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Research Article

USRP-Based Design and Implementation of Hybrid DSA Detection

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ABSTRACT

Different sensing techniques can be used to detect the white spectrum with dynamic spectrum access (DSA). The most famous sensing methods are the energy detection (ED) and matched filter (MF). Each method has its advantages and restrictions. The good features of these two methods can be gained by using combined configuration of the both, which is the hybrid sensing technique. In this paper, the performance of these three methods (individuals and hybrid) was studied by mathematical analysis, simulation design and real hardware implementation based on USRP N210. The analysis concentrates on the operational principles of DSA, limitations of each method, advantages and features of each one, and also the practical applications of each sensing method. Finally, this paper aims to submit better understanding of intelligent spectrum management systems and their importance in development of wireless communication technologies. The proposed hybrid techniques is the basic for future cognitive radio networks, due to its reliability and excellent efficiency of detection with keeping low complexity of wireless communication system. correct.

Keywords: DSA, SDR, sensing techniques, USRP N210.

INTRODUCTION

Wireless communication systems based on efficient utilization of the radio frequency (RF) spectrum, which is a finite and highly valuable resource. With the rapid growth of wireless services, including mobile communications, Internet of Things (IoT), and low-power wide area networks, the demand for frequency bands has increased significantly. However, large portions of licensed spectrum remain unutilized for long times [1], [2]. This efficiency has motivated researchs into more intelligent and flexible spectrum access paradigms.

Traditional spectrum sensing techniques, such as energy detection, matched filtering, and cyclostationary and many others have been used recently [4]–[6]. Among these methods, energy detection is particularly attractive due to its low computational complexity and no need to prior knowledge of the transmitted signal. The performance of energy detection method is highly sensitive to noise uncertainty and degrades significantly in low signal-to-noise ratio (SNR) conditions, which are common in practical wireless environments [7]. This limitation is especially relevant for low-power communication technologies such as LoRa, where signals may be received close to the noise floor.

Recent research has therefore focused on adaptive spectrum sensing techniques that dynamically adjust sensing parameters based on environmental conditions [8], [9]. Adaptive processing can be achieved by continuously estimating noise statistics, adjusting detection thresholds, or incorporating learning-based mechanisms. Such approaches improve robustness against noise variations, interference, and channel dynamics, making them more suitable for real-world deployments. In other hand, matched filter sensing method is more robustness against noise variations, since it depends on prior knowledge on signal characteristics.

Software Defined Radio (SDR) platforms provide an ideal framework for implementing and evaluating adaptive spectrum sensing algorithms in practice. By performing signal processing tasks in software rather than hardware, SDR enables flexible modification of sensing algorithms, parameters, and architectures [10]. Furthermore, SDR-based experimentation bridges the gap between simulation-based studies and real RF environments, which is often a limitation in purely theoretical research.In this research, an adaptive SDR-based spectrum sensing system is proposed that integrates both offline and online sensing phases. The offline phase is used to characterize the RF environment, estimate noise and signal statistics, and design adaptive detection thresholds.

The online phase performs real-time spectrum sensing using parameters learned offline while continuously adapting to environmental changes. The system is experimentally implemented using a USRP platform as the sensing receiver, an arbitrary waveform generator to emulate controlled transmissions, a LoRa transmitter to represent real low-power signals, and a spectrum analyzer to validate actual spectrum occupancy. The contributions of this work include the development of an adaptive sensing methodology, practical SDR-based implementation, and experimental validation of sensing performance using multiple signal sources. The outcomes of this research aim to provide insight into the effectiveness of adaptive spectrum sensing techniques in realistic wireless environments.

Dynamic Spectrum Access

Dynamic Spectrum Sensing techniques are used to dynamically detect the presence of licensed users (primary users) in a particular frequency band. The unused portions of the radio spectrum, known as spectrum holes or white spaces. When the primary users are absence, unlicensed users (secondary ones) can use these frequency bands temporarily, without causing interference to primary users.

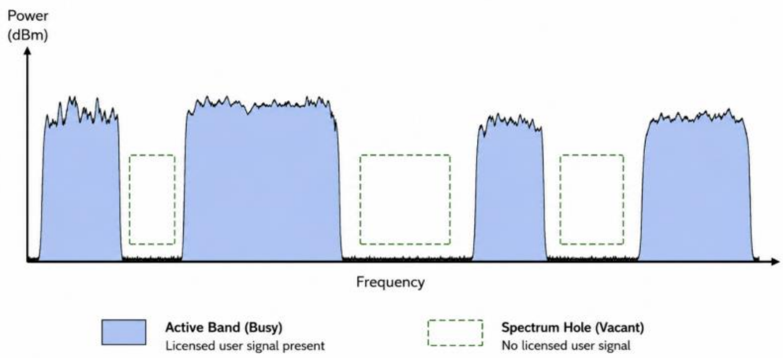

Figure 1. White spaces in frequency spectrum.

The main purpose of this is to efficiently improve the frequency spectrum by continuously monitoring the radio frequency regions and dynamically detecting the availability of white spaces. Spectrum sensing techniques enable wireless systems to adapt to changing network conditions.

To do this process, efficient spectrum sensing techniques are needed, which rely on the following:

- **Use the idle spectrum bands**
- **Leave the licensed spectrum bands immediately when the primary user is present.**

Optimal utilization of frequency spectrum

The efficient and effective use of spectrum depends on the following basic principles:

- **Spectrum sensing**
- **Spectrum sharing**
- *Spectrum mobility*
- **Spectrum decision**
- **Cognitive radio**

Figure 2 illustrates the cognitive radio cycle.

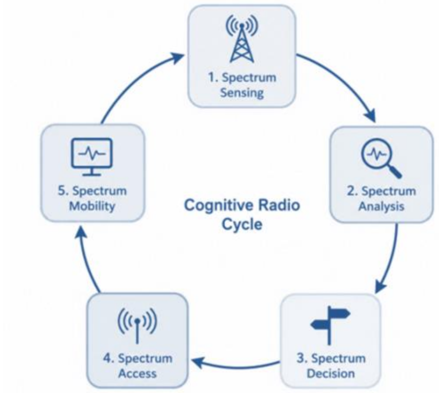

Figure 2. Optimal utilization of frequency spectrum.

Spectrum Sensing process

The basic idea of Dynamic Spectrum Access sensing or spectrum sensing in cognitive radio systems is to decide if the primary user is present (the signal is detected) or the specific channel is empty (noise only). The process is well explained in figure 3 . The orange curve represent there is only background noise, while the blue curve indicate that the primary user is in process**.** The decision threshold is the dashed vertical line. depending on this line :

[1] **Left side of threshold line, *no primary user detected.***

[2] **Right side of threshold line, *primary user detected.***

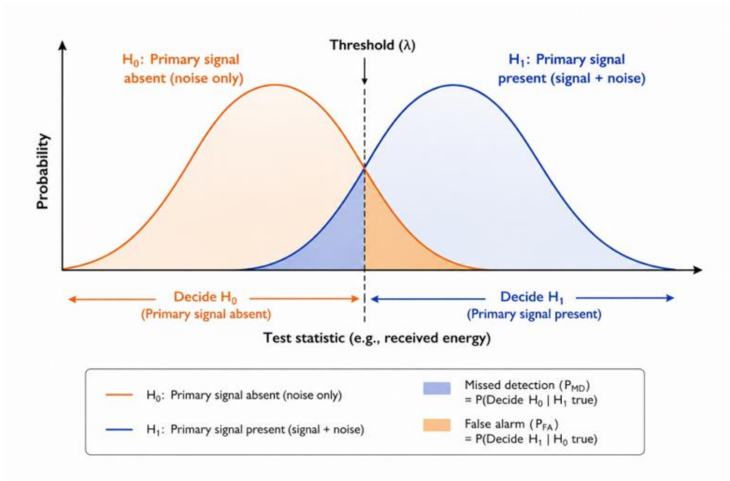

Figure 3. Detection principles of DSA.

Energy detection techniques

The energy detection sensing method is one of non-coherent signal detection techniques which used to determine the presence of signal in a specific frequency band. The main feature of this method that it does not require prior knowledge of the signal's statistics. Figure 4 shows flowchart of ED.

Spectrum occupancy detection based on by measuring the energy level of the signals. This method works under two hypothesis (H_o and H_1):

$$\begin{cases} H_0(noise\ only):\ x(t) = n(t) \\ H_1(signal + noise):\ x(t) = s(t) + n(t) \end{cases} \ldots.(1)$$

$$E_{level} = \int_0^T |x(t)|^2\ dt \ldots.(2)$$

If $E_{level} > \lambda$ → signal present

If $E_{level} < \lambda$ → noise only

Probability of false alarm (P_{fa}) is as follows:

$$P_{fa} = P(E_{level} < \lambda \,|H_0) \; \ldots .(3)$$

Probability of detection (P_d) is:

$$P_d = P(E_{level} > \lambda \,|H_1) \; \ldots .(4)$$

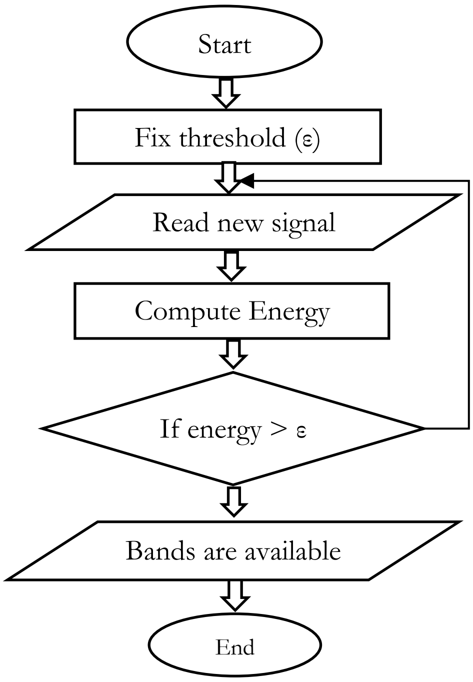

Figure 4. Energy Detection Process

Matched filter techniques

Matched filter is the optimal spectrum sensing technique used to determine the white space in frequency bands by detecting the absence of a licensed user's transmission. this method can maximizes the signal to noise ratio (SNR) in the case of Gaussian noise effect. Figure 5 shows flowchart of MF.

The same hypothesis apply for MF

$$T_{est} = \int_0^T x(t).\,s(t) \;\; dt \; \ldots .(5)$$

Yes, Return 0 No, Return 1

If $T_{est} > \lambda \rightarrow H_1$

If $T_{est} < \lambda \rightarrow H_0$

Probability of false alarm (P_{fa}) is as follows:

$$P_{fa} = Q\left(\frac{\lambda}{\sqrt{\sigma^2 A^2}}\right) \ldots . (6)$$

Probability of detection (P_d) is:

$$P_d = Q\left(\frac{\lambda - A}{\sqrt{\sigma^2 A^2}}\right) \ldots . (7)$$

$$A = |s(t)| \ldots . (8)$$

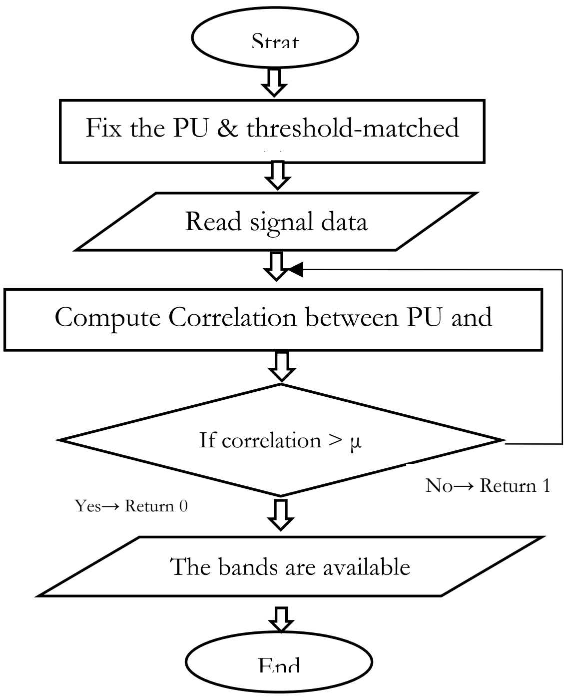

Figure 5. Matched filter process

Proposed Hybrid Sensing Techniques

To enhance the performance of DSA techniques, different approaches can be combined together in specific manner to achieve some required demand. Hybrid spectrum sensing is essential in Dynamic Spectrum Access (DSA) for wireless communication networks.

ED technique is known by its simplicity & low cost, while MF approach is famous by its high accuracy of testing. When these two techniques are merged together to obtain a new hybrid system, then the advantages of both methods can be gained and high performance may be achieved. The operation principle of the two methods is completely different, but here we try to achieve the advantages of both. Thus, energy detection and matched filtering are combined together to gain the useful characteristics of the both. It integrates low complexity of energy detection approach with the limitation of needing prior signal knowledge related to matched filtering.

Rapid signal detection and high accuracy can be achieved with this hybrid system. So, this combination leads to maximize spectrum utilization. Figure 6 illstrates tree diagram for the detection cases. Also, figure 7 shows flowchart of the proposed system.

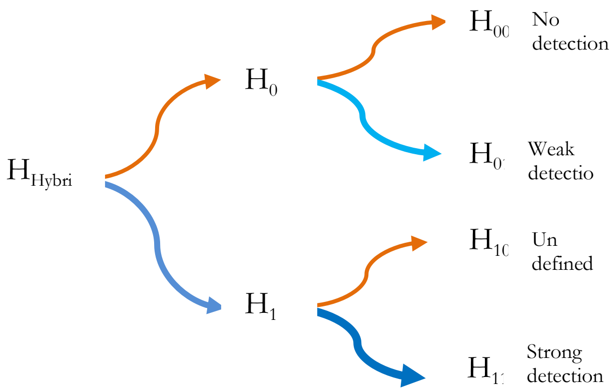

Figure 6. Principles of hybrid sensing technique.

The computation complexity of the hybrid system increases but the required processing time is highly reduced, although the spectrum testing accuracy is efficiently enhanced.

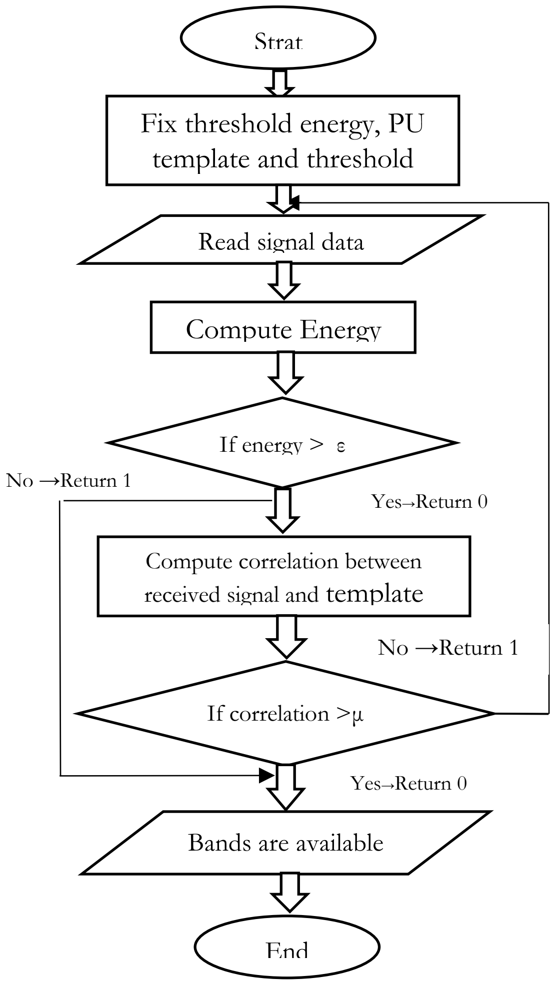

Figure 7. Hybrid ED and MF technique.

Performance Evaluation with Comparative Results

The main important and critical factors in any spectrum sensing systems, is the probability of detection and the probability of false alarm, which control the performance of sensing techniques.

- Pd is the probability of correctly detecting the signal of the primary user

- Pfa is the probability of incorrectly detecting a signal of the primary user (the spectrum is free).

The efficiency and reliability of the sensing system are evaluated depending on these two parameters for the dynamic spectrum access wireless communication systems.

The tested results of energy detection technique is shown in Table 1, that is include obtained results of Pd and Pfa for different values of signal to noise ratio (SNR).

Table 1. Detection and false alarm probabilities of ED technique.

SNR= -10		**SNR= -5**		**SNR= 0**		**SNR= 5**		**SNR= 10**	
Pfa	Pd	Pfa	Pd	Pfa	Pd	Pfa	Pd	Pfa	Pd
0.0	0. 0	0.05	0.28	0.01	0.65	0.98	0.00	0.00	1.00
0.10	0.20	0.10	0.42	0.03	0.82	0.995	0.05	0.10	1.00
0.20	0.32	0.20	0.58	0.07	0.91	0.997	0.07	0.30	1.00
0.40	0.54	0.40	0.79	0.15	0.96	0.998	0.09	0.50	1.00
0.60	0.72	0.60	0.90	0.30	0.99	0.999	0.10	0.70	1.00
0.80	0.88	0.90	0.99	0.50	1.00	1.00	0.10	1.00	1.00

For the same SNR values, the Pd and Pfa for matched filter are also computed and shown in Table. 2.

Table 2. Detection and false alarm probabilities of MF technique.

SNR= -10		**SNR= -5**		**SNR= 0**		**SNR= 5**		**SNR=10**	
Pfa	Pd	Pfa	Pd	Pfa	Pd	Pfa	Pd	Pfa	Pd
0.01	0.40	0.005	0.85	0.00	0.00	0.00	1.00	0.0	1.0
0.06	0.80	0.010	0.93	0.002	0.95	0.01	1.00	0.3	1.0
0.12	0.90	0.020	0.98	0.005	0.985	0.02	1.00	0.5	1.0
0.25	0.96	0.050	0.995	0.010	0.995	0.03	1.00	0.7	1.0
0.50	0.99	0.100	1.00	0.030	1.00	0.05	1.00	1.0	1.0

Figures 8&9 show the joints trajectory for the manipulator collapsing under gravity because the applied torques set to zero and continuous swing due to zero friction (ideal joint) also the 1st joint rotates due to coriolis effect in one direction because the links center masses right a side of base center.

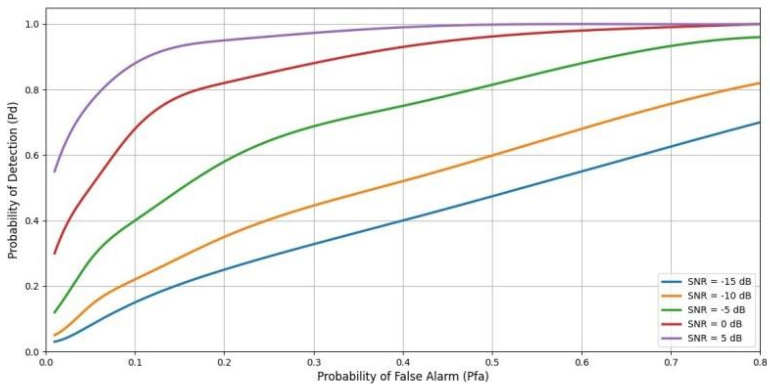

Figure 8. Probability of false alarm (PFA) vs probability of detection for different levels of SNR for ED technique.

Here, the relation between probability of detection and probability of false alarm is shown in figures 8&9 . All the obtained curves show that the sensing performance improves significantly for high values of SNR. At low values of SNR such as −10 dB, the probability of detection (Pd) is relatively low when Pfa values are small. This is due to small SNR that leads to weak received signal and then difficult to distinguish between noise and the weak signal. If the probability of false alarm increases, the signal detection gradually improves, with limited performance compared to higher values of SNR.

For medium values of SNR such as −5 dB, the detection probability increases more rapidly. The sensing capability becomes better than the SNR case, to identify the presence of primary since the signal strength in this case is more distinguishable from the noise. So, a noticeable improvement is obtained for dynamic spectrum sensing and also missed detections are reduced.

The best sensing is occurred for higher SNR levels such as 0 dB and more, the detection probability approaches the unity value (Pd≈1), even for low values of false alarm probabilities. This indicate efficient sensing performance, and hence, the sensing algorithm can accurately detect the signal and grantee the presence of the primary user with error probability as minimum as possible.

When the SNR is greater than 10 dB, the performance is accurate more than all cases, that achieves very high detection accuracy even witht small values of probability of false alarm (Pfa).

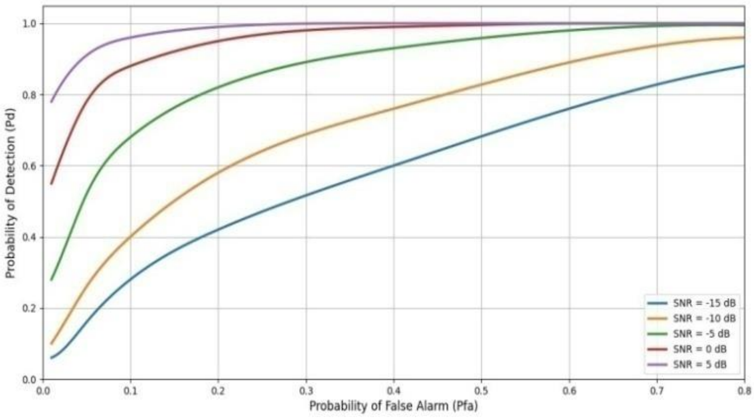

Figure 9. Probability of false alarm (PFA) vs probability of detection for different levels of SNR for MF technique.

The same discussion is applied for matched filter sensing capability, as shown in figure 10 . Thus the probability of detection is highly increased with increasing SNR.

The main important thing noticed from figures, is that the signal detection for matched filter (M.F.) technique is greatly better than energy detection technique (E.D.), for the same values of SNR. The three sensing methods, energy detection (ED), matched filter (MF) and hybrid ED & MF, are tested together and the values of Pfa are calculated for uniform varying values of Pd with zero value of SNR that presented in table 3 .

It is clear that the values of false alarm have large value range for energy detection sensing algorithm, while hybrid system takes lowest values of this parameters. Matched filter sensing is in between of ED and hybrid system. The Pfa reflects the frailer of detection process and so the specific algorithm cannot be dependent.

Table3. example that covers the width of the page.

	E.D.	M.F.	Hybrid
Pd	**Pfa**	**Pfa**	**Pfa**
0.0	0.955	0.935	0.885
0.10	0.957	0.938	0.890
0.20	0.958	0.940	0.895
0.30	0.959	0.942	0.942

0.40	0.960	0.944	0.96
0.50	0.961	0.946	0.905
0.60	0.962	0.947	0.908
0.70	0.963	0.949	0.912
0.80	0.964	0.950	0.916
0.90	0.965	0.952	0.920
1.00	0.966	0.954	0.925

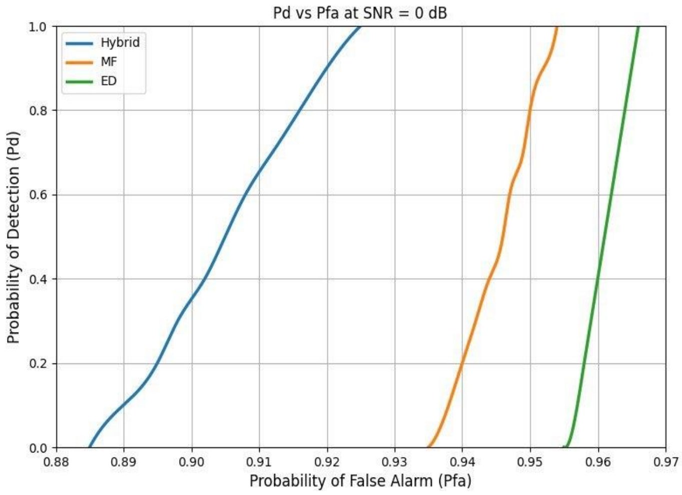

Figure 10. Probability of false alarm (PFA) vs probability of detection for different levels of SNR for Hybrid system.

The probability of false alarm is the least for hybrid system (of ED and MF), as shown in figure , that reflects an excellent performance of detecting process. While the energy detection technique has the largest value of Pfa among the three methods for same value of Pd. Thus the ED techniques shows a worst sensing performance compared to the others two tested methods. Matched filter take a moderate detecting behavior between energy detection and hybrid system. This is due to the cooperation of the ED and MF methods, so when ED algorithm fail to detect the signal then MF technique take his position to perform the detection process with high accuracy and reliable probability.

USRP based Real Time Hardware Implementation

USRP N210 was dependent to implement the hardware system of the dynamic spectrum sensing systems. The signal sources can be taken from the Gnu-radio software driven of this specialized hardware.

The USRP N210 based hardware implementation of energy detection techniques (ED), using GNU Radio, is shown in figure 11. The received signal is first transformed into the frequency domain using FFT block, to obtain the signal spectrum. The energy detection approaches was employed by using magnitude-squared energy estimation as well as threshold comparison blocks.

Matched filter algorithm hardware implementation is presented in figure 12. Special matched filtering was used to determine the similarity between the signals of the primary and secondary users, then threshold-based decision making block was needed to test the correlation between the signals. with the specified threshold value. This structure can improve detection process under low SNR conditions.

The proposed hybrid sensing system architecture, is shown in figure 13 . This system involves the combination of both energy detection and matched filter algorithms. Fast low-complexity sensing, is usually done using ED part while the MF part is used to improves detection process using prior knowledge of the signal information.

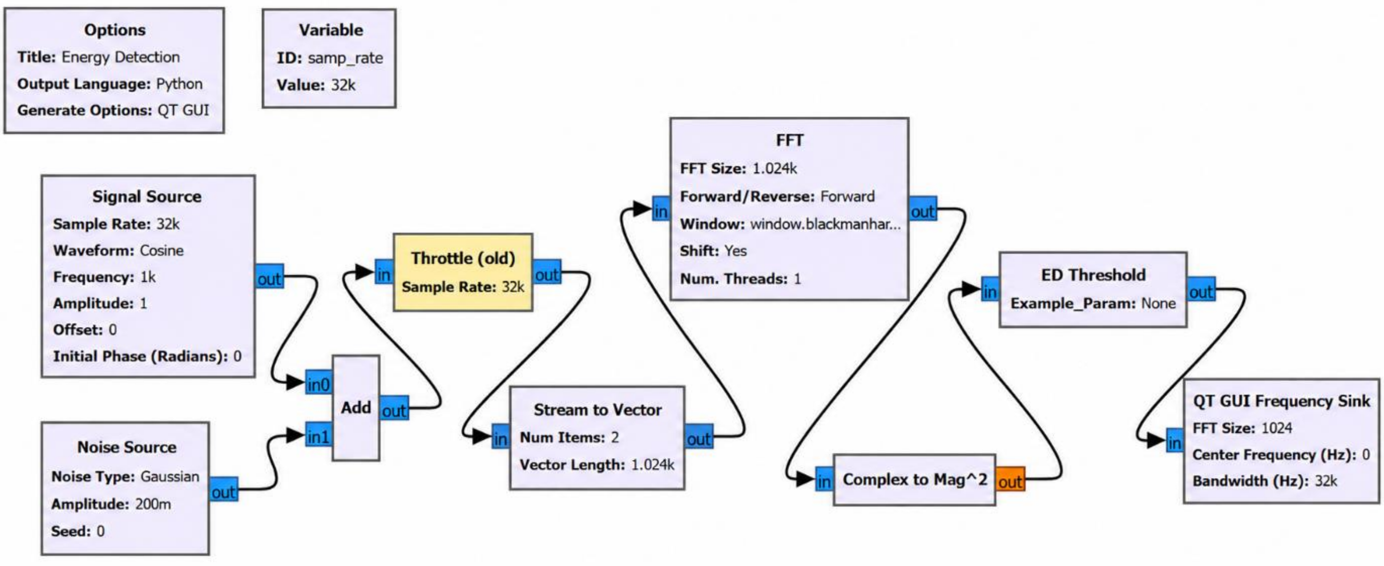

Figure 11. USRP N210 based hardware implementation of ED sensing system.

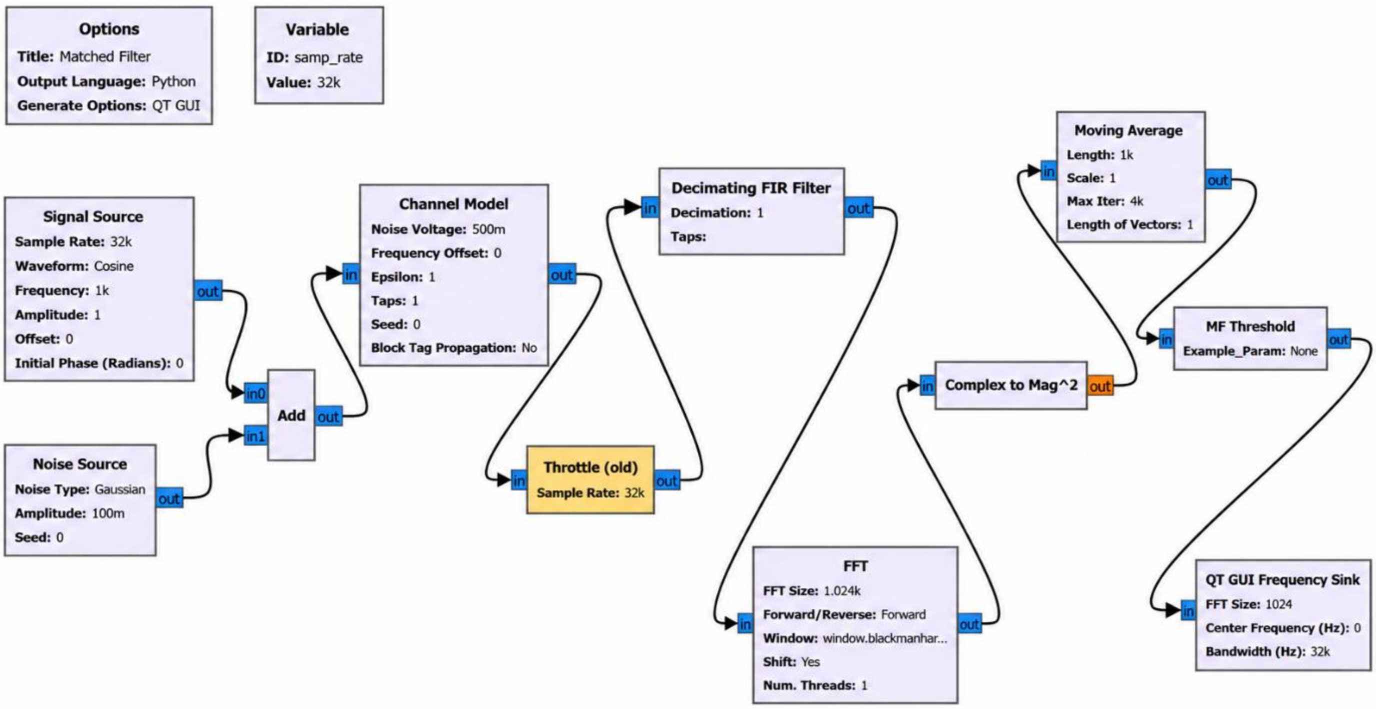

Figure 12. USRP N210 based hardware implementation of MF sensing system.

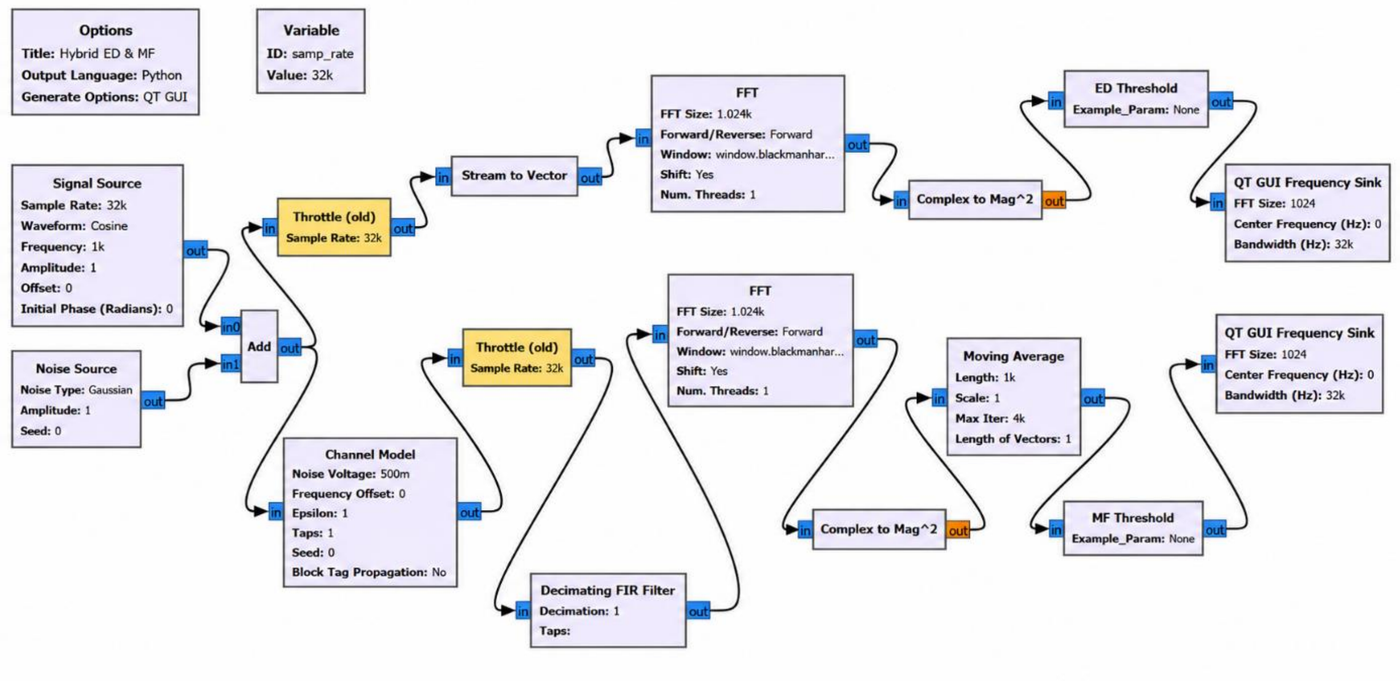

Figure 13. USRP N210 based hardware implementation of Hybrid sensing system.

CONCLUSION

The good performance of energy detection (ED) and matched filter (MF) as well as the hybrid system of the both, for signals detection and dynamic spectrum sensing demonstrates the effectiveness of these methods for the detection process in DSA and cognitive radio networks.

The results show that the energy detection technique is simple, cost effective, and easy to implement and it does not require any prior knowledge of the received signal. However, its performance decreases significantly under low (SNR) conditions, leading to lower probability of detection and higher probability of false alarm.

Matched filter technique, on the other hand, provides better sensing accuracy and achieves higher detection probability even at low SNR values. This improvement is due to the use of prior information about the transmitted signal, which allows more reliable signal recognition and lower false alarm rates

Nevertheless, the matched filter method increases system complexity and requires additional knowledge of the primary user characteristics. The proposed Hybrid system take the advantages of both individual approaches. techniques. Thus, the developed system improves many factors related to transmission efficiency, such as, spectrum sensing ability, system reliability, probability of detection, compared to using individual sensing techniques. The Hybrid system also shows better adaptability to dynamic channel. The main think with the hybrid system, it achieves a good detection performance, with keeping acceptable computational complexity.

The study in this research confirms that hybrid system of dynamic spectrum sensing can significantly support the performance of cognitive radio systems. So, the proposed hybrid techniques is therefore can be dependant as a promising tool for future wireless communication system, especially when the applications need efficient and reliable spectrum utilization

This paper proposes a rapid future-oriented content analysis of wireless networks, aiming to explore emerging trends, technologies, and challenges. By focusing on advanced methodologies and predictive insights, it seeks to understand how evolving wireless network content can shape future innovations, enhance performance, and address potential issues efficiently.

ETHICAL DECLARATION

Conflict of interest: No declaration required. **Financing:** No reporting required. **Peer review:** Double anonymous peer review.

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