Channel Sounder and Doppler Shifter using PLUTO SDR

Summer Research Internship
Report

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I Abstract

I.1 Channel Sounder

This project presents the development of a channel sounder utilizing two Pluto SDRs (Software-Defined Radios). The primary objective was to investigate and characterize the wireless communication channel's behavior in real-world environments. To achieve this, an m-sequence was generated and modulated using Long-Term Evolution (LTE) technology. The modulated signal was transmitted over the wireless channel between the Pluto SDRs. At the receiver, the transmitted signal was demodulated and correlated with the original m-sequence.

By analyzing the correlation results, valuable insights into the channel's properties were obtained. The experiment's methodology, setup, and measurement procedures are thoroughly described. The results demonstrate the effectiveness of the channel sounder in evaluating wireless channel characteristics and its potential applications in various communication systems, including 5G and beyond. The project contributes to a better understanding of channel behavior, enabling improved wireless communication system design and optimization.

I.2 Doppler Shifter

This project report presents a comprehensive overview of a channel emulator based on a Doppler shifter using ADALM PLUTO SDRs (Software Defined Radios) and implemented using MATLAB. The project involves coding and simulating the effects of Doppler shift phenomenon, which occurs when there is relative motion between a source of waves and an observer. The primary objective of this project is to understand and visualize the frequency shift in a wave due to the Doppler effect, while also correcting for it by introducing an equal but opposite shift in frequency.

II Introduction

II.1 Channel Sounder

Channel sounding is a powerful technique employed to study and analyze the wireless channel's characteristics. By examining the propagation environment, channel sounding provides valuable insights into signal propagation, channel capacity, and link quality.

Understanding these aspects is vital for the design and optimization of communication systems. In this project, we present the development of a channel sounder utilizing two Pluto SDRs (Software-Defined Radios). The Pluto SDRs offer a versatile and cost-effective platform for conducting wireless communication experiments.

The primary aim of this project was to investigate the wireless channel's properties by employing m-sequences, which are widely used in channel sounding due to their excellent correlation properties and low implementation complexity. The proposed approach involves generating an m-sequence and modulating it using Long-Term Evolution (LTE) technology. The modulated signal is then transmitted over the wireless channel between the Pluto SDRs. At the receiver, the transmitted signal is demodulated, and correlation is performed with the original m-sequence.

By analyzing the correlation results, we can gain insights into various channel characteristics, including delay spread, Doppler spread, and channel impulse response. The potential applications of channel sounders are diverse, ranging from wireless channel modeling, and link budget estimation, to antenna array calibration and beamforming. In the following sections, we provide a detailed explanation of the project methodology, experimental setup, and measurement procedures. The results obtained from the channel sounder experiment are discussed and analyzed to demonstrate the effectiveness of the system in evaluating wireless channel characteristics.

II.2 Doppler Shifter

The Doppler effect, also known as the Doppler shift, is a fundamental phenomenon in physics that describes the change in frequency or wavelength of a wave in relation to an observer moving relative to the source of the wave. This effect is commonly observed in various situations, such as in sound waves from moving vehicles and in electromagnetic waves, waves from satellites etc.
The Doppler effect can be represented through the formula

$$f^{'} = f.\frac{v + v_o}{v + v_s} \tag{1}$$

Here,

- $f^{'}$ is the observed frequency
- f is the source frequency
- v is the speed of the wave in the medium
- v_o is the observer's velocity towards/away from the source (positive if moving towards, negative if moving away)
- v_s is the source's velocity towards/away from the observer (positive if moving towards the observer, negative if moving away)

In this project, we have utilized MATLAB to simulate the Doppler effect, aiming to illustrate its behavior and implications. This Doppler simulation is in turn used to correct for the Doppler shift in the wave received from the satellite by producing an equal but opposite shift by using a Doppler Shifter.

We introduced the doppler shift in our wave using the concept that a shift in the frequency domain translates to a phased shift in the time domain. Hence,

$$X' = X.e^{j2\pi f_d t} \tag{2}$$

Where, X is the initial wave and X' is the Doppler corrected wave.

III Methodology

III.1 Channel Sounder

HARDWARE

The hardware setup for the channel sounder consisted of two ADALM-PLUTO SDRs (Software-Defined Radios) connected to a single system. The system operated on the Windows 10 operating system and utilized MATLAB 2022b as the programming environment for signal processing and data analysis. The ADALM-PLUTO SDRs served as the transmitter and receiver units in the channel sounder configuration.

The ADALM-PLUTO SDRs were positioned at a spacing of 15 cm, creating a communication link between them. The spacing was carefully chosen to emulate a realistic wireless communication scenario, allowing the study of channel effects such as path loss and multipath propagation.

SOFTWARE

The MATLAB code was developed to implement the m-sequence-based channel sounder using the two ADALM-PLUTO SDRs. The code comprised several functional blocks to perform various tasks in the channel sounding process. The main software components were as follows:

Generate m-sequence: The MATLAB code included a module to generate an m-sequence. The m-sequence, being a pseudo-random binary sequence with good correlation properties, served as the basis for channel sounding.

Generate Baseband LTE Signal: The m-sequence was modulated using Long-Term Evolution (LTE) technology to create a baseband LTE signal. Generate a baseband LTE signal using LTE Toolbox, packing the binary data stream into the transport blocks of the downlink shared channel (DL-SCH). Use the lteRMCDL function to generate the default configuration parameters for an RMC as defined in TS36.101 Annex A.3 [1]. The parameters within the configuration structure rmc allow customization as required.

Transmit LTE Waveform: The MATLAB code facilitated the transmission of the modulated LTE signal from one ADALM-PLUTO SDR (the transmitter) to the other ADALM-PLUTO SDR (the receiver) over the wireless link.

Set Up SDR Receiver: The receiver ADALM-PLUTO SDR was configured to receive the transmitted signal using its receiving antenna. The code handled the setup and configuration of the receiver for capturing the wireless signal.

Set Up LTE Receiver: The received LTE signal at the receiver was demodulated using an LTE receiver implementation in MATLAB. This step involved processing the received signal and extracting the relevant information.

Process Captured Signal: The captured and demodulated signal was processed to calculate the correlation between the received signal and the original m-sequence used at the transmitter. This correlation process allowed us to estimate the channel impulse response and identify multipath components.

Result Qualification and Display: The MATLAB code performed result qualification to validate the accuracy of the channel estimation. The results were displayed using appropriate plots and visualizations for further analysis and interpretation.

The software implementation of the channel sounder using MATLAB and the ADALM-PLUTO SDRs provided a systematic and automated approach to capture and analyze the wireless channel's behavior. The code facilitated the extraction of relevant channel characteristics, enabling a comprehensive understanding of signal propagation, channel quality, and potential impairments in wireless communication scenarios.

III.2 Doppler Shifter

HARDWARE

The hardware setup for the Doppler Shifter consisted of two ADALM-PLUTO SDRs (Software-Defined Radios) connected to a single system. However, we have also tested the same system successfully on one ADALM-PLUTO SDR operating on full duplex. The system operated on the Windows 10 operating system and utilized MATLAB 2022b as the programming environment for signal processing and data analysis. The ADALM-PLUTO SDRs served as the transmitter and receiver units in the setup.
The ADALM-PLUTO SDRs were positioned at a spacing of 15 cm, creating a communication link between them. The spacing was carefully chosen to emulate a realistic wireless communication scenario.

SOFTWARE

This section discusses the implementation of the MATLAB code that is run on the ADALM-PLUTO systems. Since the transmitter and receiver operate on bits, we convert analog signals to bit representation at the required places. The main software components are decscribed as follows:

Generate sin wave: To perform the frequency shift, we first generate a sin wave of frequency 20Hz, in lieu of the received wave from the satellite system.

Processing sin wave: The analog signal was sampled and quantized. Please refer to the image .

Encoding to Bit Value: The quantized values and then converted to bit representation through a function. This is represented in the image .

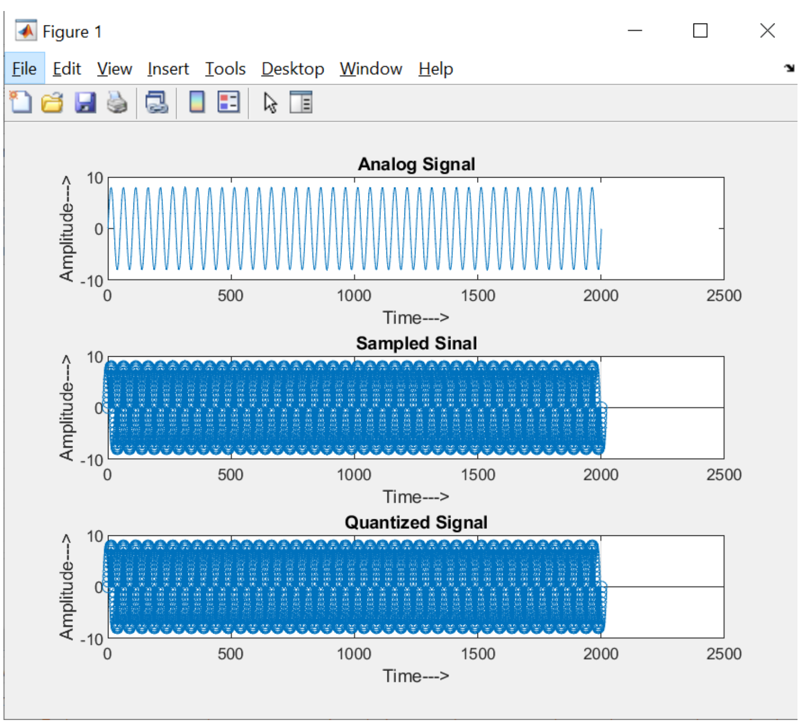
Set up SDR Transmitter The MATLAB code facilitated the transmission of the modulated LTE signal from one ADALM-PLUTO SDR (the transmitter) to the other ADALM-PLUTO SDR (the receiver) over the wireless link.

Set Up SDR Receiver: The receiver ADALM-PLUTO SDR was configured to receive the transmitted signal using its receiving antenna. The code handled the setup and configuration of the receiver for capturing the wireless signal. The received LTE signal was then demodulated using an LTE receiver implementation in MATLAB. This step involved processing the received signal and extracting the relevant information.

Demodulate Signal: The received bit signal was then demodulated to convert it back to a sin wave. The demodulated signal is represented in the image .

Doppler Shift: A doppler shift of 5Hz is introduced in the received signal using the Doppler Shifter. This frequency shift is introcuded through a phase shift in the time domain.

Result Qualification and Display: The frequency domain representation of both, the original signal and the shifted signal is plotted and discussed in the Results section.



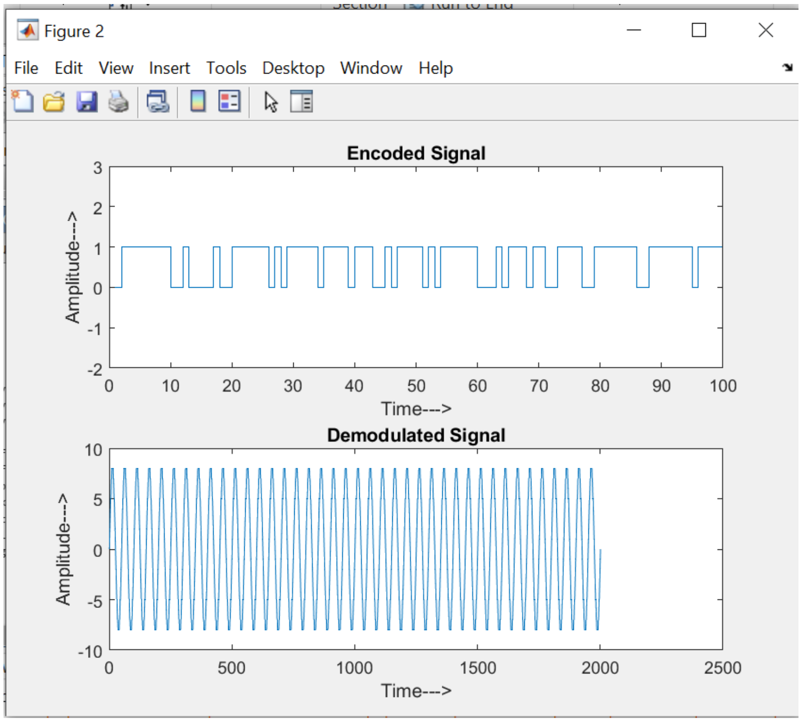


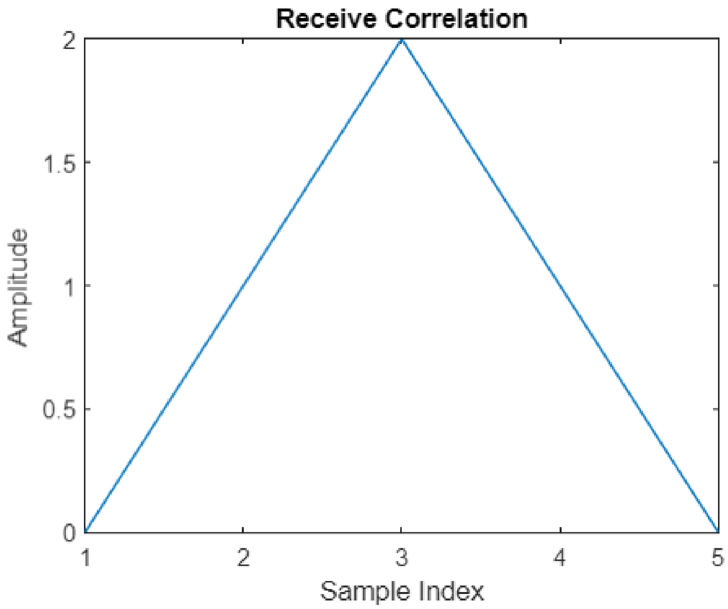
Figure 2
File Edit View Insert Tools Desktop Window Help
Encoded Signal
Amplitude--->
Time--->
Demodulated Signal
Amplitude--->
Time--->

IV Observations and Results

IV.1 Channel Sounder

OBSERVATIONS

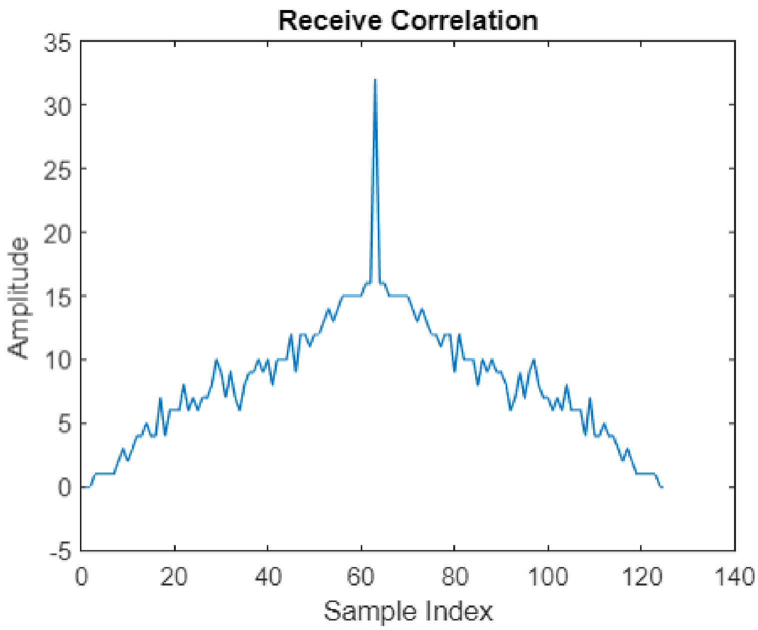
1) Number of Bits = 3:



With a small number of bits (3 in this case), the m-sequence used for channel sounding is relatively short. As a result, the correlation graph would show fewer correlation peaks corresponding to the fewer possible delay paths in the wireless channel. The channel impulse response would exhibit a limited number of significant peaks, representing the distinct paths the signal takes from the transmitter to the receiver.

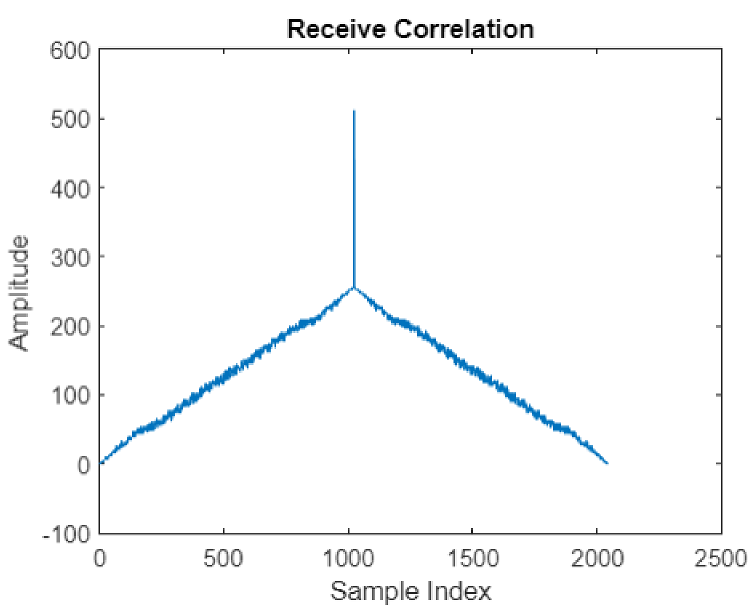
The BER being 0 indicates that the transmission of 3 bits was error-free, suggesting that the channel experienced little interference or noise.

2) Number of Bits = 63:



As the number of bits in the m-sequence increases (63 in this case), the length of the m-sequence grows, leading to more possible correlation peaks in the graph.
The correlation graph would display more pronounced and well-separated correlation peaks, indicating the presence of multiple multipath components with varying delays.
The channel impulse response would reveal a more detailed representation of the wireless channel, capturing additional multipath reflections and scattering.
The BER being 0 implies that the transmission of 63 bits was also error-free, demonstrating the channel's ability to reliably transmit data over a longer sequence.

3) Number of Bits = 1023:



With a large number of bits (1023 in this case), the m-sequence becomes much longer, resulting in an even higher resolution correlation graph with numerous correlation peaks.

The correlation graph would display a rich set of correlation peaks, indicating an extensive and complex multipath environment with many different signal paths arriving at the receiver.
The channel impulse response would show a highly dispersed and detailed response, representing the channel's extensive time dispersion and the effects of multiple signal reflections.
The BER being 0 signifies that the transmission of 1023 bits was error-free, demonstrating the channel's robustness in transmitting large data sequences.

RESULTS

The channel sounder experiment utilizing two ADALM-PLUTO SDRs and an m-sequence-based approach yielded interesting results. The Bit Error Rate (BER) was found to be 0, indicating that no errors occurred during the data transmission between the two SDRs. This result suggests that the transmitted signal was accurately received without any bit errors.

Overall, as the number of bits in the m-sequence increases, the channel sounder can capture more fine-grained details about the wireless channel's behavior. The correlation graphs become more informative and the channel impulse response becomes more detailed, offering deeper insights into the channel's multipath characteristics. The consistently low BER values across all cases indicate the channel's reliability in transmitting data without errors, suggesting that the m-sequence-based channel sounder is effective in characterizing the wireless communication channel across different bit sequences.

Additionally, the correlation graphs provided valuable insights into the wireless channel's behavior and the effectiveness of the m-sequence-based channel sounder. The correlation graphs depicted the correlation between the received signal and the original m-sequence used at the transmitter.

The correlation graphs also showcased the channel impulse response, revealing the various signal paths arriving at the receiver with different time delays and amplitudes. The sharpness and distinctness of the correlation peaks indicated a well-defined channel response and a lack of severe multipath distortion.

The absence of bit errors and the clear correlation peaks in the graphs together indicated that the m-sequence-based channel sounder successfully characterized the wireless channel and provided accurate channel estimation. The excellent performance of the channel sounder highlights its potential for various applications, such as channel modeling, link budget estimation, and system performance evaluation.

Overall, the obtained results demonstrated the reliability and effectiveness of the developed channel sounder using the ADALM-PLUTO SDRs and m-sequence modulation. The experiment's success in achieving a BER of 0 and obtaining distinct correlation peaks validates the accuracy of the channel estimation process and emphasizes the importance of understanding wireless channel characteristics for designing robust and efficient communication systems. These findings contribute to a deeper understanding of wireless communication channels and provide valuable insights for future communication technologies and system optimizations.

IV.2 Doppler Shifter

The Doppler Shifter results are displayed in the figures and . The frequency of a signal can be interpreted from the value of the peak of the FFT (Fast Fourier Transform) of the signal.

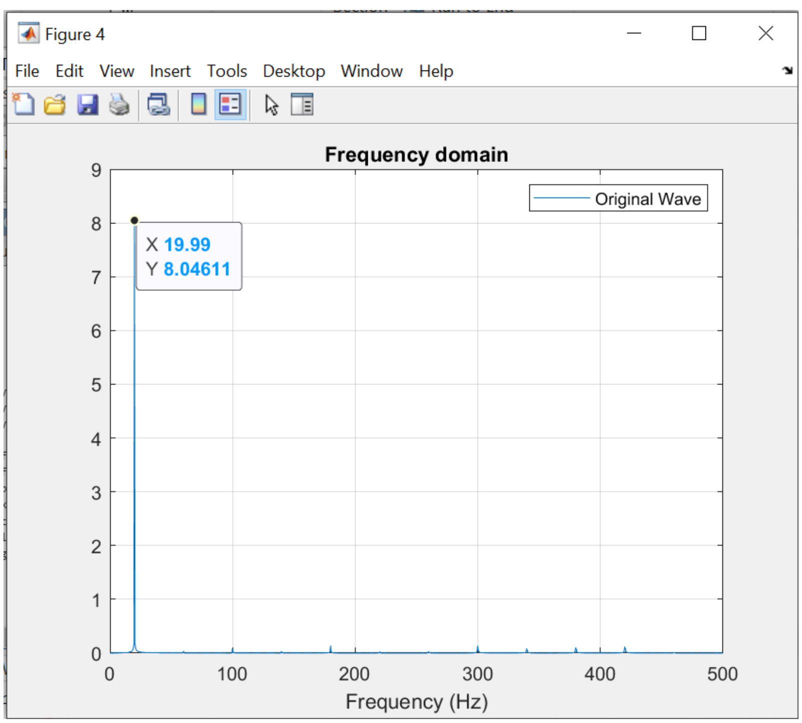
To expand on this,
The Fast Fourier Transform (FFT) is an algorithm that converts a signal from the time domain to the frequency domain. It represents a signal as a sum of sinusoidal components at different frequencies. When you apply FFT to a time-domain signal, you get an array of complex numbers that represent the amplitudes and phases of these sinusoidal components at different frequencies.

Frequency Bins:
The output of the FFT is divided into discrete frequency bins. Each bin represents a certain frequency range. The total number of bins is usually equal to the length of the FFT window. The first bin (bin 0) corresponds to the DC (direct current) component or zero frequency, and subsequent bins represent increasing frequencies.

Magnitude Spectrum:
After performing the FFT, you can calculate the magnitude spectrum by taking the absolute value of the complex numbers in the FFT output. This magnitude spectrum indicates how much energy or amplitude exists at each frequency bin.

Finding the Peak:
To determine the dominant frequency component of a signal, you need to identify the bin with the highest magnitude in the magnitude spectrum. This bin is often referred to as the "peak" bin. The frequency associated with this peak bin is the dominant frequency of the signal. Thus peaks of the FFT represent the frequency of the wave.

As evident from figure and , the frequency of the original signal and the sifted signal are obtained i.e. 20Hz and 15Hz respectively.



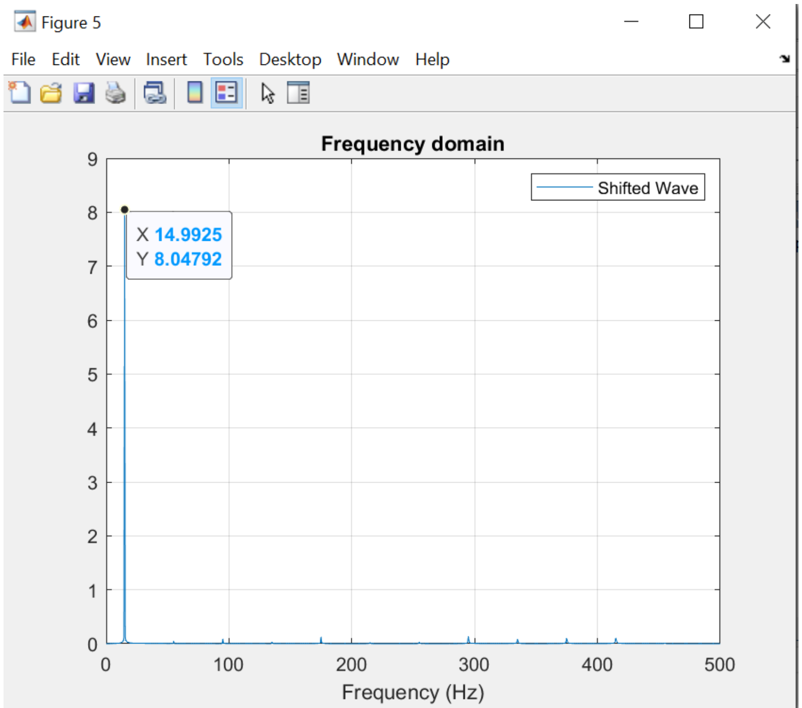


Figure 5
File Edit View Insert Tools Desktop Window Help
Frequency domain
Shifted Wave
X 14.9925
Y 8.04792
0 1 2 3 4 5 6 7 8 9
0 100 200 300 400 500
Frequency (Hz)