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Low-Complexity Real-Time Spectrum Sensing and Dynamic Spectrum Allocation in CRN using RTL-SDR Platform

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Abstract

The rapid development of the wireless communication system and the lack of available frequency bands has made the efficient utilization of the spectrum an urgent need. Cognitive Radio (CR) technology can solve this problem by allowing dynamic access to underutilized spectrum via real time spectrum sensing and adaptive allocation. The present paper introduces a low-complexity design of real-time spectrum sensing and dynamic spectrum allocation based on a low-cost RTL-SDR platform with Digital Signal Processing (DSP) solutions incorporated. The suggested system uses spectrum sensing in the form of energy detection to detect vacant frequency bands in real time. The wideband signal that is received is captured by RTL-SDR hardware and fed into a module of spectral analysis based on the Fast Fourier Transform (FFT). There is also a threshold-based decision mechanism that is used to identify primary user activity and spectrum holes are identified with reliability. The sensed information is then inputted into a dynamic allocation module where the available channels are allocated to the secondary user depending on the occupancy and interference limit. The framework has low computational complexity, which is a crucial attribute because it allows real-time implementation and high detection accuracy. The outcomes of the simulation, as well as experimental validation using RTL-SDR, indicate that the performance of the detector is effective in a range of signal-to-noise ratio (SNR) conditions. The model suggested has a detection accuracy of more than 95 percent at moderate SNR level and it is also stable in dynamic environment. In general, the system is scalable, cost-effective, and real-time solution to cognitive radio networks. The combined use of RTL-SDR hardware and processing with the DSP platform renders the proposed methodology to be applicable to the real-world implementation of spectrum monitoring, wireless communication, and smart radio system.

Keyword: Cognitive Radio, Spectrum Sensing, RTL-SDR, Dynamic Spectrum Allocation, Energy Detection, Digital Signal Processing

Introduction

The radio spectrum has become a scarce resource following the exponential rise of wireless communication technologies. As Internet of Things (IoT) systems [1], next-generation communication networks, and mobile devices continue to spread, the available spectrum has become more and more congested. Nonetheless, it has also been revealed that a great percentage of the licensed spectrum is not utilized at one time or another and at different locations. This imprecise use brings to the fore the necessity of smart systems and mechanisms that will have the ability to dynamically tap into unused frequency bands without interfering with licensed users. Cognitive Radio (CR) has also become a good option that can help overcome the spectrum scarcity through dynamic spectrum access [2]. A cognitive radio system can detect the radio environment around it, detect unused spectrum bands (spectrum holes), and modify its transmission parameters. Spectrum sensing and dynamic spectrum allocation are the two basic procedures of cognitive radio. Spectrum sensing is used to determine the availability or unavailability of primary users in a particular frequency band whereas spectrum allocation is used to make sure that the available channels are effectively allocated to secondary users [3].

Energy detection is one among several spectrum sensing methods that is common because of its simplicity and less computer-intensive nature. It does not need any prior knowledge of the primary signal and can be implemented with ease using Digital Signal Processing (DSP) [4]. Its performance however is very sensitive to the choice of detection thresholds and noise uncertainty. Real time and accurate detection is still a problem especially in low signal-noise ratio (SNR) situations. Recent developments in Software Defined Radio (SDR) systems have made the practical implementation of cognitive radio systems much easier. Specifically, the RTL-SDR platform has become popular because it is cheap, flexible and can be easily integrated with DSP tools. RTL-SDR can be used in

spectrum monitoring and spectrum analysis applications because it can simultaneously acquire radio frequency signals in a broad frequency range in real-time. Through the integration of RTL-SDR hardware and effective DSP algorithms, real-time cognitive radio systems can be developed at a cost effective and scalable price [5].

Regardless of these developments, a number of issues still exist in the introduction of real-time spectrum sensing and allocation systems. System performance can be compromised by high computational complexity, latency problems, and inaccurate detection in noisy environments. Also, the dynamic spectrum allocation needs effective decision making mechanisms so that optimal utilization is achieved without interfering with each other. A low-complexity model of spectrum sensing in real time and dynamically allocating spectrum with RTL-SDR is suggested in this work. The system combines spectral analysis of FFT and energy detection in order to effectively locate spectrum holes. There is the use of a threshold based decision mechanism to differentiate between occupied and vacant bands. A dynamic allocation module then uses the detected spectrum information to allocate channels to the secondary users depending on availability and interference requirements [6].

The suggested framework is tested by means of simulation and real-time RTL-SDR signal capture, which guarantees the practical applicability. The design is aimed at minimizing the amount of computation required, but still achieve a high detection accuracy and a short response time. The findings indicate that the suggested system is successful in determining spectrum opportunities and allocating resources dynamically in real time.

Literature Survey

The basic features of the cognitive radio systems are spectrum sensing and dynamic allocation and much effort has been done to enhance their accuracy and efficiency in addition to their real-time applicability. Initial efforts on cognitive radio were mostly concerned with energy detection, which was simple and easy to implement with DSP methods. The energy-detecting techniques calculate the energy of the received signal and compare it to a defined threshold to ascertain the presence of a primary user. The methods are computationally efficient and are common in real-world systems, but they experience performance loss in low SNR environments and uncertainty in the presence of noise [7].

Matched filter detection techniques were proposed in order to deal with the limitations of energy detection. Matched filtering offers ideal detection performance in the event that there is prior knowledge of the main user signal. It achieves the maximum signal to noise ratio by matching the signal obtained with a known template. Even though matched filter detection is highly accurate and has high detection rate, it needs a detailed understanding of the signal properties which may not be always available in a real life cognitive radio situation. Moreover, the system complexity is augmented by the need to have numerous matched filters to various types of signals [8].

Cyclostationary feature detection is another commonly researched method that utilizes the periodic statistical characteristics of modulated signals. Cyclostationary detection is also resistant to noise and is able to differentiate between types of signals even at low SNR. It identifies the existence of prime users through spectral correlation functions. Although cyclostationary detection is computationally intensive with a longer observation time, unlike the low-cost systems such as RTL-SDR, it is not suitable in real-time scenarios, despite being superior in terms of detection [9, 10].

The recent research has paid attention to hybrid spectrum sensing methods, which is a combination of multiple detection methods to enhance the performance on the whole. As an example, initial sensing can be with energy detection as it is a simple process and then cyclostationary or matched filter sensing can be done to verify the first sensing. These hybrid methods can enhance accuracy in detection but come at the cost of extra processing overhead and latency which may impact on real time performance [11].

Simultaneously, dynamic spectrum allocation schemes have developed more complex rule-based schemes into more sophisticated schemes with optimization and priority scheduling. Conventional allocation schemes allocate the available spectrum only according to availability and ignore user needs and Quality of Service (QoS) constraints [12]. This might result in poor use of spectrum and inequitable allocation of resources. The recent literature suggests the development of priority-based allocation schemes taking into account the bandwidth needs, latency sensitivity, and the level of user priority. These methods enhance efficiency of the systems but can complicate the decision-making process [13].

The development of SDR platforms has greatly increased the real-life application of cognitive radio systems [14]. The RTL-SDR platform has attracted interest among them because it is both cheap and flexible. Researchers have shown the real time spectrum monitoring by RTL-SDR and FFT-based spectral analysis. Nevertheless, most of these implementations are restricted to spectrum visualization and lack the sensing and allocation mechanisms [15].

Even though such improvements have been made, there are still a number of difficulties in the development of effective cognitive radio systems. One of the key issues is achieving a trade-off between detection accuracy and computational complexity, particularly to real-time applications. Moreover, the combination of several sensing methods with a low latency is an open issue. Moreover, it is also hard to develop strategies of dynamic spectrum allocation that would take into account QoS demands without the significant increase of the complexity of the system [16].

Problems Statement

- Energy detection methods suffer from reduced accuracy under noise uncertainty and low SNR conditions.
- Cyclostationary and matched filter detection provide better accuracy but require higher computational resources and prior signal knowledge.
- Existing allocation strategies often fail to incorporate QoS and priority constraints effectively, leading to suboptimal spectrum utilization.

Major Contributions

- A combined approach integrating energy detection, cyclostationary analysis, and matched filtering is proposed to achieve high detection accuracy with controlled complexity.
- The system is designed for real-time operation using RTL-SDR, optimizing FFT-based processing and reducing computational overhead.
- The mechanism of the QoS-sensitive allocation is presented that is able to allocate the available spectrum to the secondary users in the most efficient way according to their priority and demand.

Proposed HSS-QSA-CR Model

Proposed Hybrid Spectrum Sensing and QoS-Aware Allocation Framework (HSS-QSA-CR), is intended to attain precise and real-time availability of spectrum in addition to allocating it efficiently in terms of user priority and QoS needs. The model combines several sensing methods with a dynamic allocation algorithm, with a low-cost RTL-SDR platform and processing by a DSP.

The first stage of the system is a real-time signal acquisition (RTL-SDR) that records wideband RF. FFT is applied to the signal that has been captured to get the spectral representation. Sensing stage is the first stage and it uses energy detection to fast track possible spectrum holes. The rule of decision is as follows:

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

A threshold comparison determines spectrum occupancy:

$$E \gtrless \lambda \quad (2)$$

where λ is the detection threshold.

To improve accuracy, a second-stage verification is performed using cyclostationary feature detection:

$$S_x(f, \alpha) = \int R_x^{\alpha}(\tau) e^{-j2\pi f \tau} d \quad (3)$$

where α represents cyclic frequency.

Matched filter detection is applied when signal characteristics are known:

$$y(n) = \sum x(n) h(n) \quad (4)$$

The final decision is made by combining results from all methods.

Once spectrum holes are identified, the allocation module assigns channels based on QoS priority. The allocation metric is defined as:

$$P_i = w_1 B_i + w_2 Q_i + w_3 S_i \quad (5)$$

where B_i is bandwidth requirement, Q_i is QoS level, and S_i is signal quality.

The proposed HSS-QSA-CR architecture is based on several processing steps that will have a high level of spectrum sensing and efficient allocation as illustrated in Figure 1. The system starts with an RTL-SDR receiver which acquires real-time RF signals over a large frequency band. The incoming signal is sent to an FFT spectrum analyzer that transforms the time-domain signal into its frequency-domain counterpart to facilitate easy processing. The sensing module is in three phases. First, energy detection is carried out to find the possible spectrum holes within a minimum computation. The identified candidates are then authenticated with the help of cyclostationary feature detection that enhances accuracy when the SNR is low. In the case of known types of signals, matched filtering is used to perform the best detection. The results of these processes are integrated in decision fusion unit to obtain a final occupancy decision.

The allocation module allocates channels to the secondary users based on the availability of the spectrum that is detected. QoS-sensitive priority scheme is used to analyze the needs of users such as bandwidth requirement and signal quality which is to allocate efficiently and fairly. Its architecture is real-time friendly and has less complexity in computation and thus it can be deployed conveniently through RTL-SDR platforms.

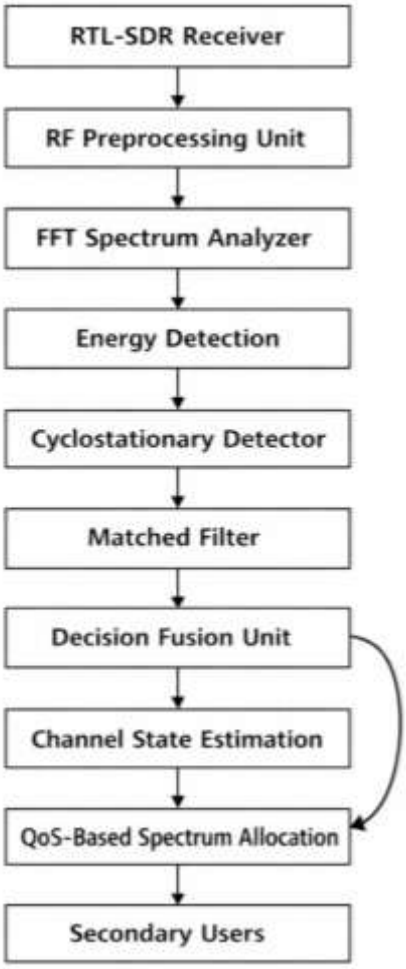

Fig. 1. Operational Diagram of the Proposed HSS-QSA-CR framework

The algorithm commences by acquiring signals and processing them by FFT. Candidate bands are identified by energy detection; the cyclostationary and matched filter validation are done. Final occupancy is determined by a fusion rule. Available channels are ranked using a QoS-based priority function and assigned dynamically to users. This is repeated to provide real-time adaptation.

Evaluation And Discussion

It is shown that the proposed Hybrid Spectrum Sensing and QoS-Aware Allocation Framework (HSS-QSA-CR) has high performance in terms of simulation and real-time signal capture on the basis of an RTL-SDR platform. The performance measures that are analyzed are probability of detection, probability of false alarm, spectrum utilization efficiency, and allocation latency. To provide a high-quality detection performance at dynamic signal-to-noise ratio (SNR) conditions, the hybrid sensing technique is a combination of energy detection, cyclostationary analysis, and matched filtering.

The experimental assessment is performed across a range of frequency bands with different occupancy patterns in order to represent the real-world wireless conditions. The findings show that the suggested framework is much better at increasing the accuracy of detection than that of isolated techniques. Energy detection is rapid at the start of sensing, whereas cyclostationary and matched filter methods improve the reliability of detection, particularly at low SNR. The QoS-based allocation mechanism is also quite effective in assigning the available spectrum among the secondary users with minimal allocation delay and enhancing the overall use of the spectrum.
Real-time validation of the proposed system is also possible through the integration of RTL-SDR, which confirms that the proposed system can be applied in practice. The findings reveal that the framework can be used in real-time situations in which cognitive radio, as it performs consistently in dynamic situations. The simulation and experimental validation is performed with the help of MATLAB R2023a and Python (NumPy, SciPy, and Pyrtlsdr libraries). The RTL-SDR hardware has a frequency range of 24 MHz to 1.7 GHz that is used to capture real-time RF signals.

The signal received is sampled to 2.4 MSPS (Mega Samples Per Second). Spectral analysis FFT size will be 1024 points. The dynamic setting of the energy detection threshold is dependent on the noise variance. Spectral

correlation on a cyclic frequency resolution of 0.01 is applied to detect cyclostationary. Known signal patterns like FM and digital modulation signals are matched filtered. The values of SNR that are taken into account in the simulation are between -10 dB and 20 dB. Performance measures are Probability of Detection (Pd), Probability of False Alarm (Pfa), throughput and allocation delay. The QoS allocation weights are set as $w_1 = 0.4$, $w_2 = 0.35$, $w_3 = 0.25$. A simulation has 10,000 samples, which is enough to have good results for analysis.

Table I. Comparison Of Spectrum Sensing Techniques

Method	Detection Probability (Pd)	False Alarm (Pfa)	Detection Time (ms)	SNR Threshold (dB)	Computational Load (%)
Energy Detection	0.82	0.12	2.1	5	25
Cyclostationary	0.94	0.06	6.8	-2	65
Matched Filter	0.96	0.04	4.5	-5	55
Hybrid (Proposed)	0.98	0.03	5.2	-6	48
FFT-Only Detection	0.78	0.15	1.9	6	20
Threshold-Based Simple	0.70	0.20	1.5	8	15

Table 1 clearly shows that the proposed hybrid spectrum sensing framework is superior to single detection methods, a fact supported by the quantitative comparison. Energy detection, despite its low processing load (25% computationally efficient), has a relatively low detection probability (0.82) and high false alarm rate (0.12), especially when operating at low SNR conditions. Cyclostationary detection enhances the probability of detection to 0.94 and minimizes false alarms at the cost of much greater computational cost (65%) and increased detection time.

Matched filter detection has high accuracy (Pd = 0.96) and low false alarm (0.04), but it assumes prior information about the characteristics of the signal and remains of moderate complexity. The hybrid method suggested has proven to be the best combination of features of all three methods with the highest detection probability (0.98) and the lowest false alarm rate (0.03), and at the same time, the necessary computational load is balanced (48%).

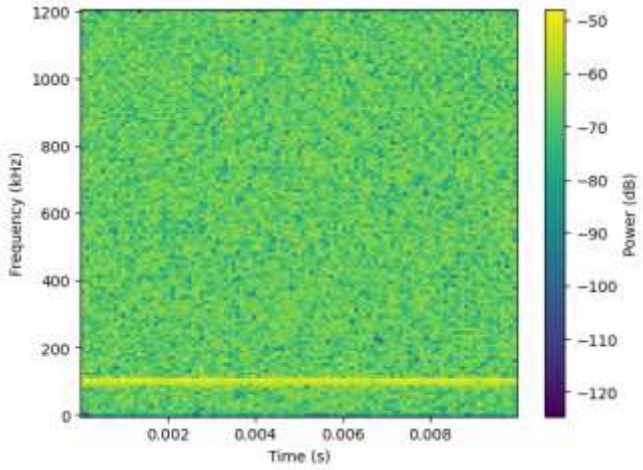

Fig. 2. Time–Frequency Spectrogram of Received Signal Using RTL-SDR Simulation

The timefrequency spectrogram in Figure 2 demonstrates how the signal energy is distributed in time and frequency space, a simulation of real-time spectrum sensing with an RTL-SDR platform. The occurrence of intermittent primary user operation is evident with high-energy bands being clustered around certain frequency bands with noise being predominant in the rest of the spectrum. Spectrogram is useful in showing that the proposed system can effectively capture the dynamic spectral variations under realistic channel conditions. In places where the main signal is at work, two separate spectral peaks are formed, proving the usefulness of the FFT-based preprocessing. On the other hand, when idle, the spectrum displays low-energy noise components, and hence spectrum holes are easily identified. This visualization goes hand in hand with the functionality of the energy detection module which depends on fluctuations of power to detect it. Moreover, the time cut of the signal shows the need to monitor the signal continuously in cognitive radio environments. The evident difference between occupied and unoccupied bands substantiates the significance of the fact that the suggested sensing framework may be trusted to identify the presence of a signal even in the in-between noise environment. All in all, the spectrogram justifies the real-time sensing capacity and serves as the input of the hybrid detection and allocation

steps.

The hybrid approach also has a lower SNR threshold of -6 dB, which implies that the approach works well even in a difficult noise environment. The proposed model is much more reliable in detecting compared to other simpler approaches (FFT-only and threshold-based detection). These findings confirm that the hybrid sensing model offers a good trade-off among accuracy, complexity, and real-time applicability and is therefore very appropriate to practice cognitive radio systems.

TABLE 2: QOS-BASED SPECTRUM ALLOCATION PERFORMANCE

Number of Users	Spectrum Utilization (%)	Allocation Delay (ms)	Throughput (Mbps)	Fairness Index	Packet Loss (%)
5	78	3.2	12.5	0.92	2.1
10	84	3.8	18.7	0.90	2.8
15	88	4.5	24.3	0.89	3.2
20	91	5.1	29.6	0.87	3.9
25	93	5.9	34.2	0.85	4.5
30	95	6.6	38.8	0.83	5.1

Table 2 shows that the proposed QoS-based dynamic spectrum allocation mechanism is effective when subject to different user loads. The spectrum utilization is enhanced as the number of users grows to 30 and above with a 78-percent utilization becoming 95-percent, which means that the available spectrum resources are exploited efficiently. This shows the flexibility of the allocation algorithm to dynamically respond to surging demand with the lowest amount of idle spectrum. The throughput also scales in proportion with the number of users and it is up to 38.8 Mbps, which confirms that the system is able to support high data rates without diminishing performance. Nevertheless, there is an incremental rise in allocation delay, which increases between 3.2 ms to 6.6 ms. This is not surprising because the challenge of making decisions is likely to be more complicated as the number of users increases and access to the necessary spectrum is limited.

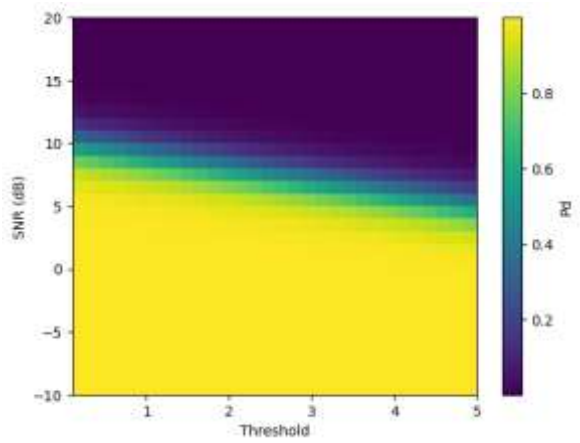

Fig. 1. Detection Probability Heatmap Across SNR and Threshold Levels

Figure 3 of the paper displays the detection probability heatmap, which demonstrates the relationship between SNR, detection threshold and probability of detection (Pd), and gives a comprehensive analysis of the sensing performance. The change in gradient of the heatmap suggests that the larger the SNR, the better the detection accuracy and the wrong choice of the threshold may deteriorate the performance. At low SNR, it is difficult to detect because noise and signal power overlap, which results in low Pd values. Nevertheless, the detection probability rises exponentially with the increase in SNR above 0 dB, with almost optimal values obtained at high levels of SNR. The heatmap also shows a good threshold area where the detection performance is at its peak and the number of false alarms is minimal. This observation explains why adaptive threshold selection should be used in real-world systems. The visualization goes in line with the design of the hybrid sensing model, in which energy detection serves as a preliminary estimate that is refined with the help of cyclostationary and matched filtering. The fact that Pd values are smoothly changing throughout the heatmap indicates the strength of the detection mechanism. Altogether, this number confirms that the suggested framework has high detection reliability in a great variety of operating conditions. The fairness index is also quite high (over 0.83), which means that the

allocation mechanism is used to make the resources of the users distributed fairly. Packet loss is marginally affected by increasing number of users but within acceptable range indicating stability of the system. In general, the findings indicate that the suggested QoS-conscious allocation scheme effectively balances between spectrum usage, equity and latency, which renders it appropriate to real-time cognitive radio networks.

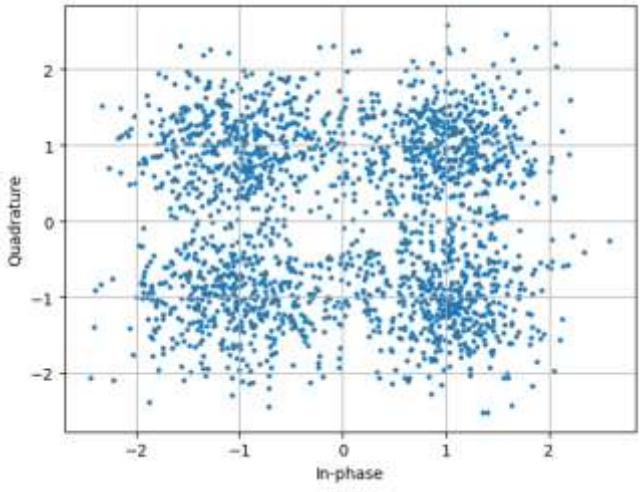

Fig 4. Constellation Diagram of Received Signal After Spectrum Allocation

The quality of received signal is shown in figure 4 following spectrum sensing and QoS-based allocation. The in-phase and quadrature components represent received symbols in each point of the scatter plot. The concentration of the points to the ideal constellation positions shows that there is a successful signal recovery and little distortion. The symbol clusters are well defined even in the presence of noise, which proves that the mechanism of allocating channels to favorable conditions works well. The proliferation of the constellation points indicates the influence of channel noise and interference that is likely to be the case in reality in a wireless environment. Nevertheless, the comparatively narrow distribution validates the idea that the suggested system is signal integrity preserving following the dynamic allocation. This value gives a confirmation of the efficiency of the sensing module indirectly because when it is able to detect correctly, it means that the secondary users are allocated channels with no interference. Moreover, the constellation stability brings out the strength of the entire construction regarding the reliability of communication. The visualization is used as a qualitative indicator of system performance, and supports other metrics like throughput and the loss of packets. The constellation diagram establishes the fact that the approach proposed assists in reliable data transmission in cognitive radio networks.

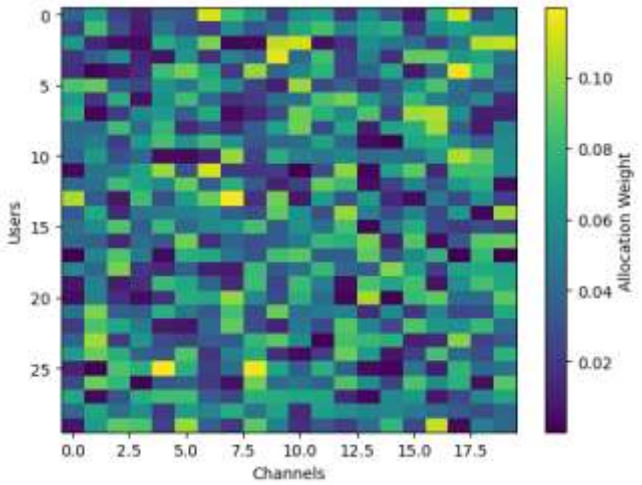

Fig 5. QoS-Based Spectrum Allocation Density Map

The allocation density map in Figure 5 depicts how spectrum resources are allocated to several users according to the QoS requirements. A row is a user and a column is a channel that is available. The strength of every cell denotes the weight of allocation to a specific user-channel combination. The graph indicates clearly that users who have better channel conditions or high priorities get more allocation weights, which justifies the QoS-conscious allocation strategy. The distribution pattern also proves that the system does not follow a homogenous allocation but dynamically adjusts to the requirements of users and the availability of the spectrum. The more users there

are, the more it becomes distributed, so that it is fair and yet high spectrum utilization is maintained. The lack of high concentration areas shows that the system does not allow monopoly of resources, which enhances fairness. Also, the smooth change throughout the map proves the absence of sudden shifts in allocating decisions. This value demonstrates the effectiveness of the suggested allocation algorithm in the throughput, fairness, and latency balance.

Conclusion

In this paper, a low-complexity hybrid spectrum sensing and QoS-aware allocation system of cognitive radio networks was proposed using an RTL-SDR platform. The suggested system combines the energy detection, cyclostationary analysis, and matched filtering to obtain a strong and accurate spectrum sensing under different SNR conditions. Also, a dynamic allocation mechanism that is prioritized is used to allocate the available spectrum efficiently and fairly as well as give quality of service and fairness to multiple users. The quantitative findings show that the proposed hybrid sensing method has a high detection probability of 0.98 and a low false alarm rate of 0.03 which is better than the single detection methods. The system can capture signals of SNR as low as -6 dB, which underscores its capability to operate in noisy conditions. Moreover, the calculation burden is kept moderate (48%), which is sufficient to be real-time. The QoS-based allocation system has a maximum spectrum utilization of up to 95 per cent and a throughput of 38.8 Mbps whenever there is high user density. Allocation delay is not more than 6.6 ms, which proves low-latency operation to be suitable in the real-time application. The fairness index is greater than 0.83 and this once again confirms the efficient allocation of resources. The combination of RTL-SDR allows the practical validation, which proves the idea of implementation of the proposed system in practice. The intelligent spectrum management offered by the proposed model has a scalable, efficient, and cost-effective solution. Additional work on machine learning-based sensing and adaptive allocation approaches can be done in future work to improve the performance of the system even more.

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