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Statistical Signal Occupancy Detection in Smart Wireless Systems

Nanda Kumar M[1], Arun Prabhakar[2]
[1]*Assistant Professor, Department of CSE, Guru Nanak Dev Engineering College, Ludhiana, India*
[2]*Assistant Professor, Department of ECE, Guru Nanak Dev Engineering College, Ludhiana, India*
Autor1 E-Mail: nandakumarselva@gmail.com **Autor2 E-Mail:** arunece46@gmail.com

ABSTRACT

Cognitive Radio (CR) systems enable adaptive spectrum usage by monitoring licensed bands and allowing unlicensed users to access idle frequencies without causing harmful interference. Conventional spectrum sensing approaches typically rely on high-rate sampling, leading to increased system complexity and processing delay. In this work, a statistical sensing framework based on probability density function (PDF) analysis is introduced, employing randomly acquired samples for reliable spectrum opportunity detection. The proposed approach minimizes the dependence on time-aligned sampling while improving detection accuracy. The effectiveness of the method is demonstrated through extensive MATLAB-based simulation results.

Keywords: Cognitive Radio, Spectrum Sensing, PDF, Random Sampling, Wideband Detection

I. INTRODUCTION

The rapid expansion of wireless services has exposed the limitations of fixed spectrum allocation policies. Cognitive Radio (CR) systems address this challenge by enabling secondary users (SUs) to opportunistically access underutilized licensed bands while ensuring minimal interference to primary users (PUs). Achieving this objective requires spectrum sensing mechanisms that are both highly reliable and time-efficient to enhance spectral utilization and protect licensed transmissions [1, 2]. In this study, an alternative sensing strategy is introduced to mitigate the drawbacks of conventional high-rate sampling techniques. The proposed approach exploits the statistical properties of the received signal through probability density function (PDF) estimation, enabling the detection of spectrum vacancies using a reduced number of samples. As a result, sensing duration and computational overhead are significantly lowered.

Conventional wideband sensing methods typically depend on high-speed analog-to-digital converters (ADCs) to satisfy Nyquist sampling requirements, leading to increased hardware complexity and power consumption in CR systems. To address these issues, random sampling-based approaches such as compressed sensing (CS) and histogram-oriented detection schemes have emerged as effective alternatives. By taking advantage of the inherent sparsity in wideband spectrum occupancy, these techniques allow accurate spectrum inference with fewer measurements, supporting low-complexity and energy-efficient sensing solutions [3, 4].

II. SPECTRUM MONITORING STRATEGIES

A variety of methods have been developed to determine spectrum occupancy, each offering distinct advantages and limitations. Energy-based detection identifies the presence of a signal by measuring the received power level. This method is straightforward and does not require any prior information about the transmitted signal, making it easy to implement. However, its reliability is strongly affected by noise

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uncertainty, often resulting in inaccurate decisions. Performance deteriorates considerably in low signal-to-noise ratio (SNR) environments, and the technique is unable to distinguish noise from actual user signals.

Cyclostationary feature detection utilizes the inherent periodic characteristics of modulated signals to differentiate them from noise. This approach performs well under severe noise conditions and remains effective even at low SNR levels. Additionally, it can successfully separate noise from structured signals. Nevertheless, the method involves high computational complexity and requires longer sensing durations due to the processing of cyclic features. Its effectiveness also depends on the existence of signal periodicity, which may not always be guaranteed.

Matched filter-based detection achieves optimal sensing performance when detailed knowledge of the primary user's signal is available. It provides rapid and reliable detection, particularly for weak signals, making it suitable for applications requiring high accuracy. Despite these advantages, the method demands precise synchronization and complete signal information, often necessitating multiple receivers for different signal types. These requirements increase system complexity, power consumption, and limit its applicability in dynamic spectrum environments (Fig. 1).

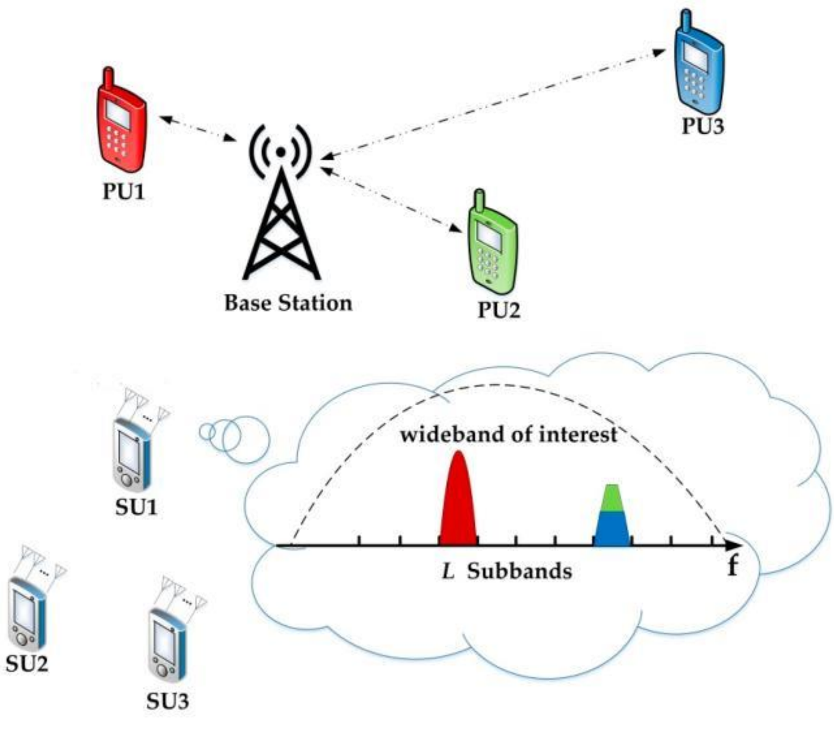

Figure 1: CR system Model [5]

III. SPARSE AND STATISTICAL SAMPLING TECHNIQUES FOR SPECTRUM AWARENESS

Recent studies indicate that combining compressed sensing (CS) with histogram-based analysis forms an effective framework for spectrum sensing in cognitive radio systems [6]. Compressed sensing enables the acquisition of wideband signals at rates below the Nyquist limit by exploiting the sparse nature of spectrum utilization across frequency bands. Using appropriate reconstruction algorithms, active spectral components can be identified without capturing the complete signal waveform.

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In contrast, histogram-based approaches particularly those involving probability density function (PDF) estimation from randomly collected samples facilitate signal detection without requiring precise time alignment. These methods evaluate the statistical distribution of signal amplitudes to determine primary user activity, maintaining reliable performance even under noisy conditions. Together, these techniques substantially reduce both hardware complexity and computational burden associated with wideband spectrum sensing. This reduction supports the development of energy-efficient, real-time cognitive radio systems suitable for practical deployment.

IV. STATISTICAL SIGNAL DETECTION USING RANDOM SAMPLES

This section presents a new spectrum sensing approach that relies on the statistical evaluation of randomly acquired signal samples. In contrast to traditional techniques that depend on synchronized or uniformly spaced sampling, the proposed method removes the requirement for precise timing, leading to reduced system complexity and lower processing overhead. The method functions by gathering signal amplitude samples at random intervals within a specified sensing period. A histogram is formed from these samples and subsequently processed to obtain an estimate of the probability density function (PDF). The resulting PDF captures the statistical characteristics of the received signal, exhibiting distinct patterns based on the presence or absence of primary user (PU) activity.

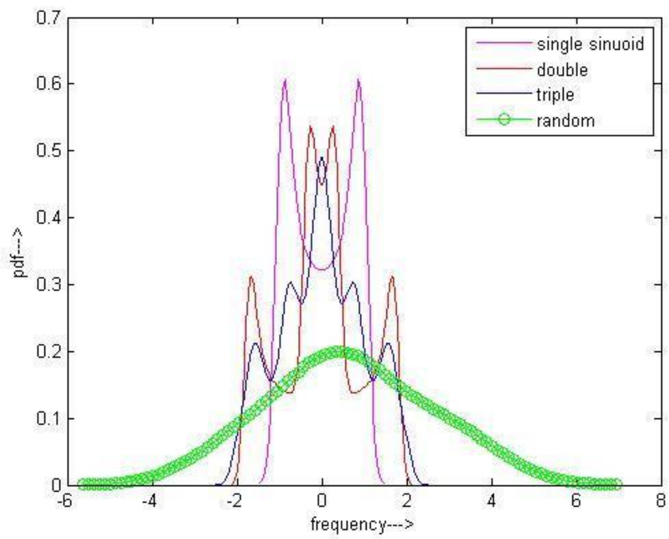

Figure 2: PDF of signals

Compressed sensing (CS) has become a prominent technique for wideband spectrum sensing by enabling signal acquisition at rates below the Nyquist limit through exploitation of spectrum sparsity [3]. Conventional CS-based methods, however, generally depend on accurate knowledge of sampling instants to enable reliable signal reconstruction. In contrast, the proposed approach eliminates this dependency by utilizing only amplitude-based statistical information extracted from nonuniformly sampled observations.

Spectrum occupancy is determined by comparing the estimated probability density function (PDF) with a predefined decision threshold, denoted by λ. A decision statistic Λ, derived from the deviation or structural characteristics of the estimated PDF, is used to distinguish between noise-only conditions and the presence of a primary user (PU). The corresponding decision criteria are defined as:

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$$P_f = P(\Lambda \geq \lambda \mid H_0)$$

$$P_m = P(\Lambda < \lambda \mid H_1)$$

where $H_0$and H_1represent the hypotheses of absence and presence of a PU, respectively.
System performance is evaluated using two standard metrics:

- Probability of False Alarm (P_f): the likelihood of declaring PU activity when the spectrum is unoccupied.
- Probability of Missed Detection (P_m): the likelihood of failing to detect PU activity when it is present.

These probabilities can be expressed as:

$$P_m = \int_{\Lambda \geq \lambda}^{\infty} P(x)\,dx \quad (1)$$

$$P_f = \int_{-\infty}^{\Lambda \leq \lambda} P(w)\,dx \quad (2)$$

Fig. 2 demonstrates the estimated PDFs corresponding to different signal categories, including single-tone signals, multi-tone combinations, and random waveforms. Each category yields a unique statistical distribution, allowing effective discrimination through PDF-based analysis.

Overall, the proposed framework is consistent with recent advances in compressed sensing and nonuniform sampling methodologies. By relying on the statistical distribution of signal amplitudes rather than precise sampling information, the method achieves efficient wideband spectrum sensing with reduced sample requirements and computational complexity, while maintaining robust detection performance in noisy environments.

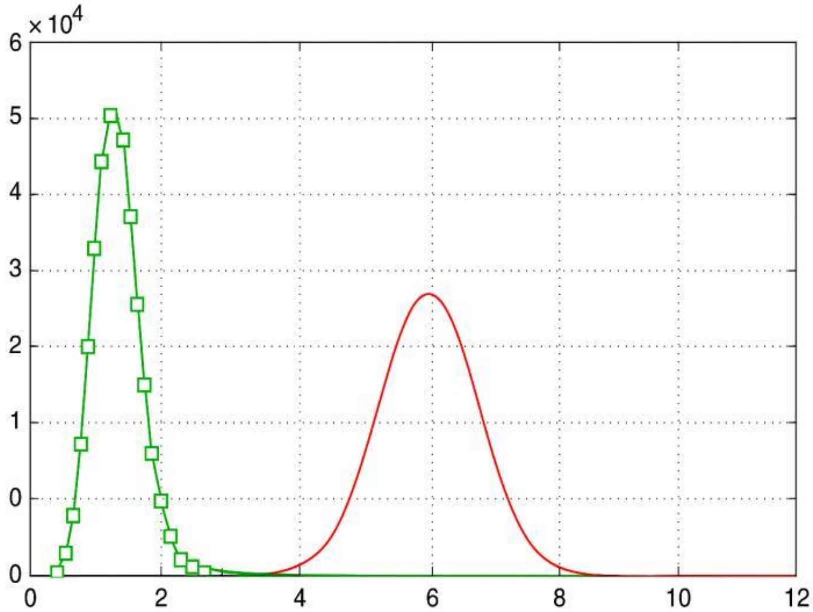

Figure 3: Probability of false alarm and the probability of missed detection

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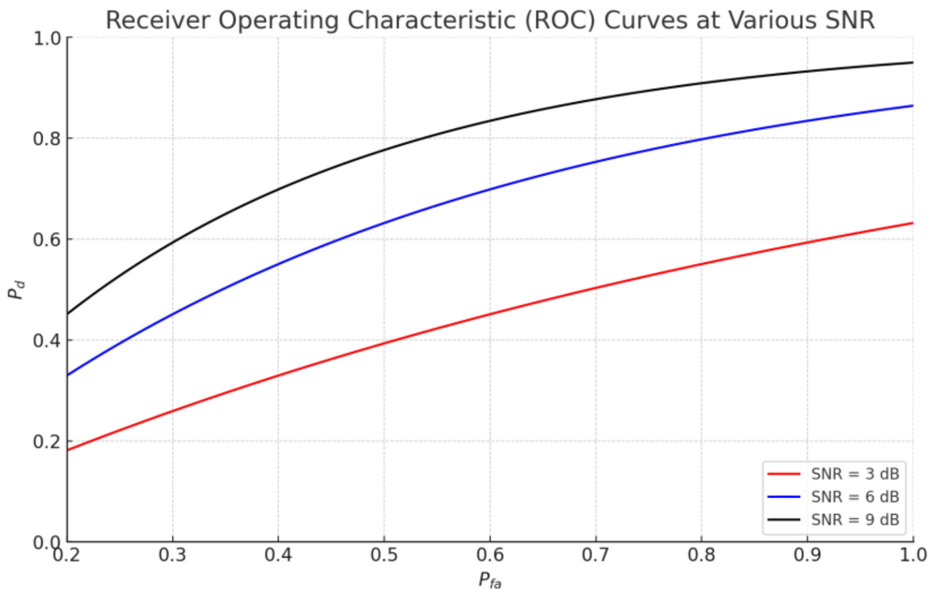

Figure 4: Receiver operating characteristics

V. PERFORMANCE METRICS

System performance is assessed using two key indicators: the probability of false alarm (P_f) and the probability of missed detection (P_m). The evaluation is carried out through MATLAB-based simulations considering various signal models, including single-tone, multi-tone, and random signals, in the presence of additive Gaussian noise. Receiver Operating Characteristic (ROC) curves are generated to examine the trade-off between P_f and P_m across different signal-to-noise ratio (SNR) values and antenna gain settings.

Fig. 3 illustrates the relationship between false alarm and missed detection probabilities, providing insight into the effectiveness of the proposed decision mechanism and its overall detection performance. Fig. 4 illustrates the Receiver Operating Characteristic (ROC) curves corresponding to different antenna gain settings, demonstrating the impact of gain variation on detection performance. The results indicate that the proposed approach maintains reliable operation under noisy conditions and exhibits improved robustness and decision threshold stability when compared with conventional energy detection methods.

VI. CONCLUSIONS

This paper presents an effective wideband spectrum sensing approach for cognitive radio networks that is based on probability density function (PDF) estimation using randomly acquired samples. By removing the dependence on time-aligned sampling, the proposed method significantly lowers computational requirements and reduces energy consumption. MATLAB-based simulation results demonstrate consistent detection performance across different signal models, even in the presence of strong noise. Compared with conventional energy detection schemes, the proposed technique exhibits enhanced robustness and improved decision reliability, as reflected in the Receiver Operating Characteristic (ROC) analysis. Owing to its low complexity and resilience to noise, the method is well suited for real-time operation in dynamic spectrum access scenarios. Future research will focus on hardware-level implementation and validation under practical spectrum environments.

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