Hardware Emulations

using 5G Toolkit and SDRs: Hands-on

GIGAYASA

For academia only

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1 | Analysis of Wireless Channel Spectrum using ADALM-Pluto SDR

Wireless spectrum refers to the range of electromagnetic radio frequencies used for wireless communication. It encompasses all the frequencies used for transmitting data wirelessly, including radio waves, microwaves, and infrared radiation. The wireless spectrum is a critical resource for various communication technologies, including radio and television broadcasting, mobile communication, Wi-Fi, satellite communication, and many other wireless applications.

1.1 | What is a Wireless Spectrum Analysis?

Wireless channel spectrum analysis involves the examination and study of the frequency spectrum characteristics of a wireless communication channel. The goal is to understand the frequency distribution, channel conditions, and potential sources of interference in a given frequency band. Thw wireless channel spectrum is analyzed for following purposes,

- **Frequency Spectrum Overview**: It involves identifying the frequency bands available for wireless communication and understanding the allocation of frequency ranges for various services.
- **Channel Characteristics**: Analyzing the characteristics of individual communication channels within the spectrum. This includes studying factors such as bandwidth, signal strength, noise levels, and other parameters that affect the quality of communication.
- **Interference Detection**: Identifying and analyzing any interference present in the spectrum. Interference can come from other wireless devices, electronic equipment, or environmental factors. Detecting interference is crucial for optimizing the performance of wireless networks.
- **Signal Propagation**: Understanding how signals propagate in the frequency domain, including factors like signal attenuation, fading, and multipath effects. This knowledge helps in designing communication systems that can cope with different propagation conditions.
- **Frequency Selectivity**: Analyzing how different frequencies are affected differently by the channel. Some frequencies may experience higher attenuation or interference, and spectrum analysis helps in making informed decisions about channel selection.
- **Occupancy Analysis**: Examining how frequently different frequency bands are occupied or used by existing wireless services. This information is essential for selecting clear frequency bands to avoid interference.
- **Dynamic Spectrum Access**: In some cases, wireless channel spectrum analysis is used for dynamic spectrum access, allowing systems to adapt their operating frequency based on real-time analysis of the spectrum.

1.2 | How to Analyze the Wireless Spectrum?

This analysis is essential for designing and optimizing wireless communication systems, ensuring efficient use of available frequencies and minimizing interference. The wireless spectrum is analyzed and visualized using following tools tools,

- Spectrum analyzers,
- Software-defined radios.

In this chapter, we will use software defined radio for real time and quasi-real time wireless spectrum analysis.

1.3 | Spectrum Analysis Techniques

Spectrum analysis techniques involve various methods for examining and understanding the frequency components of a signal within the electromagnetic spectrum. These techniques are crucial for tasks such as identifying signal characteristics, detecting interference, and optimizing the use of available frequency bands. Here are some common spectrum analysis techniques:

1. **Spectral Density Analysis**:

- **Description**: Analyzing the power distribution of a signal across different frequency components.
- **Application**: Understanding how signal power is distributed across the spectrum.

2. **Fast Fourier Transform (FFT)**:
   - **Description**: Transforming a time-domain signal into its frequency-domain representation.
   - **Application**: Identifying specific frequencies within a signal and understanding their amplitudes.
3. **Swept-Tuned Spectrum Analysis**:
   - **Description**: Sweeping a narrowband filter across the frequency range to measure the signal power at different frequencies.
   - **Application**: Identifying the frequency components and detecting narrowband signals.
4. **Real-Time Spectrum Analysis**:
   - Description: Continuously monitoring and analyzing the spectrum in real-time.
   - Application: Detecting and responding to dynamic changes in the spectrum, such as identifying intermittent interference.
5. **Vector Signal Analysis (VSA)**:
   - **Description**: Analyzing both amplitude and phase information of a signal in the frequency domain.
   - **Application**: Comprehensive analysis of modulation and encoding characteristics in communication signals.
6. **Pulse-Analysis Techniques**:
   - **Description**: Focusing on analyzing signals with pulses or time-varying characteristics.
   - **Application**: Characterizing radar signals, pulsed communication systems, or other signals with specific time-domain features.
7. **Coherence Analysis**:
   - **Description**: Examining the degree of correlation between two signals in the frequency domain.
   - **Application**: Understanding the relationship between different signals and identifying coherent components.
8. **Waterfall Display**:
   - **Description**: Displaying the spectral content of a signal over time, providing a visual representation of signal changes.
   - **Application**: Monitoring how the frequency content of a signal evolves over time.
9. **Power Spectral Density (PSD) Analysis**:
   - **Description**: Estimating the power distribution of a signal per unit frequency.
   - **Application**: Quantifying the signal power at different frequencies, helping to identify frequency bands with high or low power.
10. **Intermodulation Analysis**:
    - **Description**: Detecting and analyzing unwanted signals created by the interaction of multiple signals.
    - **Application**: Identifying and mitigating intermodulation interference in communication systems.

In this Chapter, we will implement some of these techniques on the SDR to analyze and visualize the wireless channel spectrum.

1.4 | Fast Fourier Transform (FFT) based Spectrum Analysis

Among various techniques, Fourier transform based spectrum analysis is considered the most computationally efficient. The received signal y(t) can be transformed to frequency domain using continuous time Frequency transform (CTFT) as follows,

$$Y(f) = \frac{1}{2\pi}\int_{-\infty}^{\infty} s(t) * \exp^{-j2\pi ft}\, dt \tag{1.1}$$

The CTFT is non causal in nature and hence can not be implemented practically. However, the exact same processing can be performed if the sample the time domain signal and frequency spectrum satisfying the Nyquist criterion for sampling. The time domain samples can be organized in frames of size N_{FFT}. Sampling the time domain sample $s(t)$ at $t = n * T$ and frequency domain spectrum Y(f) at $f = k * \Delta f$ results in,

$$Y[k * \Delta f] = \sum_{n=0}^{N_{\text{FFT}}-1} s[n * T] * \exp^{-j2\pi k*\Delta f*n*T} \tag{1.2}$$

if the s(t) is band-limited to $N_{\text{FFT}} * \Delta f$. We can drop the frequency and time scaling factor of Δf and T, respectively, from equation 1.2 to simplify the representation to,

$$Y[k] = \sum_{n=0}^{N_{\text{FFT}}-1} s[n] * \exp^{-j2\pi k*n/N_{\text{FFT}}} \tag{1.3}$$

where the critical sampling or Nyquist sampling is performed such that $T = \frac{1}{N_{\text{FFT}}*\Delta f}$. It can be observed that the frequency domain version of the time domain can be simply computed by the taking the FFT of the time domain samples provided they are sampled at a rate higher than $N_{\text{FFT}} * \Delta f$ and bandwidth of the signal is not higher than $N_{\text{FFT}} * \Delta f$.

$$Y[k] = \text{FFT}_{N_{\text{FFT}}}\left(\left\{s[n]\right\}_{n=l*N_{\text{FFT}}}^{(l+1)*N_{\text{FFT}}-1}\right), \qquad k = 0, 1, 2, \ldots, N_{\text{FFT}} - 1. \tag{1.4}$$

1.5 | Results

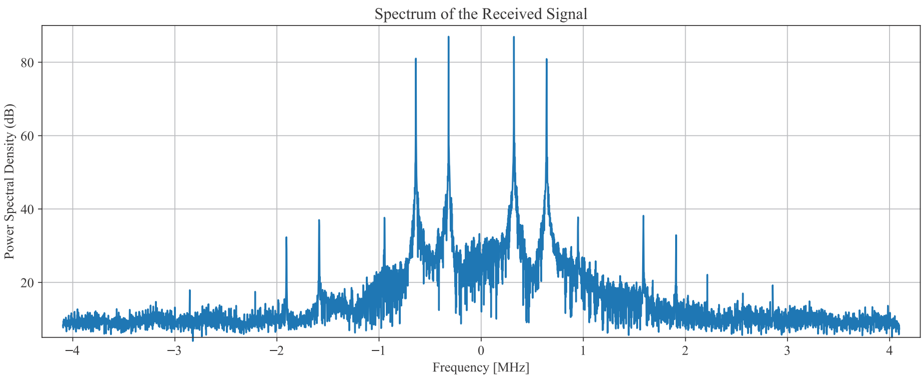
We will discussed the performance and results of quasi real-time and real-time implementation of FFT based spectrum analysis.
Observation-1: The high sample-rate improves the time resolution and increases the bandwidth of the spectrum being sensed.
The higher sample rate also requires higher buffer size (DRAM size) to compute the spectrum of the received signal. Furthermore, the higher sample-rate reduces the sample duration and higher FFT size resulting in higher computational complexity. Both these factors results in higher cost and higher power consumption.

Observation-2: Reducing the subcarrier spacing improves the resolution of the signal spectrum but requires higher FFT-size to process the same bandwidth.

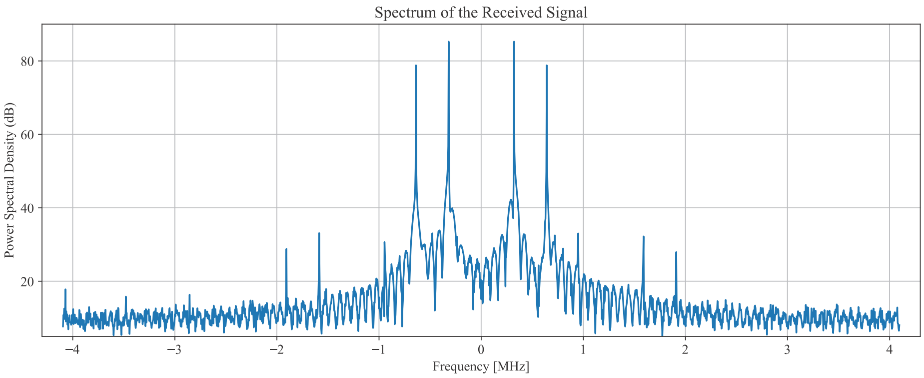
1.6 | Useful Links

The following links provides higher amount of details on computation of signal spectrum.

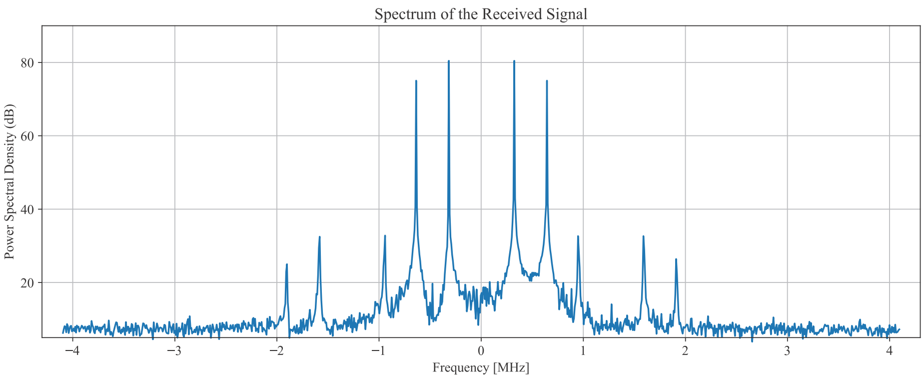
- Quasi real-time spectrum computation.
- Real-time spectrum computation.



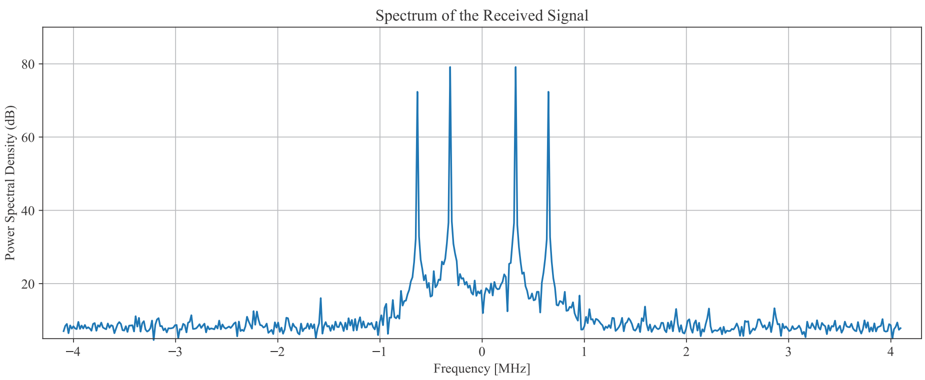
(a) Spectrum Computation with 1kHz subcarrier spacing and 4096 point FFT



(b) Spectrum Computation with 2kHz subcarrier spacing and 2048 point FFT

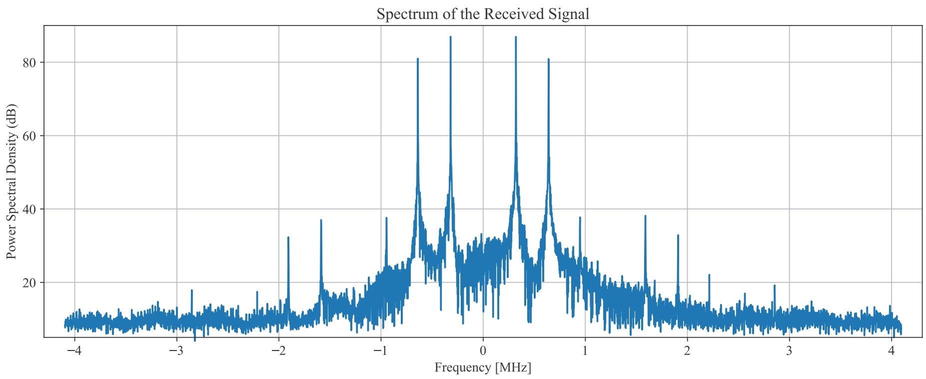


(c) Spectrum Computation with 4kHz subcarrier spacing and 1024 point FFT

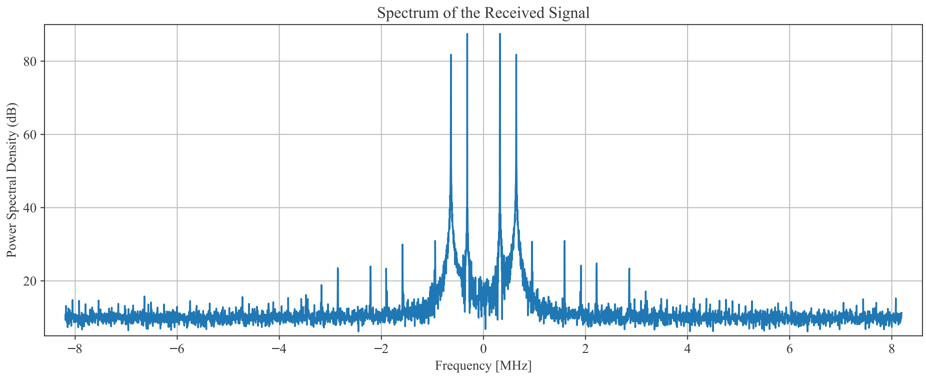


(d) Spectrum Computation with 8kHz subcarrier spacing and 512 point FFT

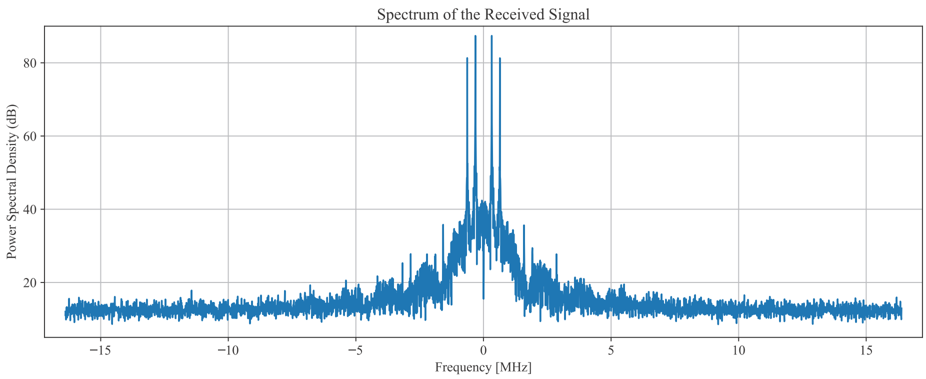
Figure 1.1: Variation in the resolution of spectrum for different subcarrier spacing



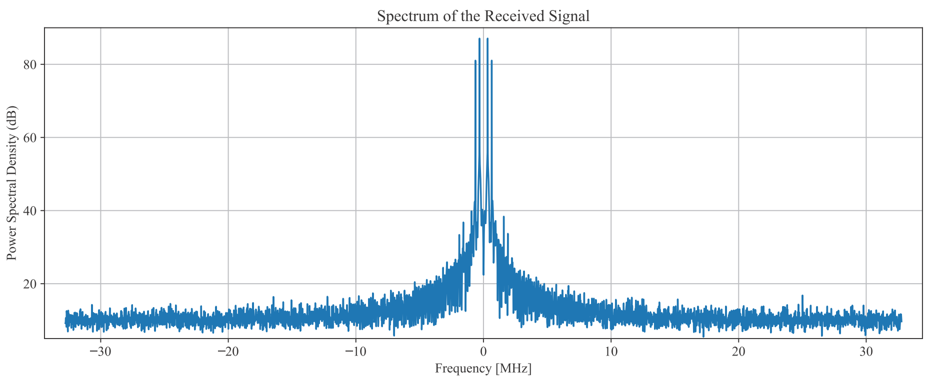
(a) Spectrum Computation with 1kHz subcarrier spacing and 4096 point FFT



(b) Spectrum Computation with 2kHz subcarrier spacing and 4096 point FFT



(c) Spectrum Computation with 4kHz subcarrier spacing and 4096 point FFT



(d) Spectrum Computation with 8kHz subcarrier spacing and 4096 point FFT

Figure 1.2: Variation in the resolution of spectrum for different sample-rate

2 | References