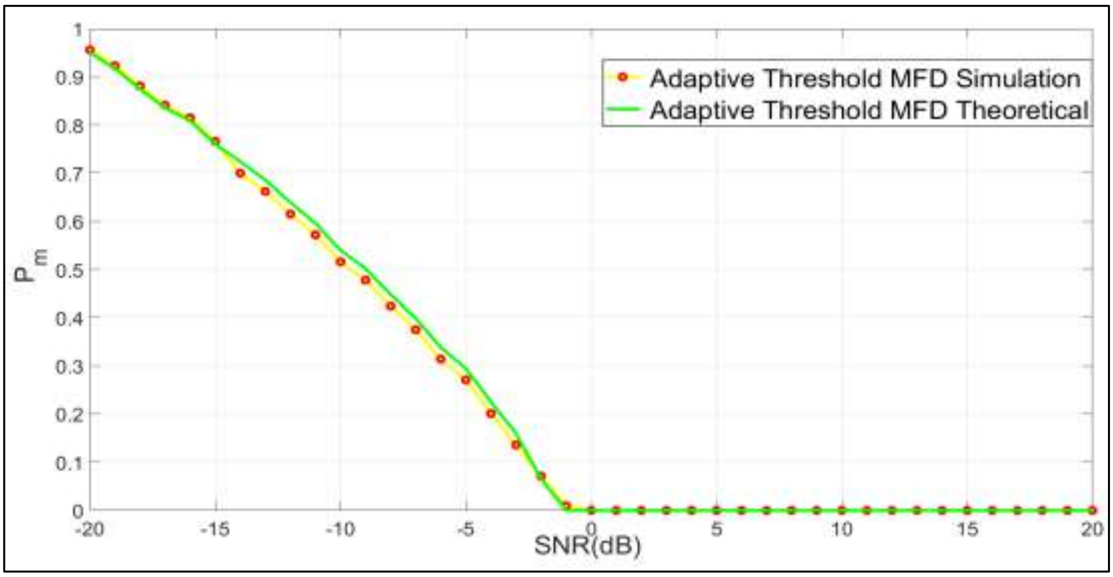

Figure 6. Theoretical and simulation Pm for the MFD case vs. SNR

Figure (7) shows the relationship between the probability of false alarm for a matched filter detector (Pf) and SNR. In both theoretical and simulation cases, Pf values in simulation are high (about 0.94) at a very small value of SNR till -20dB, and then they decrease to 0 at SNR equal to -1dB up to 20 dB. In the theoretical case, the figure seems to be very close to the simulation case. All the theoretical and simulation values for Pd, Pm, and Pf are summarized in Table (3) for various SNR values.

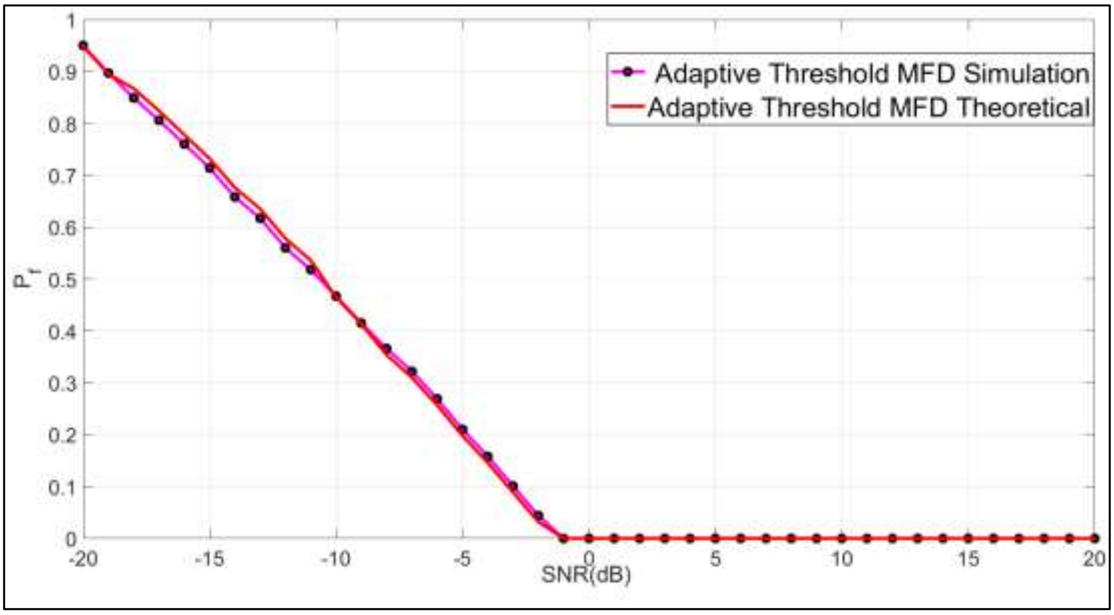

Figure 7. Theoretical and simulation Pf for the MFD case vs. SNR

Table 3 Summery results of matched filter detector using an adaptive threshold.

SNR	Pd Simulation	Pd Theoretical	Pm Simulation	Pm Theoretical	Pf Simulation	Pf Theoretical
-20	0.044	0.05	0.956	0.95	0.95	0.948
-19	0.077	0.083	0.923	0.917	0.897	0.895
-18	0.119	0.125	0.881	0.875	0.849	0.867
-17	0.159	0.165	0.841	0.835	0.806	0.824
-16	0.185	0.191	0.815	0.809	0.76	0.778
-15	0.234	0.24	0.766	0.76	0.714	0.732
-14	0.3	0.276	0.7	0.724	0.658	0.676
-13	0.338	0.314	0.662	0.686	0.617	0.635
-12	0.385	0.361	0.615	0.639	0.56	0.578
-11	0.428	0.404	0.572	0.596	0.518	0.536
-10	0.484	0.46	0.516	0.54	0.467	0.465
-9	0.522	0.498	0.478	0.502	0.415	0.413
-8	0.576	0.552	0.424	0.448	0.366	0.354
-7	0.625	0.601	0.375	0.399	0.322	0.31
-6	0.686	0.662	0.314	0.338	0.269	0.257
-5	0.729	0.705	0.271	0.295	0.21	0.198
-4	0.799	0.775	0.201	0.225	0.158	0.146
-3	0.864	0.84	0.136	0.16	0.101	0.089
-2	0.929	0.935	0.071	0.065	0.044	0.032
-1	0.99	1	0.01	0	0	0
0-20	1	1	0	0	0	0

The following figures give the results of the analysis of the cooperative matched filter detector algorithm in Figure (4) using AT level. It is seen that the result of cooperative MFD is better than a single MFD because there is more than one detector doing the check on the channel. Figure (8) illustrates the relationship between Pd and SNR using six SUs with various environmental conditions (gain, noise). As shown in Table (4).

Table 4 The environmental conditions for six SUs using step noise (-20 – 20)

Secondary user	Normalcy again
Su1	0.4
Su2	0.3
Su3	0.8
Su4	0.5
Su5	0.9
Su6	1

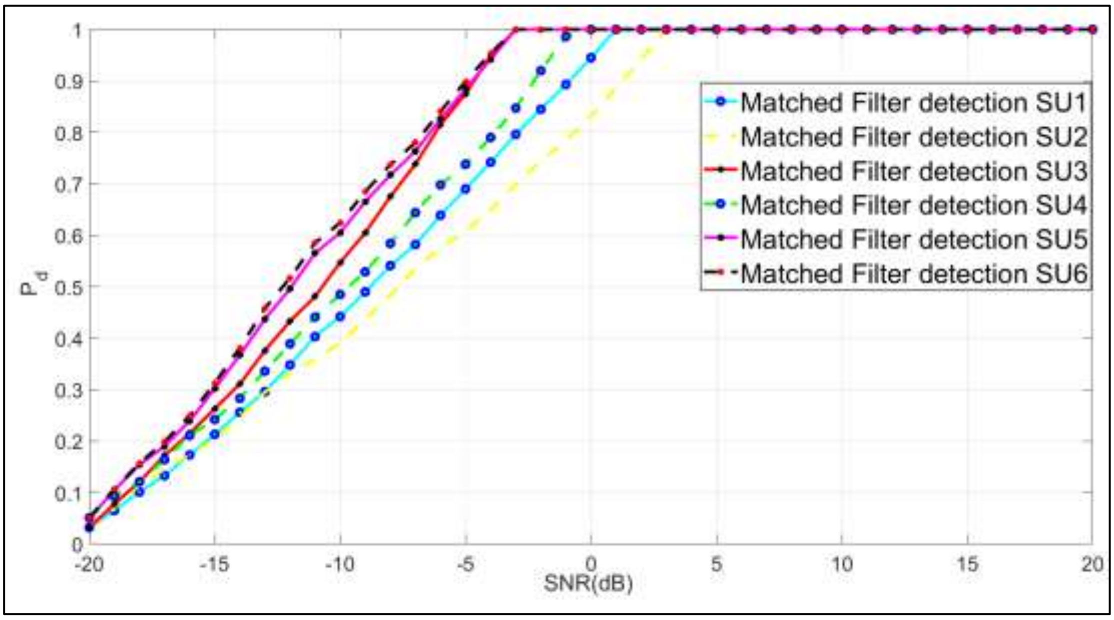

Figure 8. Pd for six individual SUs vs. SNR for MFD

Figure (9) shows the relationship between Pd and SNR when using the two fusion rules (OR-Cooperative, AND-Cooperative). Also, the MFD case is plotted. It is noticed that OR-Cooperative is the better, where Pd value is (0.19) at -20 dB and it rises to be 1 at SNR equal to -5 dB to 20 dB. While in the AND-Cooperative, it is seen that the Pd value is very small (0.005) at a small value of SNR till -20 dB, and it rises to be 1 at SNR equals 0 dB to 20 dB. In the results of the non-cooperative case, it is seen that the Pd value is small (0.045) at a small value of SNR till -20 dB, and it rises to be 1 at SNR equal to -2 dB to 20 dB. The values of OR-Cooperative, AND-Cooperative, and non-cooperative cases are summarized in Table (5).

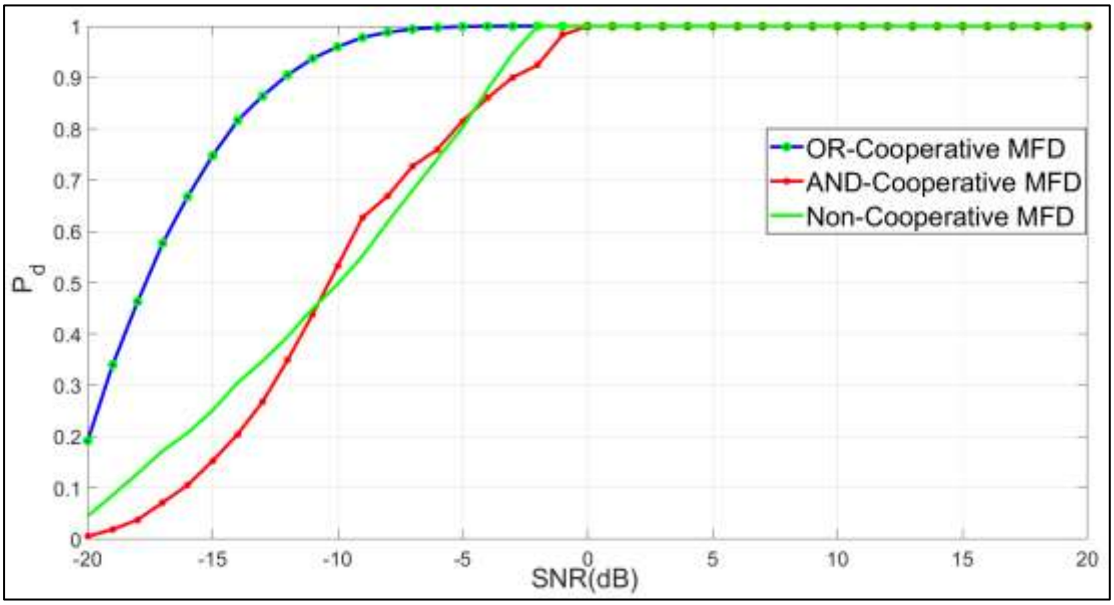

Figure 9. Pd (OR-Cooperative, AND-Cooperative, Non-Cooperative) vs. SNR for MFD

Table 5 P_d (OR-Cooperative, AND-Cooperative, Non-Cooperative) and SNR for MFD

SNR	OR-Cooperative	AND-Cooperative	Non-Cooperative
-20	0.191517	0.005376	0.045
-19	0.339672	0.018887	0.086
-18	0.462811	0.037752	0.128
-17	0.576826	0.0714	0.172
-16	0.667771	0.105462	0.207
-15	0.747588	0.15264	0.251
-14	0.816109	0.204288	0.305
-13	0.863957	0.267804	0.347
-12	0.904998	0.349325	0.395
-11	0.936993	0.438	0.449
-10	0.959762	0.532539	0.497
-9	0.978095	0.627	0.552
-8	0.988115	0.669	0.618
-7	0.994216	0.727	0.68
-6	0.997313	0.76	0.742
-5	1	0.815	0.802
-4	1	0.86	0.877
-3	1	0.9	0.946
-2	1	0.924	1
-1	1	0.983	1
0-20	1	1	1

Figure (11) describes the relationship between Pm and SNR, for OR-Cooperative, AND-Cooperative, and Non-Cooperative. It is clear that the OR-Cooperative case is the better of the three, while the two other cases are nearly identical. The values (OR-Cooperative, AND-Cooperative, and Non-Cooperative) for MFD are summarized in Table (6).

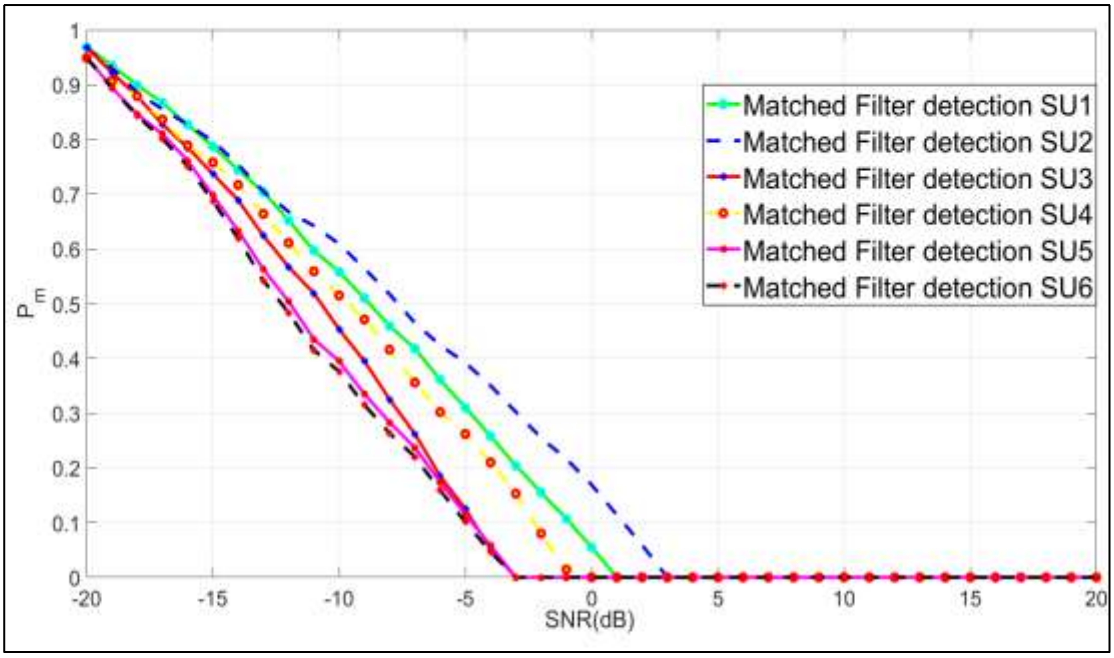

Figure 10. Pm for six individual SUs vs. SNR for MFD

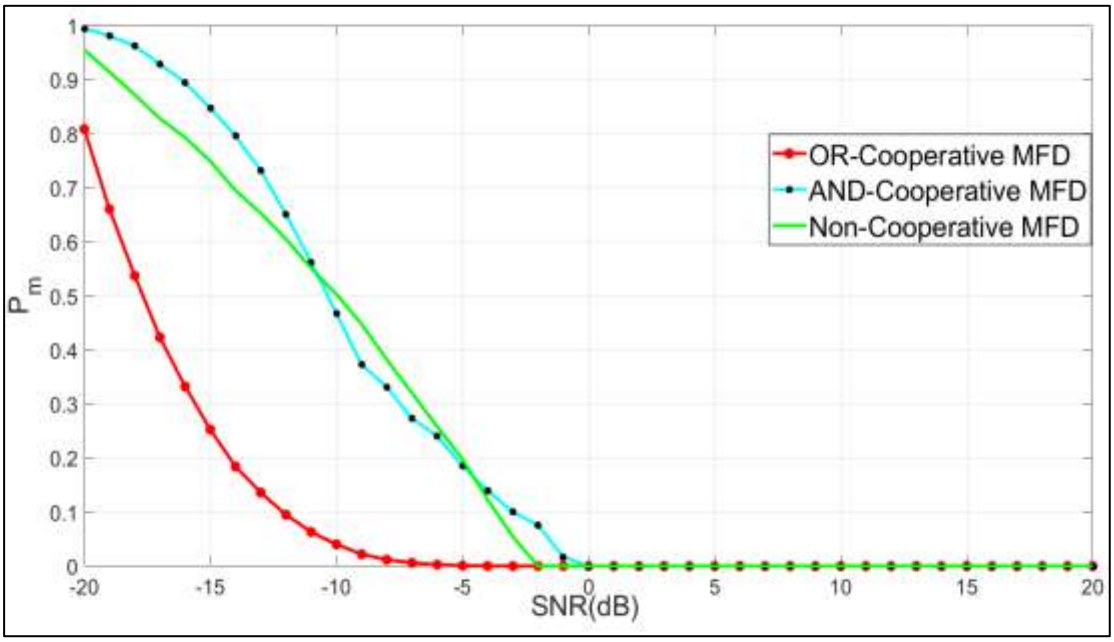

Figure 11. Pm (OR-Cooperative, AND-Cooperative, Non-Cooperative) vs. SNR for MFD

Table 6 P_m (OR-Cooperative, AND-Cooperative, Non-Cooperative) and SNR for MFD

SNR	OR-Cooperative	AND-Cooperative	Non-Cooperative
-20	0.808483	0.994624	0.956
-19	0.660328	0.981113	0.923
-18	0.537189	0.962248	0.881
-17	0.423174	0.9286	0.841
-16	0.332229	0.894538	0.815
-15	0.252412	0.84736	0.766
-14	0.183891	0.795712	0.7
-13	0.136043	0.732196	0.662
-12	0.095002	0.650675	0.615
-11	0.063007	0.562	0.572
-10	0.040238	0.467461	0.516
-9	0.021905	0.373	0.478
-8	0.011885	0.331	0.424
-7	0.005784	0.273	0.375
-6	0.002687	0.24	0.3140
-5	0	0.185	0.271
-4	0	0.14	0.201
-3	0	0.1	0.136
-2	0	0.076	0
-1	0	0.017	0
0-20	0	0	0

Figure (12) illustrates the relationship between Pf and SNR using six SUs individually with different environmental conditions (gain, noise). Figure (13) indicates the relationship between Pf and SNR, for (OR, AND, and Non-Cooperative MFD). Here also, the better case is the OR case, and the other two cases are nearly the same. The values (OR-Cooperative, AND-Cooperative, Non-Cooperative) are summarized in Table (7).

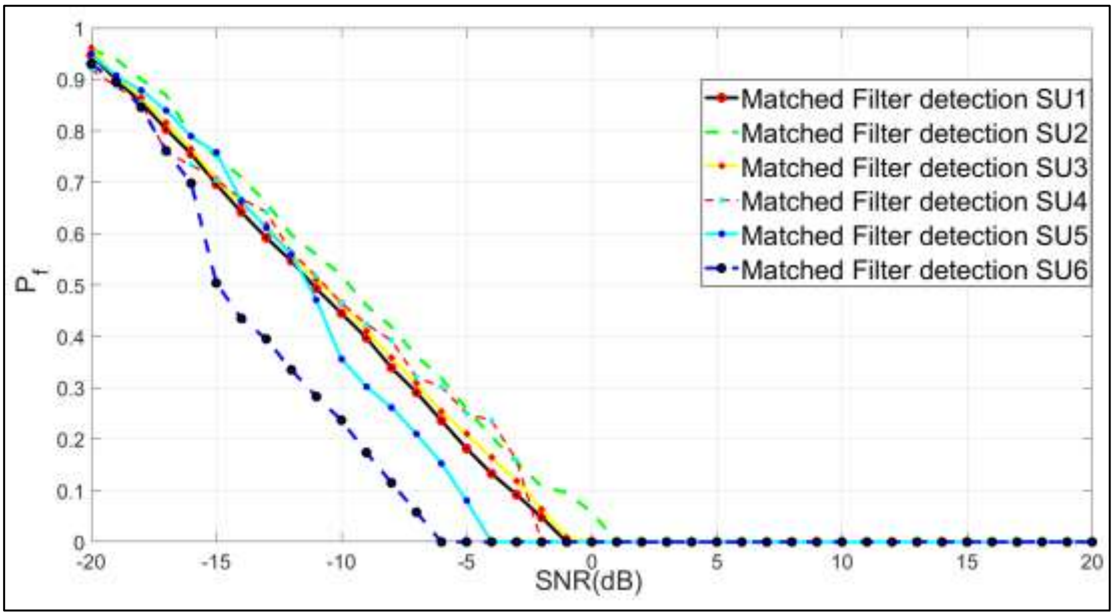

Figure 12. Pf for six individual SUs vs. SNR for MFD

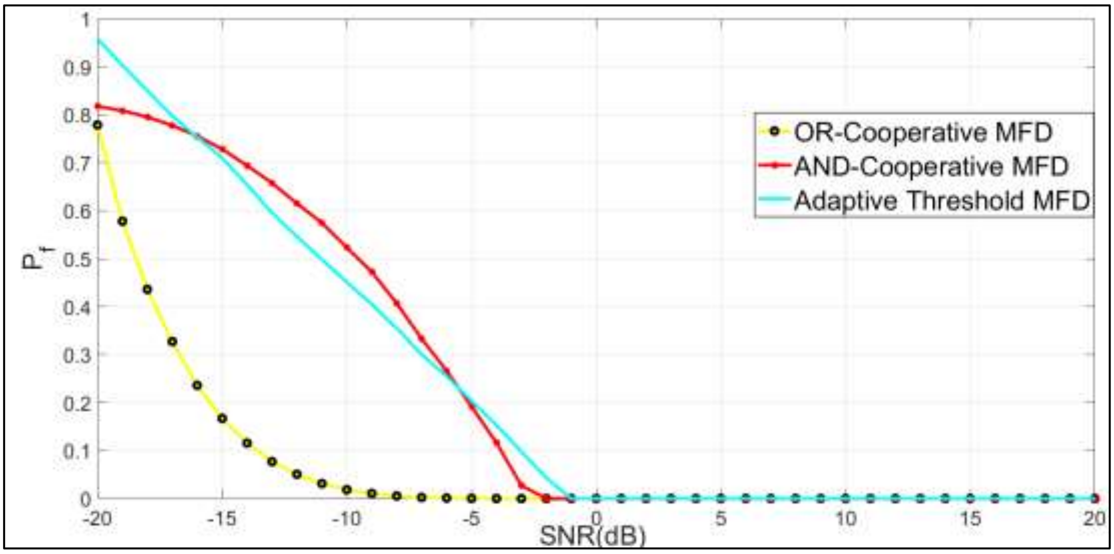

Figure 13. Pf (OR-Cooperative, AND-Cooperative, Non-Cooperative) vs. SNR for MFD

Table 7 $\mathbf{Pf\ (OR-Cooperative, AND-Cooperative, Non-Cooperative)\ and\ SNR\ for\ MFD}$

SNR	OR-Cooperative	AND-Cooperative	Non-Cooperative
-20	0.778626	0.994624	0.94
-19	0.578038	0.981113	0.887
-18	0.435889	0.962248	0.839
-17	0.327209	0.9286	0.796
-16	0.235948	0.894538	0.75
-15	0.166959	0.84736	0.704
-14	0.115614	0.795712	0.648
-13	0.076924	0.732196	0.607
-12	0.05063	0.650675	0.55
-11	0.031206	0.562	0.508
-10	0.018598	0.467461	0.457
-9	0.010696	0.373	0.405
-8	0.003507	0.331	0.356
-7	0.000139	0.273	0.312
-6	0	0.24	0.259
-5	0	0.185	0.2
-4	0	0.14	0.148
-3	0	0.1	0.091
-2	0	0	0.034
-1- 20	0	0	0

5. Conclusion

The Cognitive radio (CR) known as a smart wireless communication method was developed over the years to be more efficient and more reliable and low cost than other wireless communications devices available such as RFID or Ad Hoc networks which requires complex operations and security measurements [18], [19] and [20].

This paper proposes a matched filter detector with an adaptive threshold and a cooperative matched filter detector with an adaptive threshold to address two major issues arising in spectrum sensing. The first issue is that narrow-scope detection is difficult to detect due to the lack of noise level. The primary user is hidden from all secondary users, which is the second major issue. To determine the spectrum's sensing precision, the proposed methods are evaluated using the Pd, Pm, and Pf criteria.

The simulation results using MATLAB [21], [22] and [23] show that in the matched filter detector using an adaptive threshold case, the Pd value at -20 dB SNR is 0.045 and increases to 1 when SNR is -1dB. The Pm value was 0.956 at SNR equal to -20 dB and decreased to 0 at SNR of -1 dB. Pf is 0.94 when the SNR is -20 dB, but it is 0 when the SNR is 1 dB. While in the case of cooperative matched filter detector using an adaptive threshold for OR cases, the results were:

- At SNR -20 dB, the Pd value is 0.19 and goes up to 1 at SNR -6 dB. Pd is 0.005 for the AND case when SNR is -20 dB and increases to 1 when SNR is -1 dB;
- The Pm value at SNR -20 dB is 0.8 and goes down to 0 at -2 dB. For the AND case, when SNR is -20 dB, Pm is 0.99 and decreases to 0 at SNR of 0 dB;
- The Pf value at SNR at -20 dB is 0.77 and goes down to 0 at SNR -6 dB. For the AND case, when SNR -20 dB is 0.99 and decreases to 0 at SNR -3 dB;

It is noticed from the results that the cooperative matched filter detector which we presented is better than the single matched filter detector used in previous work.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: Conceptualization, Zozan Ayoub and G.Khalil; methodology, Zozan Ayoub and G. Khalil; software, Zozan Ayoub and Ayoob Ayoob; validation, Zozan Ayoob and G. Khalil; formal analysis, Zozan Ayoob and Ayoob Ayoob; investigation, Zozan Ayoob and Ayoob Ayoob; resources, Zozan Ayoob; data curation, Zozan Ayoob; writing—original draft preparation, Zozan Ayoob.; writing—review and editing, Zozan Ayoob and Ayoob Ayoob; visualization, G. Khalil.; supervision, G. Khalil.; project administration, Ayoob Ayoob and G.Khalil.; funding acquisition, G. Khalil. All authors have read and agreed to the published version of the manuscript."

Funding: **"**This research received no external funding"
Institutional Review Board Statement: **"**Not applicable"
Informed Consent Statement: "Not applicable"

Data Availability Statement: In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Please refer to suggested Data Availability Statements in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics. If the study did not report any data, you might add "Not applicable" here.

Acknowledgments: In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Conflicts of Interest: **"**The authors declare no conflict of interest."

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