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Analysis of Hybrid Spectrum Sensing for 5G and 6G Waveforms

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Abstract: More spectrum bands are needed as the number of wireless applications rises. The spectrum band, though, is now very difficult to adapt to new applications. Because of this, the spectrum is getting more crowded, which also affects quality of service (QoS). One of the most promising technologies to address the issue of spectrum scarcity is cognitive radio (CR). Spectrum sensing (SS) is thought to be essential to CR. It determines that when primary users (PUs) are not using the spectrum, the spectrum can be allocated to secondary users (SUs). In this paper, a novel 5G spectrum sensing technique was implemented using a hybrid matched filter (HMF) algorithm based on the fusion of two matched filters (MF). In addition, we compared the performance of the HMF and traditional MF in Rayleigh and Rician channels. It has been observed that the HMF performs more effectively than the conventional MF in both channels.

Keywords: mobile communications; 5G; beyond 5G; 6G; cognitive radio; spectrum; matched filter (MF); hybrid matched filter

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1. Introduction

The demand for several applications with quality of service (QoS) and high data rates in cellular systems will increase the requirement for free spectral bands. In the present scenario, the particular application is allocated a specific spectrum. However, there is a scarcity of spectrum since many applications are already using the allotted spectrum. As per the protocol of the government, the licensed spectrum cannot be utilized by an unlicensed user. It is also true that most of the spectrum is being overutilized. In recent years, the research outcomes indicate that the underutilization of OFDM spectrum is mainly due to the fixed spectrum allocation protocols of the Federal Communications Commission (FCC) [1]. Cognitive radio (CR) is considered an effective solution that can solve the spectrum scarcity problem. It scans the idle spectrum from the primary users (PUs) and allocates the idle spectrum to the secondary user without causing any interference to the primary user. This process of identifying the idle spectrum is known as "spectrum sensing techniques". In recent years, several spectrum sensing techniques, such as energy detection (ED), MF [2], and cyclo-stationary (CS) [3], have been proposed. In the present scenario, sensing is possible only when PUs are absent. Hence, the major challenge is to implement a spectrum sensing technique in both the presence and absence of PUs. However, it is seen that the performance of the sensing algorithm degrades for various reasons, such as multipath properties, the time-varying nature of the channel, and shadowing. Spectrum sensing plays an important role in the cognitive system and helps to overcome the interference issue during the allocation of spectrum from PUs to SUs [4]. The use of power and spectrum must be efficient in next-generation communication systems. In this sense, innovative spatial multiplexing methods, such as orbital angular momentum (OAM), are thought to have advantages over frequency multiplexing methods, such as orthogonal frequency division multiplexing (OFDM) [5]. OAMs are produced by bulk spatial light modulators, which produce an azimuthal changing phase. It is a desirable device for the creation of single photon devices necessary for quantum key distribution (QKD). Additionally, optical trapping, quantum metrology, and distant detection benefit from OAM. Each aperture incorporates a spiral phase plate (SPP), which adds data to the incoming signal [6]. OAM multiplexing provides many GHz of multiplexed bandwidth and has a good modulation bandwidth. Metasurfaces are also novel approaches for creating multiple OAM beams [7]. To increase the coverage area and efficiency of 5G networks, reconfigurable intelligent surfaces (RIS) and CR will be used to build a smart transmission system. In addition to what RIS technologies can already do, these improvements are meant to help deliver high-frequency signals for 5G to places where transmission is difficult because of obstacles, which will improve service. Although RIS-supported wireless communication offers benefits, research on RIS-supported CR networks is scant [8]. The employment of RISs in CR situations can enhance spectral sensing performance and successfully separate the UP signal from noise signals. Metasurfaces are a type of optical framework made up of arrays of subwavelength-spaced optical scatterers that are placed on top of a flat surface [9]. Reflective metasurfaces (RM) have been utilized to modify and regulate the radio wave transmission path in the context of 5G. RM are supposed to help 5G waves avoid obstacles by directing them away from them. This lowers overall attenuation and increases range [10]. The evaluation of spectrum sensing applied to CR using MATLAB simulations is discussed in this study. It aims to understand how changes in specific parameters, such as SNR, sample number, and false alarm, can affect miss-detection. First, well-known spectrum sensing methods are taken into consideration, including energy detection and matched filter detection. Then, using MATLAB simulation, a novel HMF detection method is investigated, and its effectiveness is contrasted with that of conventional MF. The proposed method, which is based on matched filter detection, is hybrid since it exhibits two distinct behaviors depending on whether the chance of a false alarm is less than or greater than 0.5. In [11], the authors implemented a spectrum sensing algorithm for binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) transmission systems. The outcomes of the experiments reveal that the present sensing methods have several drawbacks. However, cyclo-stationary gave good performance with low complexity as compared with ED and MF. In [12], the ED-based adaptive FFT sensing method is designed for the GNU's Not Unix (GNU) Platform. It is concluded that the proposed method reduces the latency as compared with existing methods. In [13], the analysis of ED and MF algorithms is carried out in the fading and non-fading channels. The experimental outcomes reveal that the performance of the sensing algorithms is improved when an ideal threshold is selected. In [14], the authors introduced an ED algorithm based on square law, combining MIMO and OFDM waveforms. It is seen that the complexity of the proposed algorithm is low and that its performance is better than that of conventional algorithms. The authors in [15] implemented a matched filter for the 5G waveform. The proposed algorithm is applied to the 64-QAM and 256-QAM modulations, and the performance is compared with the conventional algorithms. It is concluded that the MF gives better detection at low SNR and that the complexity of the spectrum is also low for 64-QAM as compared with 256-QAM. In [16], cognitive radio is designed for the NOMA waveform. The throughput of the proposed system is better than that of conventional methods. In [17], a matched filter algorithm is implemented for the OFDM waveform-based WLAN system. The outcome of the work reveals that the sensing time for detection of the idle algorithm is lower compared with traditional sensing algorithms. The authors in [18] introduced a matched filter algorithm based on the dynamic threshold characteristics of the detector. The simulation results reveal that the efficiency of the proposed detector is better than the conventional algorithms based on the static threshold characteristic. The authors of [19] created a detection algorithm that made use of the multi-framework antenna. The key characteristic of the proposed algorithm is its ability to sense the low-level idle signal for the secondary user. The work's outcome demonstrates that the proposed method provided efficient performance. The paper published in the related field is given in Table 1.

Table 1. Related work.

Ref.	Remarks
[20]	The authors of [20] examined the deployment of cognitive technologies in practical applications as well as their architectural design. Additionally, the function of sophisticated techniques in SS algorithms is assessed and examined. Finally, the CR deployment limits for an advanced radio architecture are estimated.
[21]	The properties of SS approaches were thoroughly examined and analyzed in the article that was presented [21]. It is clear that noise has a negative impact on the 5G radio's effectiveness. The adaptive method may successfully boost the framework's spectrum access, it is finally concluded.
[22]	The article in [22] illustrates a number of effective ways to obtain bandwidth. It is concluded that the cooperative spectrum method provided the highest level of efficiency in the fading scenario.
[23]	A compressed sensing algorithm for cutting-edge radio systems was introduced in the article. It is anticipated to have a significant impact on a cutting-edge radio waveform. It is clear that the compressed approach operated at its most effective level at low SNR [23].
[24]	The parameters of the unauthorised bandwidth allotment were dynamically provided by the authors in [24]. It is evident that the throughput of the framework was effectively boosted by the proposed approach.
[25]	The framework for IOT-based systems will benefit greatly from the use of the spectrum detection technique. In comparison to traditional methods, the proposed method increased the framework's spectral efficiency [25].
[26]	The multi-agent spectrum algorithm was created by the authors to increase the framework's throughput [26]. The proposed technique achieves optimal performance at low SNR values when the offered algorithm is compared to the current spectrum sensing techniques.
[27]	For the 5G framework, the authors of [27] presented a cascaded matching filter algorithm. Comparisons between the suggested algorithm and the customary ED and MF approaches are made. According to the experimental findings, the cascaded MF outperformed conventional systems.

The contributions of this article are listed as follows:

- We look at how well double-stage matched filters and conventional matched filters work with 5G waveforms.
- Figuring out the different parameters, such as probability of detection (Pd), probability of false alarm (Pfa), bit error rate (BER), complexity, and power spectral density (PSD), and comparing them to the conventional MF algorithms.
- A novel 5G spectrum sensing technique that combines two matched filters was introduced to improve the detection sensitivity while enhancing the throughput of the framework.

The remainder of this work is organized as follows: Section 2 presents the system model. Section 3 presents the results and discussions of the proposed system. Finally, conclusions are made based upon the observed outcomes.

2. System Model

2.1. Energy Detection (ED)

The schematic of ED is shown in Figure 1. In this method, the received energy is compared with a predefined threshold value, and channel availability is determined. One of the main characteristics of ED is that it does not need precedent channel state information

(CSI) [28]. However, the performance degrades in the presence of noise. The detection and absence of a primary user can be defined as:

$$h_0 \; : z(n) = \sigma_n \tag{1}$$

$$h_1 \; : z(n) = x(n) + \sigma_n \tag{2}$$

where h_0 and h_1 represent the availability and non-availability of Pu, $z(n)$ is the receive signal, and σ_n is the Gaussian noise. The energy of the received signal is given by:

$$T_{ED} = \sum_{n=1}^{N} (z(n))^2 \tag{3}$$

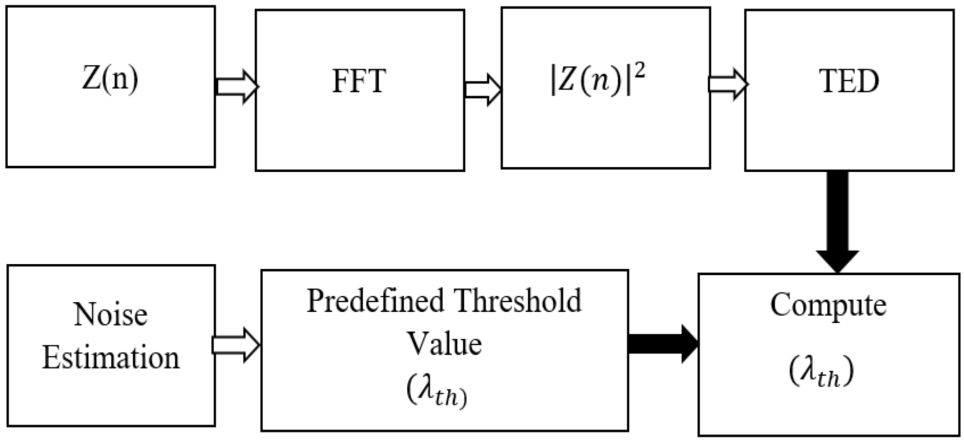

Figure 1. Energy Detection System.

The receiver signal in Equation (3) is compared with the predefined threshold value (λ_{th}), and the following decision is made:

$$T_{ED} < \lambda_{th} : Non\ Availabilty\ of\ Pu$$

$$T_{ED} \geq \lambda_{th} : Availabilty\ of\ Pu$$

The performance of the ED is defined by the probability of detection P_d and the probability of a false alarm (P_{fa}) given by:

$$P_d = Prob(T_{ED} \geq \lambda_{th}) : \; h_1 \tag{4}$$

$$P_{fa} = Prob(T_{ED} < \lambda_{th}) : h_0 \tag{5}$$

2.2. Cyclo-Stationary (CS)

It is considered one of the most efficient algorithms to detect idle spectra due to its characteristics of retrieving every minute detail of the signal at low SNR. Using the periodic nature of the Pu in the energy of the received signal, it is possible to find out if Pu is available [29].

2.3. Matched Filter (MF)

The schematic of conventional MF is given in Figure 2. It is considered one of the most effective methods to detect the availability and non-availability of Pu at low SNR [30]. It needs prior details about the noise; however, MF outperforms the ED [31].

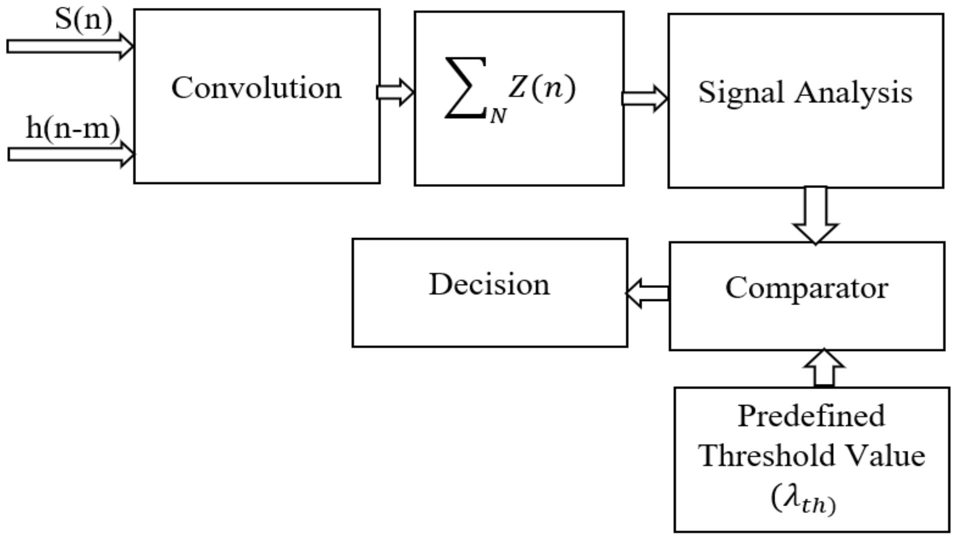

Figure 2. Matched filter convention for spectrum sensing.

The detection process of a matched filter can be given as follows:

$$z(n) = \sum_{m=-\infty}^{\infty} h(n-m)\; S(m) \tag{6}$$

where $h(n-m)$ the characteristics of the filter, $S(m)$ is the undetermined signal. To analyze the performance of the MF, P_d and P_{fa} are evaluated and given by:

$$P_d = Q\left(\frac{\lambda_{th} - T_{ED}}{\sqrt{T_{ED}\sigma_n{}^2}}\right) \tag{7}$$

$$P_{fa} = Q\left(\frac{\lambda_{th}}{\sqrt{T_{ED}\sigma_n{}^2}}\right) \tag{8}$$

From Equations (7) and (8), the threshold can be estimated as:

$$\lambda_{th} = \frac{\lambda}{Q}\left(P_{fa}\right)\,\sqrt{T_{ED}\sigma_n{}^2} \tag{9}$$

2.4. Hybrid Match Filter (HMF)

The schematic of the proposed method is given in Figure 3. This method combines the double *MFD* with the already-existing MF. Due to its hybrid nature, it exhibits two distinct behaviors: one when the likelihood of a false alarm is less than 0.5 and another when it is more than or equivalent to 0. This HMF detector basically relates to multiplications of two normal MF, where the threshold is the linear combination of two thresholds from a normal MF and the detection statistic is the linear combination of two thresholds from a double MF. The first detector, a normal MF, is used when the chance of a false alarm is greater than or equal to 0.5. We propose to combine conventional Mf $P_{fa} < \frac{1}{2}$ and two-stage MF for $P_{fa} \geq \frac{1}{2}$. The MF detection response for $P_{fa} < \frac{1}{2}$ and $P_{fa} \geq \frac{1}{2}$ is given by:

$$MFD = \sum_N z(n)x_p(n) . \frac{1}{N}\sum_N z(n)x_p(n) \tag{10}$$

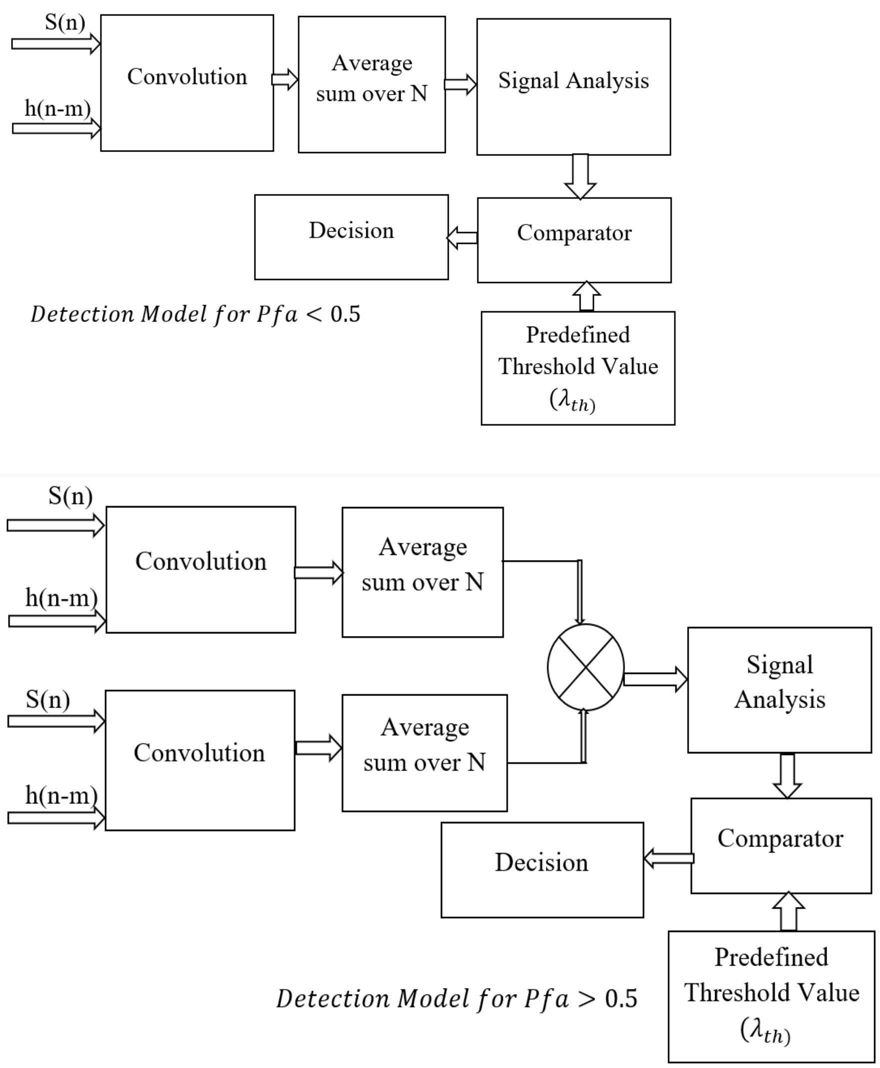

Figure 3. Proposed hybrid detection system.

The threshold for $P_{fa} < \frac{1}{2}$ and $P_{fa} \geq \frac{1}{2}$ is estimated by using the following equations:

$$\lambda_{th}(P_{fa} < \frac{1}{2}) = \frac{1}{Q}\left(P_{fa}\right)\sqrt{T_{ED}\sigma_n{}^2} \quad (11)$$

$$\lambda_{th}(P_{fa} \geq \frac{1}{2}) = \frac{1}{Q}\left(P_{fa}\right)\sqrt{E\sigma_n{}^2} \quad (12)$$

where E is the energy signal of the $x_p(n)$.

3. Simulation Results

3.1. Probability of Detection Performance

The proposed HMF and conventional MF are implemented using Matlab 2014. We considered the number of samples (N = 50, 100), 64-sub-carrier, 64-QAM transmission, and Rayleigh and Rician channels used. The parameters, such as Pd, Pfa, and BER, are analyzed and evaluated. The probability of detection (Pd) performance for the HMF and conventional MF for N = 50 and 100 in the Rayleigh channels is given in Figure 4. In Figure 4, it is seen that the HMF for N = 100 obtained a gain of 2.3 dB, 4 dB, and 6 dB as compared with the HMF (N = 50) and MF (N = 100 and 50). It is concluded that the HMF obtained a signal at a lower SNR as compared with the MF. However, the intricacy of detection in 100 samples is higher as compared with 50 samples.

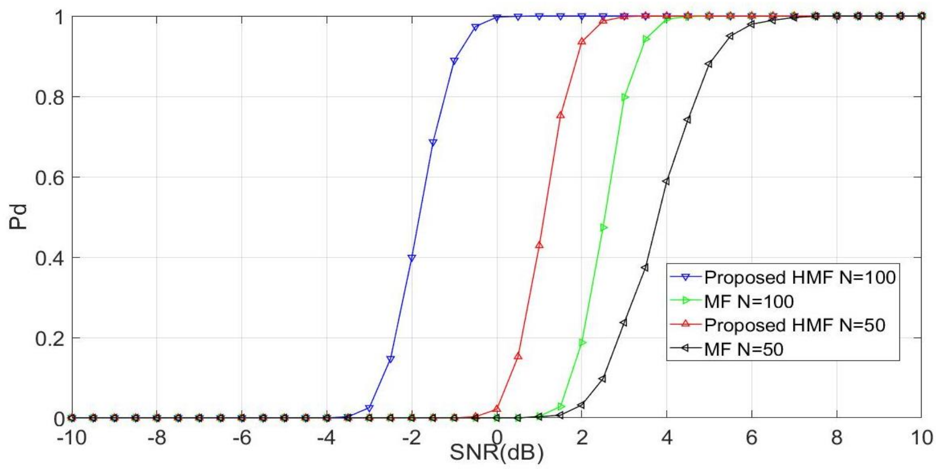

Figure 4. Performance of Pd and SNR for HMF and MF, considering number of samples = 50 and 100 in the Rayleigh Channel.

The detection capability for the Rician channel is given in Figure 5. It is seen that the performance is drastically improved as the detection is achieved at an SNR of −2 dB, −2.2 dB, 1.2 dB, and 1.3 dB for HMF (N = 100, 50) and MF (N = 100, 50). So, we can say that the proposed algorithm works well with the Rician and Rayleigh channels.

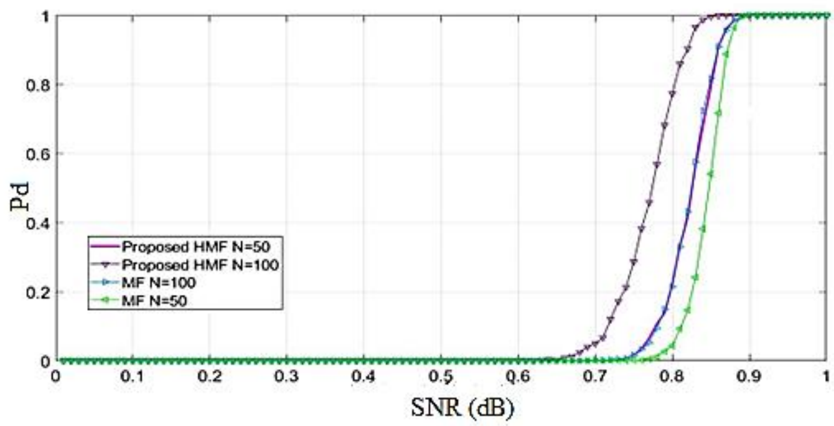

Figure 5. Performance of Pd and SNR for HMF and MF, considering number of samples = 50 and 100 in the Rician Channel.

3.2. Probability of False Alarm (Pfa) Performance

To assess the framework's throughput, it is crucial to analyze the false alarm's features. In a noisy environment, the features will influence how robust the spectrum sensing methods are. In sensing algorithms, the recognition of noise as the original signal is a critical problem that might impair the framework's performance. The proposed HMF and MF algorithms' performance is assessed and provided in Figures 6 and 7. It can be seen that for N = 100, the performances of HMF and MF are equivalent for the Rican and Rayleigh channels. Thus, it can be said that, when compared to current standards, MF is the most reliable method.

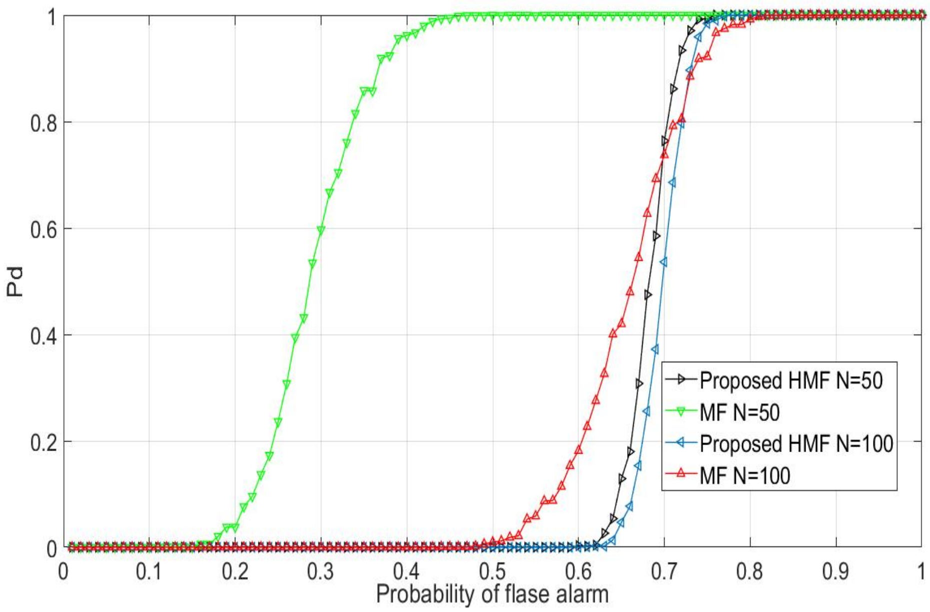

Figure 6. Performance of probability of detection and probability of false alarm for HMF and MF, considering number of samples = 50 and 100 in the Rayleigh Channel.

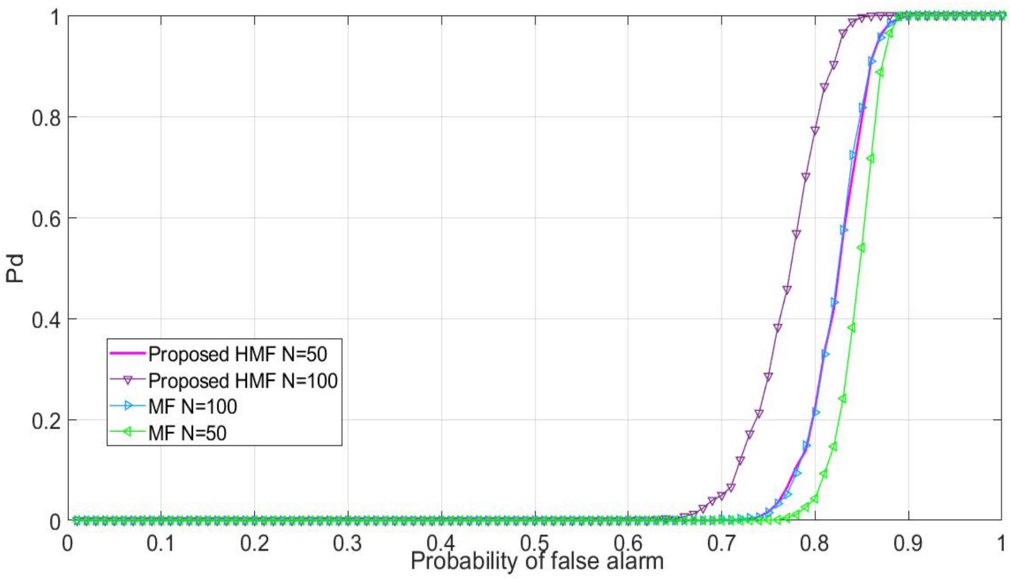

Figure 7. Performance of probability of detection and probability of false alarm for HMF and MF, considering number of samples = 50 and 100 in the Rician Channel.

3.3. BER Performance

To estimate the throughput of the proposed HMF, the BER is evaluated for the proposed HMF and conventional MF, as given in Figures 8 and 9. From the figures, it is clear that the performance of the system increases when a matched filter is applied as a detection technique. In Figure 8, the BER is estimated for the Rayleigh channel, and it is seen that the BER of 10^{-2} is obtained at an SNR of 4 dB for HMF (N = 100), 6.2 dB for HMF (N = 50), 7.3 dB for MF (N = 100), and 9 dB for MF (N = 50) for the Rayleigh channel. Similarly, Figure 9 represents the BER performance of the Rician channel, and it is seen that a BER of 10^{-2} is obtained at an SNR of 5 dB for HMF (N = 100), 9.8 dB for HMF (N = 50), 15 dB for MF (N = 100), and 25 dB for MF (N = 50) for the Rayleigh channel.

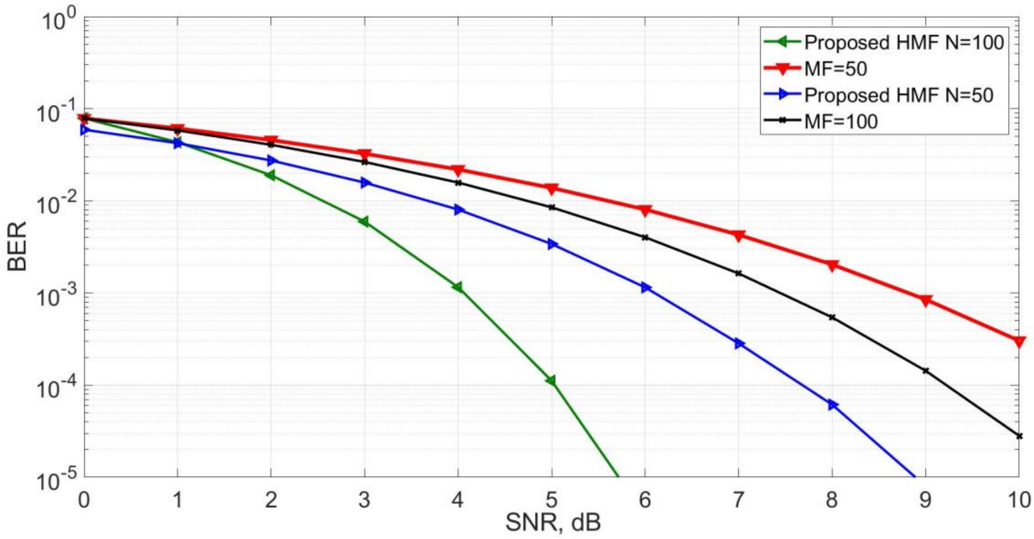

Figure 8. SNR Vs. BER performance for HMF and MF, considering number of samples = 50 and 100 in the Rayleigh Channel.

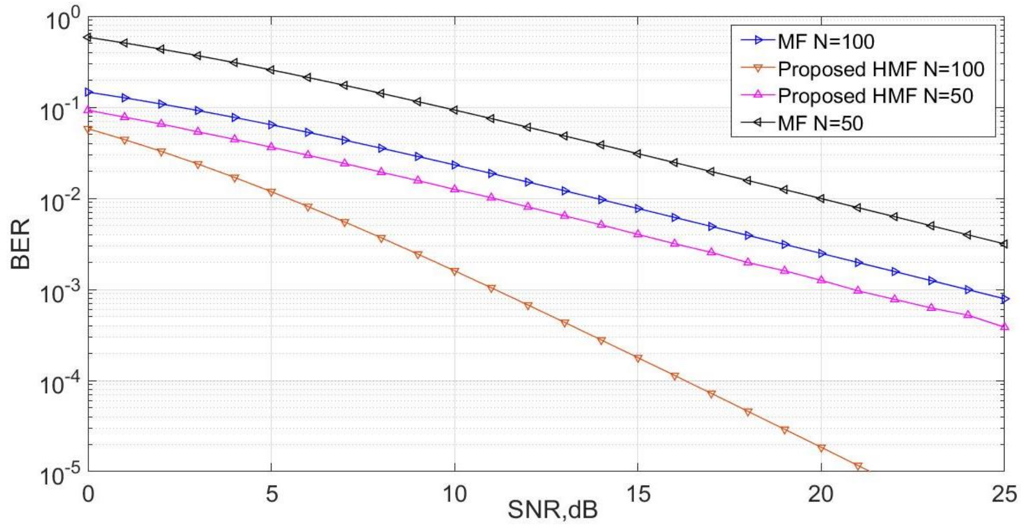

Figure 9. SNR Vs. BER performance for HMF and MF, considering number of samples = 50 and 100 in the Rician Channel.

This section analyzes, for the Rician channel with N = 100 samples, the risk of false alarm and the SNR characteristics of HMF and MF. It can be shown that the HMF performs better than the MF by achieving a gain of 5 dB. It follows that the HMF is considered a top choice for 5G and the radio that follows 5G. Figures 10 and 11 provide the Pfa and SNR characteristics for the Rayleigh and Rician channel. The proposed HMF outperformed the current MF detection approach in terms of efficiency, even at low SNR.

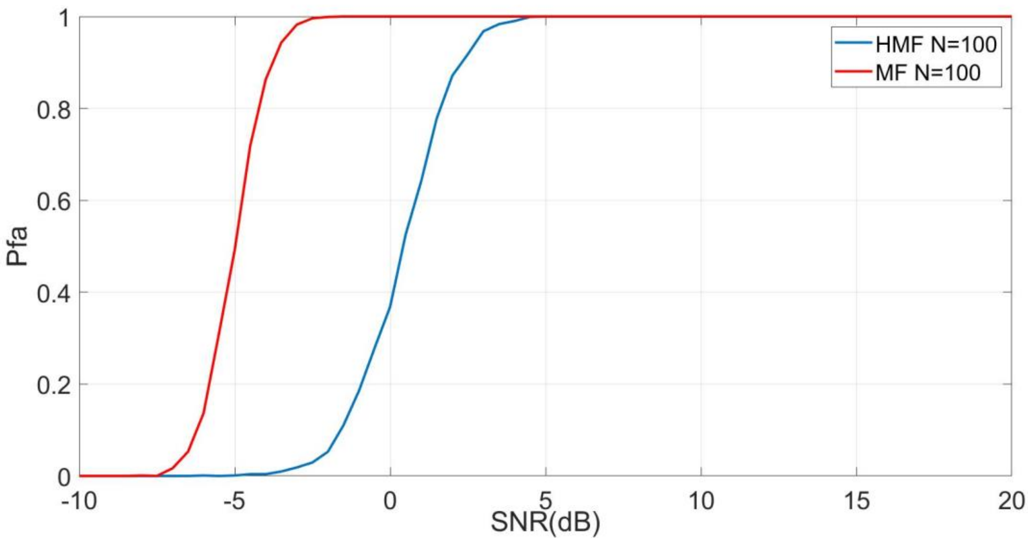

Figure 10. Performance of probability false alarm and signal-to-noise ratio (SNR) for HMF and MF, considering number of samples = 100 in the Rician Channel.

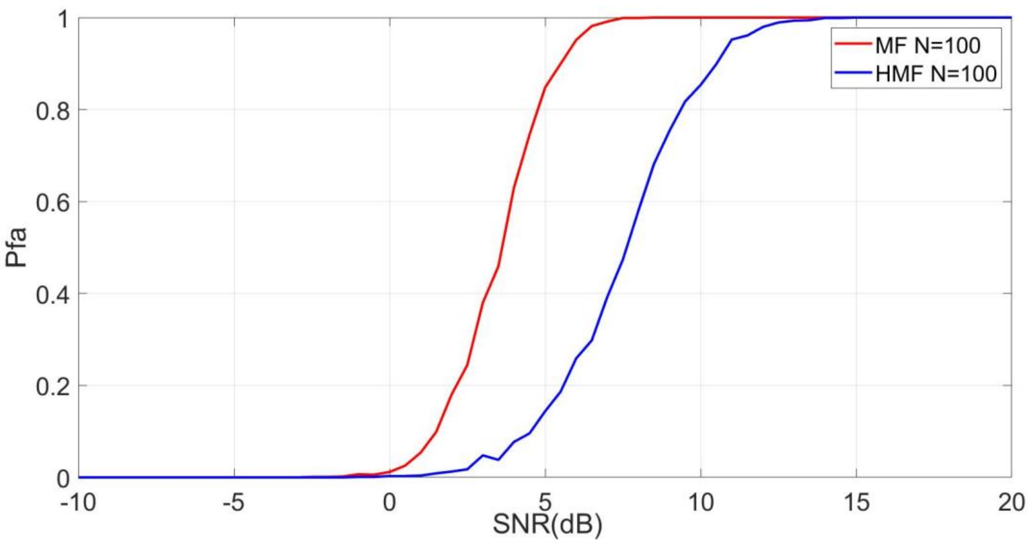

Figure 11. Performance of probability false alarm and signal-to-noise ratio (SNR) for HMF and MF, considering number of samples = 100 in the Rayleigh Channel.

As depicted in Figure 12, the effectiveness of the various SS algorithms for accurate spectrum detection is examined. The HMF, MF, CS, and ED, respectively, acquired a detection at an SNR of −2 dB, 3 dB, 5.1 dB, and 5.3 dB. As a result, it can be said that, when compared to traditional algorithms, the proposed HMF obtained optimal detection.

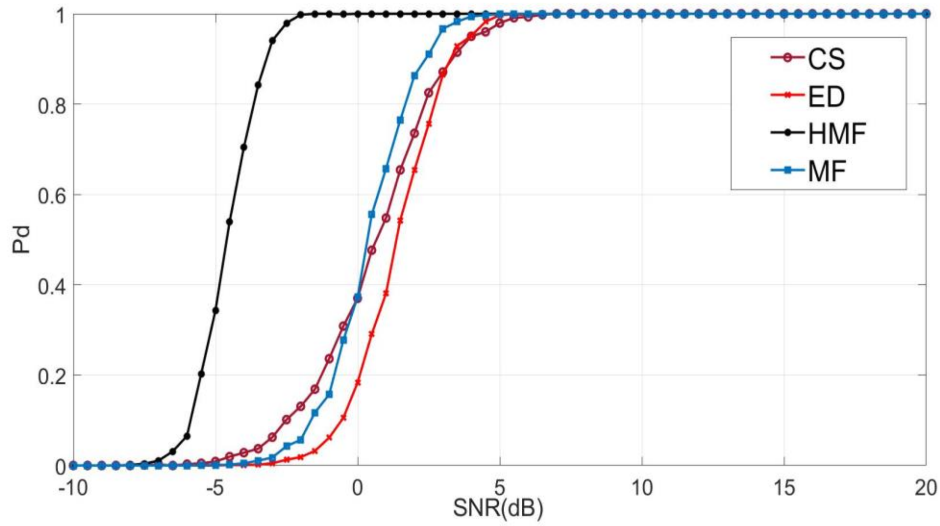

Figure 12. Pd and SNR for Rician channel.

In Figure 13, we have estimated the performance of proposed HMF and conventional SS algorithms for a condition where noise is detected as a required signal. It is seen that the HMF takes more time to detect the false signal as compared with the existing SS techniques. Hence, it is concluded that the HMF obtained optimal performance even in fading conditions.

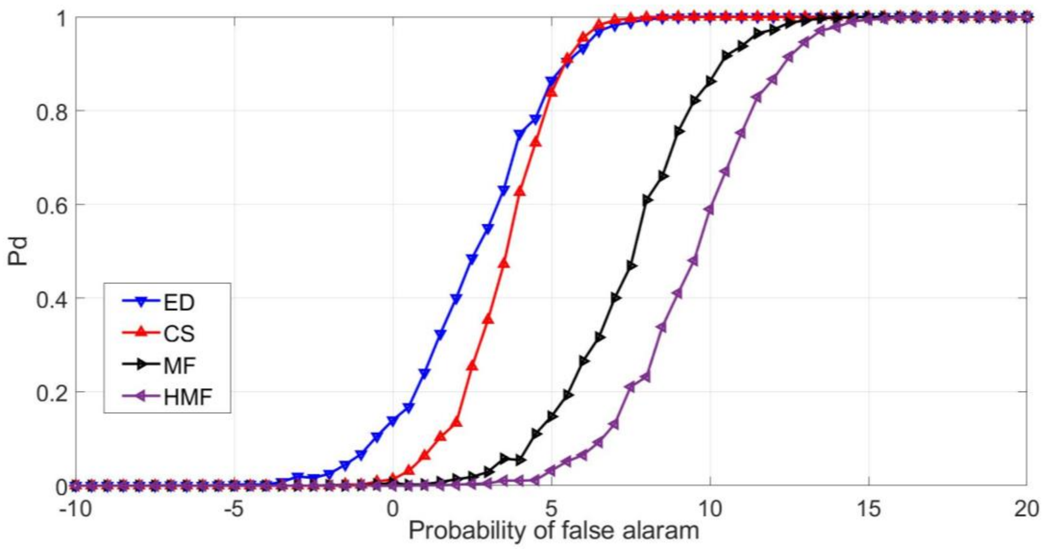

Figure 13. Pd and Pfa for the Rician channel.

3.4. Complexity

The number of athematic calculations required during a procedure is thought to represent the computation of the SS approaches, as shown in Figure 14. It can be seen that the use of HMF improved spectral efficiency while also making the framework more complex. The complexity of the framework is additionally increased by the use of the Fourier transform. For HMF, the number of convolutions is $N * \left(\frac{S}{2} log_2(S)\right)$ (2889, 5779) for HMF and $2N * \left(\frac{S}{2} log_2(S)\right)$ (5778, 11,337) MF, as well as the additions $S * \left(log_2\left(\frac{N}{2}\right)\right)$ (89, 108) for HMF, and $N(2 * log_2(N))$ (169, 400) for MF, that are necessary to achieve a detection for N = 50 and 100 samples.

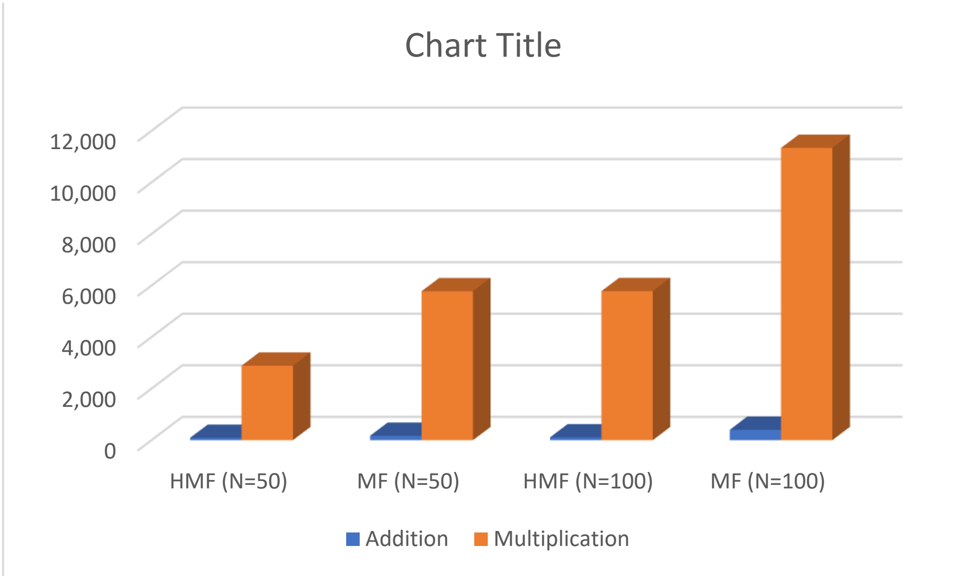

Figure 14. Complexity graph.

4. Conclusions

The proposed work highlights the capability of the HMF algorithm to sense the idle spectrum when the Pfa is greater than 0.5. The HMF and conventional MF algorithms are simulated for N = 100 and 50 samples, respectively. It is seen that the increasing number of samples will take more time to detect, and the complexity of the system will also increase. However, it enhances the performance of spectrum-sensing algorithms. The proposed HMF will take 21 s to simulate 100 samples, whereas the conventional MF will take 17 s. The parameters such as Pd, Pfa, and BER are estimated for the Rican and Rayleigh channels. It has been seen that the proposed algorithm outperforms the conventional MF. In the end, it can be said that the proposed system requires a lot of computing power but works much better than existing methods in noisy environments.

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