A Comprehensive Study of Spectrum Sensing Techniques for Wireless Communication systems

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Abstract

The electromagnetic spectrum is a natural resource. The increase in the wireless applications, higher demand for bandwidth, more users have lead to spectrum scarcity. In this paper we made an extensive study of the techniques that will identify the white spaces or unused frequencies which are to be used by a secondary user. Herein, various types of spectrum sensing techniques are being explained along with their uses in terms of wireless communication technology which is being used in 5G communication.

Keywords : Spectrum sensing, Narrowband Spectrum Sensing, Wideband Spectrum Sensing, 5G communication.

Introduction

As wireless communication technology increases, so does the demand for bandwidth, resulting in increasingly restricted wireless spectrum resources. Cognitive radio (CR) has emerged as a promising solution to address the spectrum scarcity issue, with the main principle being dynamic spectrum access. The system may use idle spectrum without impacting primary users' rights. This allows several services or users to use a portion of the spectrum, reducing the need for costly spectrum resets and enhancing resource usage. To satisfy the essential demands of 5G mobile networks—namely, Wider Coverage, More Capacity, Connectivity, and Low Latency—the spectrum range utilized in 5G is expected to extend significantly, potentially covering frequencies from 1 GHz to 100 GHz, ushering in a full spectrum era.[1]. For 5G mobile communication systems Generalized Frequency Division Multiplexing a non-orthogonal waveform is used due to its flexibility and as cognitive radios (CRs) can cater to a variety of application requirements. GFDM addresses the significant issue of the high PAPR ratio of OFDM by potentially lowering it. Additionally, GFDM generates minimal out-of-band radiation due to the superiority of its root-raised cosine filters over the rectangular pulse-shaping filters used in OFDM, thereby reducing interference with adjacent frequencies. GFDM is particularly suitable for scenarios with fragmented spectra. Another notable feature of GFDM is the tail-biting cyclic prefix. (CP).[2].

Techniques used in Spectrum Sensing [1][2]:

Spectrum sensing is an essential aspect of wireless communication systems, particularly for those utilizing dynamic spectrum access or cognitive radio technology. Fundamentally, spectrum sensing involves radio equipment or systems detecting whether signals are present or absent within certain frequency bands or channels. This detection process employs various methods to assess the spectral environment and pinpoint vacant or less used bands of the radio frequency (RF) spectrum, which can subsequently be used for communication purposes.

1.1 Narrowband Spectrum Sensing:

- **Energy Detection:**

  Energy Detection technique is the simplest spectrum sensing technique. Energy Detection, monitors the energy level in the frequency range of interest and compares it to threshold which is predefined. If the measured energy exceeds tes threshold, it indicates the presence of a signal in that frequency band. Energy Detection is commonly used because of its simplicity and usefulness, particularly in circumstances where signal and noise properties are unknown or unpredictable[3]. However, it is important to note that, while Energy Detection is simple, it may not be ideal in all scenarios, especially when dealing with very low signal-to-noise ratios or non-Gaussian noise. This technique is commonly utilized in cognitive radio systems, spectrum sensing and other applications that need spectrum awareness for efficient spectrum use.

- **Matched Filter Detection:**

  This method compares the incoming signal to a known reference signal, often known as a "matched filter." The matching filter's purpose is to improve the SNR of the received signal, hence enhancing the detectability of the intended signal. Matched filter detection works better when the characteristics of the signal to be detected are known ahead of time, like in communication systems that use specified broadcast signal waveforms. By correlating the received signal with the matched filter, the approach takes finds the similarity between the received signal and the reference signal, enhancing detection performance. This method is commonly used in radar systems, communication systems, and other applications where the broadcast signal is known and may be used to provide a suitably matched filter for detection. When compared to energy detection, matched filter detection can give higher detection performance, especially in low SNR circumstances in presence of other interfering signals. [3]

- **Cyclostationary Feature Detection:**

  Cyclostationary detection takes use of the cyclostationary features of communication signals, which result from periodicities or cyclical patterns in the signal caused by modulation schemes or signaling formats employed in communication systems. Cyclostationary detection analyzes the signal in the cyclic frequency domain rather than only the time or frequency domains. This involves examining the cyclic autocorrelation or cyclic features of the received signal to identify certain periodicities or cyclical patterns that indicate the presence of a signal [2]. Cyclostationary detection outperforms other strategies, especially when signals are contained in noise or other interfering signals. By taking use of the intended signal's cyclostationary features, it can increase detection performance and interference robustness. This technology has several uses, including spectrum sensing for cognitive radio systems, signal identification in communication systems, and spectrum monitoring for spectrum control reasons. It is especially beneficial in situations where standard detection methods may be hindered by noise or interference.

- **Cooperative Sensing:**

  Cooperative Spectrum Sensing involves several users or cognitive radios working together to increase spectrum sensing accuracy and dependability. Each user does local spectrum sensing and then communicates its sensing data with other users to reach a consensus on the occupancy status of the spectrum with a primary user. Cooperative Spectrum Sensing has a few benefits over solo sensing approaches:

  1. Cooperative Spectrum Sensing can accomplish diversity gain by aggregating the sensing findings of several users, increasing detection reliability, particularly in fading or shadowing settings [4].

2. In instances where some users may be unable to recognize a primary user because they are in a concealed node situation, Cooperative Spectrum Sensing can offset this difficulty by utilizing information from other users who have superior sensing conditions [5].
3. It can also improve the resilience of spectrum sensing systems by merging data from different sources [6].

- **Sub-Nyquist Sampling Technique:**
  Sub-Nyquist sampling, also known as compressed sensing or under sampling, is the process of sampling a signal at a rate that is less than the Nyquist rate, which is twice the signal's maximum frequency. This technique exploits the sparsity or structure present in the signal to accurately reconstruct it from fewer samples than required by traditional Nyquist sampling. Sub-Nyquist sampling is beneficial for reducing sampling complexity and data processing requirements, particularly in wideband spectrum sensing applications where high sampling rates may be impractical.

1.2 Wideband Spectrum Sensing:

- **Sliced Sensing:**

  Sliced sensing is a technique used to improve efficiency and accuracy. It involves dividing the spectrum into smaller sub-bands or "slices" and performing sensing operations on each slice independently. This approach can be particularly useful in scenarios where the spectrum is wide and dynamic, allowing for more efficient use of resources and faster detection of spectrum opportunities. Sliced sensing can help in reducing the complexity of the sensing process and improving the overall performance of spectrum sensing systems.

- **Sweeping Receiver:**
  The receiver sweeps across a broad frequency range, successively tuning to various frequencies within it. At each frequency point, the receiver measures the received power level, resulting in a power spectrum measurement throughout the whole frequency range of interest. Wideband Spectrum Sensing generally detects signals by comparing measured power levels at each frequency point to a preset threshold [6]. When the measured power level reaches this threshold at a certain frequency, it indicates the presence of a signal in that frequency band. This is especially beneficial in situations when the spectral environment is dynamic or the properties of the signals of interest are unknown in advance. This approach gives a complete picture of the spectrum by sweeping across a large frequency range, allowing for the detection of both narrowband and wideband signals. This technique is widely utilized in cognitive radio systems, spectrum monitoring applications, and dynamic spectrum access networks, where precise and efficient spectrum sensing is critical for spectrum management and use. Furthermore, Wideband Spectrum Sensing may be integrated with other spectrum sensing techniques to enhance detection performance in complex and difficult settings.

- **Multiband Sensing:**
  Multiband Spectrum Sensing uses numerous narrowband sensors to cover different frequency bands at the same time. Each sensor detects a specific frequency range or group of frequency bands. The sensing findings from these various sensors are then integrated or aggregated to produce a complete picture of spectrum occupancy throughout the whole frequency range of interest. This aggregation may be accomplished using a variety of fusion approaches, including basic averaging, weighted averaging, and more advanced methods such as cooperative sensing algorithms.

1. Improved Coverage: By deploying numerous sensors to cover different frequency bands at the same time, Multiband Spectrum Sensing may provide larger spectrum coverage, guaranteeing that no frequency band goes unmonitored.
2. Reduced Complexity: Narrowband sensors are often easier and less expensive to deploy than wideband sensing technologies. Multiple narrowband sensors can simplify the complexity of individual sensors while yet providing broad spectrum detection.
3. Enhanced Reliability: Distributed sensing decreases the possibility of missing or incorrect detection events. Multiband Spectrum Sensing, which combines sensing findings from several sensors, can increase the reliability and accuracy of spectrum occupancy detection[].
4. Scalability: Multiband Spectrum Sensing may be readily scaled by adding or deleting sensors in response to changes in the spectrum environment or coverage needs.

- **Deep Sensing:**
  Deep sensing refers to the use of deep learning algorithms to address spectrum sensing challenges. Deep learning models, like CNN and RNN, are capable of automatically discerning complex patterns and features from raw data, making them useful for spectrum sensing in dynamic and diverse settings. Deep sensing can be used for various tasks, such as signal detection, modulation recognition, and interference mitigation. Deep learning models extract features from raw spectrum data, such as spectrograms or time-frequency representations, and use these features to classify signals or detect anomalies. One advantage of deep sensing is its capacity to adjust to changing signal circumstances and environments. Deep learning models may be trained on vast volumes of labelled data, allowing them to generalize effectively to previously unknown signals and noisy conditions. This flexibility makes deep sensing particularly effective in settings where the spectrum is extremely dynamic or when standard sensing techniques may fail to cope with the environment's complexity.

- **Cognitive Radio Network:**
  Cognitive radios use spectrum sensing to determine the presence of primary users (incumbent users) and find available spectrum resources.[6] This includes techniques like energy detection, cyclostationary detection, wideband spectrum sensing, and multiband spectrum sensing. Cognitive radios decide on spectrum access, channel selection, and transmission characteristics based on the findings of spectrum sensing. These selections are made intelligently in order to maximize spectrum use while maintaining interference mitigation and service quality. Can transition between different frequency bands or channels in real time in response to changes in the spectral environment. This allows for more effective use of spectrum resources while also accommodating fluctuating communication needs and interference circumstances. Cognitive radios utilize interference mitigation strategies to reduce the impact on main users and other cognitive radio users. This might involve spectrum sensing, spectrum sensing fusion, spectrum etiquette standards, and adaptive transmission techniques.

2 Some Studies on Spectrum Sensing Techniques in 5G.

HYBRID MATCHED FILTER DETECTION SPECTRUM SENSING [3]:

When the ratio of signal-to-noise is low, the Energy Detection performs poorly, and the Matched Filter Detection needs the primary user's prior information. The new technique described in this study performs better or on par with Matched Filter Detection and, in contrast to Energy Detection, performs well for low SNR. It explains the development, research, and assessment utilizing a series of MATLAB-based spectrum sensing simulations applied to Cognitive Radio. It aims to understand how changes in a few critical variables, Factors such as SNR, Probability of false alarm and detection number, samples, can influence the likelihood of a missed detection. This study examines two strategies for wide-spectrum sensing: energy detection and matched filter detection[3]. Using MATLAB simulations, an innovative Hybrid Matched Filter Detection technique is investigated, and its accuracy is compared to that of energy detection and matrix detector detection. This proposed hybrid method, which is based on matched filter detection, exhibits different behaviors depending on the specific conditions:

- The likelihood of false alarms is less than 0.5.
- The likelihood of a false alert exceeds or equals 0.5.

In this paper, the probability of false alarm is determined as:

$$P_{fa} = Q\left(\frac{\lambda-\sigma_n^2}{\sqrt{2\sigma_n^2/N}}\right)$$

Where, σ^2n= noise variance, P_{fa} is the probability

The probability of detection is defined as:

$$P_d = Q\left(\frac{\lambda-(P+\sigma_n^2)}{\sqrt{2(P+\sigma_n^2)^2/N}}\right)$$

Relationship between N, SNR and the probabilities can be explained as:

$$P_d = Q\left(\frac{Q^{-1}(P_{fa})\cdot\sqrt{2/N}-SNR}{\sqrt{2/N}\cdot(SNR+1)}\right)$$

The paper highlights the following analysis:

- The findings indicate that the Matched Filter Detection and Hybrid Matched Filter Detection techniques surpass the Energy Detection method when evaluated under the same parameters. Moreover, the proposed technique demonstrates superior performance over the Matched Filter Detection in the licensed spectrum.
- The false alarm probability is somewhat lower than 0.5, with a low SNR.
- The likelihood of erroneous detection increases towards 0.5 with fewer.

SUB NYQUIST CYCLOSTATIONARY DETECTION OF GFDM FOR WIDEBAND SPECTRUM SENSING [2]

Generalized Frequency Division Multiplexing is a multicarrier modulation technique that builds upon the principles of traditional OFDM by some additional degrees of freedom in time and frequency domains[2]. This allows for flexible waveform design and efficient spectrum shaping, making it suitable for various communication scenarios, including wideband spectrum sensing applications.

$$d=[d_{m,k}]_{MK\times 1}=[d_0,d_1\cdots d_{k-1}]^T$$

where $d_{m,k}$ signifies the specific symbol that is conveyed in the m^{th} sub symbol on K^{th} subcarrier of the block. Data $d_k[m]$ is upsampled by a factor N.

$$d_k^N[n]=\sum_{m=0}^{M-1}d_k[m]\delta[n-mN],\ n=0,\ldots,NM-1$$

where $\delta[\cdot]$ is the Dirac delta function. The pulse-shaping filter $g[n]$ is applied to the sequence $d_k^N[n]$, followed by digital subcarrier upconversion.

Then, a CP is used to avoid ISI. So $y[n]$ is represented as:

$$y[n] = x[n] \otimes h[n] + w[n]$$

wherein $\otimes$ denotes circular convolution operation, $\mathrm{h[n]}$ denotes channel impulse response and w[n] is AWGN. Spectrum Shaping: Spectrum shaping refers to the process of modifying the spectral characteristics of a signal to achieve specific objectives, such as reducing out-of-band emissions, improving spectral efficiency, or mitigating interference. In the context of GFDM, spectrum shaping techniques are employed to optimize the spectral characteristics of the transmitted signal according to the requirements of the communication system and regulatory constraints.

Sub-Nyquist Sampling Technique:

Sub-Nyquist sampling,is also called as the compressed sensing or under sampling, involves sampling a signal at a rate lower than the Nyquist rate is twice the highest frequency component in the signal. This technique exploits the sparsity or structure present in the signal to accurately reconstruct it from fewer samples than required by traditional Nyquist sampling. Sub-Nyquist sampling is beneficial for reducing sampling complexity and data processing requirements, particularly in wideband spectrum sensing applications where high sampling rates may be impractical. Cyclostationary detection is a signal processing technique to detect the presence of cyclostationary features in a signal. Cyclostationarity refers to the periodic or quasi-periodic statistical properties of a signal, which can arise from modulation, periodicity, or other underlying structures. Cyclostationary detection exploits these cyclostationary features to distinguish between signals and noise in a noisy environment, making it particularly useful for wideband spectrum sensing applications where multiple signals may be present.

The GFDM signal is treated as a zeromean Cyclostationary process, and the received signal may be represented as:

$$\tilde{x}_i(t) = \sum_{m_k}^{K-1} \sum_{m=0}^{M-1} d^{(i)}_{m_k,m} g_p\big((t - mT_s)T_B\big)$$

[where K is the number of subcarriers, M is the number of subsymbols, T_S is the symbol duration, T_B is the block duration, $\mathrm{d}^{(i)}_{\mathrm{mk,m}}$ is the transmitted symbol at the m^{th} symbol]

Frequency Fading and Frequency-Selective Fading: Frequency fading refers to the phenomenon where the signal experiences fluctuations in its amplitude and phase characteristics as a function of frequency. Frequency-selective fading, on the other hand, occurs when the fading effect varies across different frequency components of the signal. These fading effects are typically caused by multipath propagation, where signals travel via multiple paths with different propagation delays and attenuation levels. Frequency fading and frequency-selective fading can degrade the performance of wireless communication systems, necessitating the use of techniques such as equalization and diversity to mitigate their effects. The paper demonstrates the effectiveness of combining sub-Nyquist sampling and cyclostationary detection techniques for wideband spectrum sensing of GFDM signals, offering promising results for applications in cognitive radio, spectrum monitoring, and dynamic spectrum access.

OPTIMIZED WAVEFORMS FOR 5G-6G COMMUNICATION WITH SENSING [4]:

"Radio frequency (RF) convergence" describes the latest methods for addressing the challenge of limited spectrum by enhancing both sensing and communication capabilities simultaneously. This convergence is facilitated by the use of common hardware solutions, such as phased arrays, in both systems. Consequently, a Joint Communication and Sensing (JCAS) system in this paper was be developed using similar waveforms and hardware without compromising performance for either function[4]. JCAS research can be applied to various scenarios, including cellular networks, cooperative vehicular communication systems, and indoor mapping. In these contexts, the transmit antennas for both subsystems are assumed to be the same, enabling a single joint waveform to meet the needs of both subsystems.

Utilizing CRLB equations for range and velocity estimations from existing literature, the solution to the combined optimization of the two CRLBs for an OFDM JCAS system is analytically derived to determine the optimal radar subcarrier allocation.

In this paper [4] A computationally efficient solution is given for optimizing latency and Doppler CRLBs.

TX downlink is given by:

$$x(t) = \sum_{m\in\mathcal{M}} \frac{p(t-t_m)}{N} (\sum_{n\in\mathcal{R}_m} X_{\mathrm{r},n,m} e^{j2\pi f_n (t-t_m)}$$

The delay and doppler shift estimation is given by:

$$\mathbf{Y} = \mathbf{DXB} + \mathbf{V}$$

Power optimization for CRLB minimization is given by:

$$\mathrm{var}\{\hat{\tau}\} \geq \mathrm{CRLB}\ (\hat{\tau}),\ \mathrm{var}\{\hat{f}_{\mathrm{D}}\} \geq \mathrm{CRLB}\ (\hat{f}_{\mathrm{D}})$$

where,

$$\mathrm{var}\ \{\cdot\} = \text{variance}$$

$\mathrm{CRLB}\ (\hat{\tau})$ and $\mathrm{CRLB}\ (\hat{f}_{\mathrm{D}})$ denote the CRLB of the delay and Doppler estimate

The joint minimization of delay and Doppler CRLBs aims at finding the following:

$$\min_{P_{n,m},\mathcal{R}_m} \mathrm{CRLB}\ (\hat{\tau})$$

Subject to $\mathrm{CRLB}\ (\hat{f}_{\mathrm{D}}) \leq \phi$

$P_{\mathrm{r}} \leq P_{\mathrm{t}} - P_c,$

$0 \leq P_{n,m} \leq P_{\max},\ n \in \mathcal{R}_m, \forall m.$

The delay estimate's CRLB at this point is given by:

$$\mathrm{CRLB}\ (\hat{\tau}) = \phi \frac{\mathrm{NUM_c} + P_{\max} \sum_{m\in\mathcal{M}} \sum_{n\in\mathcal{R}_{m,\,\mathrm{act}}} \bar{t}_m^2 + \bar{t}_L^2 P_\Delta}{\mathrm{DEN_c} + P_{\max} \sum_{m\in\mathcal{M}} \sum_{n\in\mathcal{R}_{m,\,\mathrm{act}}} \bar{f}_n^2 + \bar{f}_K^2 P_\Delta}$$

The PAPR of the m^{th} OFDM symbol is:

$$\mathrm{PAPR}_{x_m[a]} = 10\log_{10} \frac{\max\{|x_m[a]|^2\}}{\mathbb{E}\{|x_m[a]|^2\}}$$

Cramer-Rao lower bound (CRLB):

The CRLB sets the lower bound on the variance of estimators for a deterministic parameter. It is used for performance analysis and optimization of various signal processing algorithms, such as channel estimation, synchronization, and parameter estimation.

Reasons why CRLB is widely used in 5G:

- **Performance Evaluation:** The CRLB provides a benchmark against which the performance of different estimation algorithms
- **Optimization:** By understanding the theoretical lower bound on the estimation error. This optimization is crucial in achieving the desired data rates, reliability, and latency requirements in 5G networks.
- **Resource Allocation**: Efficient utilization of resources such as bandwidth, power, and time is crucial.

Thereby we conclude that:

- This article is focused on optimizing OFDM waveforms for 5G–6G JCAS systems. It proposed filling empty subcarriers within the waveform with optimized frequency-domain samples to enhance the radar subsystem's performance. This optimization involves reallocating a portion of the power from communication subcarriers.
- The findings suggest that the optimization methods described effectively manage and reduce the CRLBs and RMSEs associated with range and velocity estimation, as well as the Peak-to-Average Ratio (PAPR) of the transmit waveform.
- RF measurements were conducted over-the-air at 28 GHz, utilizing both optimized and unoptimized 5G NR waveforms, within an outdoor environment sensing mapping scenario. These measurements aimed to showcase the enhancement in range side-lobe performance resulting from the optimization efforts.

CRLB: CRAMER-RAO LOWER BOUND TECHNIQUE [4]:

Cramer-Rao lower bound (CRLB) is a technique where the lower bound on the variance of estimators for a deterministic parameter is fixed. It is used for performance analysis and optimization of various signal processing algorithms, such as channel estimation, synchronization, and parameter estimation.

Reasons why CRLB is widely used in 5G:

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Limitations:

- Tradeoff between lower bounds and communication capacity.
- Inverse relation between lower bounds and peak side-lobe levels.

Ways to overcome the limitation:

- Design and optimize various system components, such as physical layer algorithms, medium access control (MAC) protocols, and network designs.
- Use adaptive transmission techniques to vary the transmission parameters based on noise, channel parameters and system requirements.
- **Adaptive Modulation and Coding (AMC):** AMC changes the modulation order and coding rate dependent on the channel circumstances. larger modulation orders and lower coding rates can be employed to obtain larger data rates in favorable channel circumstances, but lower modulation orders and higher coding rates are preferred in poor conditions to ensure stable communication.
- DSA approaches allow for flexible allocation of frequency bands based on spectrum availability and interference.

CONCLUSION:

In this paper a detailed study of various spectrum sensing techniques has been done. It is found that the CLRB can be used to increase Efficient utilization of resources such as bandwidth, power, and time is crucial. But simultaneously AMC can be applied for better data rates. The sub-Nyquist sampling and X`cyclostationary detection techniques for wideband spectrum sensing is good to identify low SNR and faded signals. Hence an extensive study has been done.

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