Full Duplex Communication System on ADALM PLUTO

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In the name of ALLAH, the Most benevolent, the Most Courteous

CERTIFICATE OF CORRECTNESS AND APPROVAL

This is to officially state that the thesis work contained in this report

"Full Duplex Communication System on ADALM PLUTO"

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under my supervision and that in my judgment, it is fully ample, in scope and excellence, for the degree of Bachelor of Electrical Engineering in Military College of Signals, National University of Sciences and Technology (NUST), Islamabad.

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DECLARATION OF ORIGINALITY

We hereby declare that no portion of work presented in this thesis has been submitted in support of another award or qualification in either this institute or anywhere else.

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Allah Subhan'Wa'Tala is the sole guidance in all domains.

Our parents, colleagues and most of all our supervisor, Dr Hussain Ali. The group members, who through all adversities, worked steadfastly.

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ABSTRACT

The integration of cost-effective equipment, such as the analog devices ADALM PLUTO platform, with sophisticated simulation tools like Simulink, presents a groundbreaking opportunity within the realm of analog and digital communications. This project delves into the practical aspects and potential applications of full-duplex communication systems, leveraging the functionalities offered by the ADALM PLUTO platform and Simulink. The project's focal points include the reception of signals, the design of a Double-Sideband Suppressed Carrier (DSBSC) Modulated Signal, the creation of a Quadrature Amplitude Modulation (QAM) transceiver, and the transmission of images using QAM. Through a comprehensive approach encompassing theoretical exploration, simulation-based analysis, and hands-on experimentation, the project seeks to showcase the effectiveness of full-duplex communication in enhancing spectral efficiency and data throughput. The literature review highlights the existing research concerning the ADALM PLUTO, Simulink and other modulation techniques for Self-interference cancellation and its educational implementation. The research objective is a direct bridge between the advancement of knowledge and practical applications which lead to a full duplex communication system. This will ultimately help in developing and progressing the wireless technology, thus promoting and fostering innovation.

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Chapter 1: Introduction

In the modern era of wireless communication, the advancements in spectral efficiency and throughput have played a vital role in enhancing the impact of technology. The development of full-fledged duplex communication has made it possible the transmission and the reception of the same frequency bands. These cater to the utter demand of the technology and have proven to be the most efficient method of all. This thesis tends to explore the value, performance, challenges and productivity of the full duplex communication systems by using Analog devices ADALAM Pluto Platform.

ADALM Pluto platform is the core of the full duplex communication. Its frequency ranges from 325MHz to 3.8 GHz. It allows the integrated RF transceiver to implement wireless communication systems. FPGA also arranges powerful signal processing algorithms, necessary for self-interference and optimizing the overall performance of the system in a full duplex scenario.

Full duplex communication emerges with the transformative technology as the demand of the efficient spectrum utilization and network capacity soars with extensive and far-fetched impact. Full duplex communication system unlocks the unseen advanced levels of spectral efficiency by using transmission and reception simultaneously, thus reducing latency and spreading the wireless applications in different dimensions, paving way for the new realms and the beginning of a new era.

However, it still brings challenges like overcoming significant technical challenges. Full duplex communication must shift its focus on self-interference where transmitted signals and received signals may interfere or mingle with one another, giving us the view of a messed-up situation. This must be taken care with high precision and proper channels, processing techniques and adaptive cancellation algorithm. Also, the hardware constraints also add to the complexity of design and implementation.

For challenges and opportunities, the thesis aims to investigate the implementation and performance of full duplex communication using ADALM Pluto platform as the base. In terms of simulation studies and practical implications and experiments, the thesis highlights the limitations, suitability, usage and benefits of full duplex communication. Opening the secrets of full duplex communication and mingling it with ADALM Pluto platform, the thesis tends to contribute to wireless communication technology, thus paving ways for the brightest future where the transmission and reception will redefine the era of connectivity and communication, proving its worth for efficiency.

1.1 Overview

Full duplex communication, transmission and reception of data simultaneously on a single band, thus giving spectral efficiency and throughput. The Analog Devices, ADALM Pluto platform serves to be fully indulged in the full duplex communication, thus supporting its integration in RF transceiver and programmable FPGA.

Here, we have mentioned the overall process of achieving a full duplex communication in using ADALM Pluto:

1.1.1 Hardware Capabilities:

ADALM Pluto platform has a wideband RF transceiver with frequencies ranging from 325 MHz to 3.8 GHz. These easily provide a proper channel in both the transmission and reception of the signals. Also, the programmable FPGA helps the user to take pre-defined signal processing algorithms to cater full-duplex system effectively.

1.1.2 Signal Processing:

Full duplex communication uses advanced signal processing techniques to lessen self-interference with the received one. Software like Simulink along with ADALM Pluto platform assists in canceling algorithms and digital signal processing in order to successfully diminish self-interference and make the signal tenfold of its original size.

1.1.3 Adaptive Cancellation:

Adaptive cancellation refers to the algorithms adjusting themselves using different channels in order to successfully nullify the self-interference. These algorithms usually take in consideration the feedback mechanisms and consistently update its cancellation framework. This is totally based on the characteristics of the received signals. Programmable FPGA of the ADALM Pluto platform provides these facilities to grasp these adaptive algorithms.

1.1.4 Software Compatibility:

ADALM Pluto platform works efficiently with a variety of software including MATLAB/Simulink, MATLAB based open sources like Pluto-SDR and GNU Radio. These software offer intelligent design, simulations and full-fledged full duplex communication system. One of the software, particularly Simulink provides graphical programming, thus simplifying the complex and intricate signal processing algorithms.

1.1.5 Performance Assessment:

The evaluation of the performance of full duplex communication on ADALM Pluto platform is vital to identify and calculate self-interference cancellation and system efficiency. The infamous metrics like bit error rate (BER) and signal-to-interference-plus-noise ratio (SINR) acts as the standard in gauging the efficiency and stability of the full duplex communication system.

All in all, the ADALM Pluto platform is an unavoidable source to analyze, evaluate full duplex communication systems. The integration of RF transceiver, programmable FPGA and the compatibility with Simulink can provide excellent opportunities to explore full duplex communication, thus leading the future to an even better and advanced wireless connectivity solutions.

1.2 Problem Statement

In the era of modern communication systems, research in analog and digital communication requires hands-on learning and practical experimentation. In the education sector, especially in electrical engineering, research is conducted at graduate and undergraduates. For that matter, they require Universal Serial Radio Peripherals (USRPs) which are very expensive and infeasible to be acquired at such levels. Therefore, students are deprived of such valuable knowledge, its conduct and practical manifestation. The void in between extreme functionality and low-price tag needs to be fulfilled to enable the education sector with a glorious moment to conduct their valuable research and future endeavors.

1.3 Proposed Solution

A significant reduction of price for Active Learning Module Analog Devices ADALM-PLUTO (around $250) derives a successful functionality and covers the gap of expense and function. ADALM-PLUTO provides a variety of opportunities regarding the functionality of wireless transceivers, making it a prize for educationalists. The affordable price range allows everyone across the globe to use it for experimentation, hands-on experiences, digital communication, and analog and digital concepts without the tension of it being a serious expense.

The increased accessibility for researchers and educationalists revolves around innovation, creativity among the students. ADALM-PLUTO's versatile and less costly appeals, with the addition of the hands-on learning experience, in the classroom and during research proves fruitful. As a result, it generates advancements (digital and analog) in the curriculum development, which gives us a huge benefit of its usage.

1.4 Working Principle

The project mainly is about the implementation of a full duplex communication system keeping the Analog Devices ADALM Pluto platform and Simulink. Working principle mainly involves the simultaneous transmission and reception of data on the same frequency, thus unlocking the enhanced spectral efficiency and throughput. Let's discuss the overview of the working principles and the tasks involved.

1.4.1 Reception of Various Signals using ADALM Pluto:

- Receiving signals from and across different frequencies using ADALM Pluto platform.
- Using RF transceiver to apprehend sinusoidal waves, AM, FM and digital data.
- Analyze the characteristics of the signals received and use the information necessary or vital using Simulink.

1.4.2 Design of a DSB-SC Modulated Signal:

- Use Simulink to generate and develop signal processing blocks using Double-Sideband Suppressed Carrier (DSBSC) modulated signals.
- ADALM Pluto platform to receive and transmit signals simultaneously to assess the performance.

1.4.3 Design of a QAM Transceiver:

- Using Simulink, designing a QAM (Quadrate Amplitude Modulation) using modulation and demodulation blocks.

- Implementation of QAM on ADALM Pluto platform and to receive and transmit QAM modulated signals.

1.4.4 Image Transmission using QAM:

- Using binary code to encode and map using QAM symbols through Simulink.
- On the ADALM Pluto platform, transmission of QAM modulated image data while using the designed QAM transceiver. It also ensures the receival of the transmitted signals with demodulation to receive the transmitted image data.

1.5 Objectives

1.5.1 Investigate Reception Capabilities:

To analyze, investigate and evaluate ADALM Pluto platform with signals like sinusoidal, square waves, AM, FM and digital signals. This will help in gauging and understanding the efficiency of these analog and digital signals.

1.5.2 Design DSBSC Modulated Signal:

The design includes the development and implementation of Double Sideband Suppressed Carrier (DSBSC) modulated signals focusing on processing of the blocks and modulating DSBSC signals for transmission.

1.5.3 Create QAM Transceiver System:

Creating, designing and locating Quadrature Amplitude Modulation (QAM) transceiver using Simulink and ADALM Pluto platform given a smooth integration and compatibility for specific modulation and demodulation.

1.5.4 Transmit Images via QAM:

Transmitting image while exploring its performance and other attributed using QAM with full duplex communication system. This also includes image data conversion to binary form, thus identifying the effectiveness in the real world.

1.6 Scope

This project aims to focus on exploring, designing, implementing and analyze the full duplex communication using Analog devices ADALM Pluto platform and Simulink. The design element includes architecture of the system, components' specification, signal flow of pathway, modulation and demodulation, strategic cancellation algorithms and all sorts of adaptation using full duplex communication. Both the ADALM Pluto platform and Simulink, setting up proper communication channels to exchange data successfully and configure hardware for a smoother sending and receiving operations. Simulink mostly works with generating and receiving signals, also testing sinusoidal waves, modulated signals (using QAM) and data streaming. ADALM Pluto platform receives and analyzes the quality of the signal and the extraction of information. Performance then helps us identify and make us evaluate it under a variety of circumstances, keeping in view the signal-to-interference-plus-noise ratio (SINR), throughput, latency, and bit error rate (BER). For overall reliability and performance of the system, continuous iterations and optimization based on the results are obtained from the simulations. Documentation of the entire process and comprehensive reporting mechanism summarizes the project's objectives, methodologies, findings and conclusions which in return offers valuable insights into full-duplex communication technology and its practical applications.

1.7 Deliverables

1.7.1 Reception of Various Signals using ADALM Pluto:

- Configure the ADALM Pluto platform for signal reception.
- Capture signals across different frequency bands and modulation schemes.
- Analyze received signals to extract relevant information.

1.7.2 Design of a DSB-SC Modulated Signal:

- Develop a Simulink model for generating a Double-Sideband Suppressed Carrier (DSBSC) modulated signal.
- Configure modulation parameters such as carrier frequency and modulation index.
- Verify the functionality of the DSBSC modulation scheme.

1.7.3 Design of a QAM Transceiver:

- Create a Simulink model for implementing a Quadrature Amplitude Modulation (QAM) transceiver system.
- Design modulation and demodulation blocks for QAM signal processing.
- Validate the QAM transceiver's performance through simulation.

1.7.4 Image Transmission using QAM:

- Develop a MATLAB code/ Simulink model for encoding image data and transmitting it using QAM modulation.
- Configure the QAM modulation parameters based on image data characteristics.
- Transmit and receive the QAM-modulated image data for verification.

1.8 Sustainable Development Goals

SDG 9 aims to promote inclusivity and well stabled, sustainable industrialization, resilient infrastructure, thus fostering innovation [13]. It encompasses various targets related to enhancing access to information and communication technology (ICT), promoting research and development, and ensuring universal access to affordable and reliable internet connectivity.

This project aligns with SDG 9 in the following ways:

- **Promotion of Innovation:** By leveraging reduced-cost equipment like the ADALM Pluto platform and advanced simulation tools like Simulink, the project fosters innovation in the field of analog and digital communications. It enables students, researchers, and practitioners to explore novel ideas, experiment with new technologies, and develop innovative solutions to address communication challenges.
- **Access to ICT:** The project contributes to expanding access to information and communication technology by providing affordable and accessible tools for learning and research. The ADALM Pluto platform, priced competitively for academic use, democratizes access to wireless communication technology, empowering individuals from diverse backgrounds to engage in hands-on experimentation and learning.
- **Capacity Building:** By equipping students and researchers with practical skills and knowledge in full-duplex communication, the project supports capacity building efforts in the field of ICT. It prepares the workforce with the necessary expertise to contribute to the development and deployment of advanced communication systems, thereby fostering economic growth and sustainable development.
- **Infrastructure Development:** The project underscores the importance of resilient and reliable communication infrastructure, essential for supporting technological innovation and economic

activities. By exploring the feasibility and performance of full-duplex communication systems, it contributes to the development of robust infrastructure capable of meeting the growing demands for high-speed, low-latency communication.

By addressing the challenges and opportunities in full-duplex communication using innovative tools and methodologies, the project directly contributes to advancing SDG 9 and promoting sustainable development through technological innovation and infrastructure development.

1.9 Proposed Methodology and Block Diagram

The thesis encompasses various transceiver systems comprising of different modulation schemes such as Dual Side Band Suppressed Carrier, Quadrature Amplitude Modulation (QAM), 16 QAM and 64 QAM. These transceiver systems helps in developing the understanding and lays down the foundation to devise a solution of designing a transceiver system capable of transmitting an Image using Quadrature Amplitude Modulation. The block diagram for the intended transmission of image is shown in Figure 1.

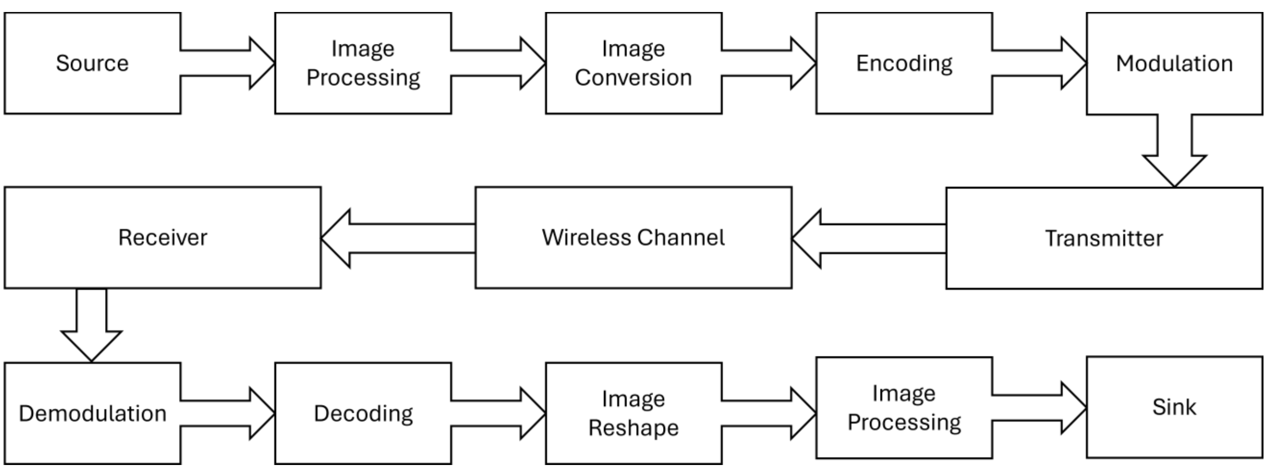

Figure 1: Block Diagram of Image Transceiver System

1.10 Structure of Thesis

Chapter 2 contains the literature review and the background and analysis study this thesis is based upon.

Chapter 3 contains the design and implementation of the project.

Chapter 4 contains the conclusion of the project.

Chapter 5 highlights the future work needed to be done for the commercialization of this project.

Chapter 2: Literature Review

In the vast landscape of scholarly research and industry insights, the literature review sets the stage by exploring both the theoretical frameworks and practical implementations of full-duplex communication. Drawing from a diverse array of sources such as research articles, academic papers, and industry reports, this review casts a wide net over several critical areas:

- **Full-Duplex Communication Techniques:** This section delves into the various strategies employed in full-duplex communication systems. Techniques like self-interference cancellation (SIC), analog and digital cancellation methods, and adaptive cancellation algorithms are scrutinized for their efficacy, complexity, and hardware requirements.
- **Spectral Efficiency and Throughput Enhancement:** Here, existing literature illuminates how full-duplex communication can significantly boost spectral efficiency and throughput by allowing simultaneous reception and transmission on the same frequency band. Studies often juxtapose the optimization and performance of full-duplex systems against traditional counterparts (half-duplex), highlighting notable gains in data rates and network capacity.
- **Interference Mitigation:** The review navigates the challenges posed by self-interference in full-duplex communication. Researchers explore latest techniques such as antenna isolation and digital signal processing to lessen the trade-offs such as efficiency, cost and functionality.
- **Hardware Platforms and Testbenches:** Various hardware platforms and testbenches ensures the evaluation and analysis of full duplex communication systems such as ADALM Pluto and MATLAB. This includes a close inspection of software-defined radios such as ADALM Pluto which is well-known for its flexibility in programming and the ease it provides in various experimentation.

- **Practical Deployments and Case Studies:** Real-world deployments and case studies provide valuable insights into the challenges posed by full-duplex communication. By analyzing scenarios in wireless networking, cognitive radio systems and emerging technologies like 5G, researchers gain practical knowledge and experience for further analysis and future endeavors.
- **Standardization Efforts and Trends of Various Industries**: The review scrutinizes the efforts for standardization of various platforms and standards such as IEEE and 3GPP standardization efforts. This establishes multiple protocols for full duplex communication. Furthermore, it tracks industry trends, commercial development and technological advancements showcasing how full-duplex capabilities are integrated into next-generation wireless devices and infrastructure.
- **Double-Sideband Suppressed Carrier (DSBSC) Modulation:**

  DSBSC modulation is the amplitude modulation (AM) where both the upper and lower sidebands are transmitted just in time for the carrier signal to be suppressed (Upgrade Staff, 2022). This modulation technique is often used in radio transmission systems where efficient use of bandwidth is essential, as it eliminates the need to transmit the carrier signal, thereby reducing bandwidth requirements. However, DSBSC modulation requires precise synchronization of the carrier at the transmitter and receiver end in order to extract the original message signal accurately.
- **Quadrature Amplitude Modulation (QAM):**

  QAM is a digital modulation technique which uses the amalgamation of both amplitude and phase of its signal such that it is varied simultaneously to represent multiple digital symbols. QAM is most influential in the modern communication systems, including digital cable television, digital subscriber line (DSL) systems and wireless networking (Wi-Fi). The primary advantage of QAM is its ability to transmit multiple bits per symbol that allows the user to transmit data at higher rates and with a higher spectral efficiency. QAM offers various techniques such as 16-QAM, 64-QAM, or 256-QAM or higher-order offering increased data throughput at the expense of higher susceptibility to noise and interference. QAM is widely used in digital communication systems due to its efficiency, robustness, and ability to achieve high data rates.

- **Transmitter System:**

  A transmitter system converts digital data or information into electromagnetic waves that are sent through their antennas over a communication channel. It typically consists of the following components:

  - **Data Source:** The data source provides the information in raw form to be transmitted. Data sources can include digital data from a computer, audio signals from a microphone or video signals from a camera.
  - **Digital Modulator:** The digital modulator encodes the data onto a carrier signal, typically using modulation techniques such as QAM (Quadrature Amplitude Modulation) or PSK (Phase Shift Keying) [11]. It modulates the amplitude, phase, or frequency of the carrier signal according to the requirement.
  - **Analog Modulator (Optional):** In some cases, an analog modulator may be used to further modulate the signal. This can include techniques like amplitude modulation (AM) or frequency modulation (FM) for analog signals [11].
  - **RF (Radio Frequency) Amplifier:** The RF amplifier, amplifies the power of the modulated signal to such a level at which it is suitable for transmission over the

communication channel. This ensures that the signal can reach its intended destination with sufficient strength.

- **Antenna:** The antenna is responsible for radiating the modulated RF signal into the environment. It converts the electrical signal into electromagnetic waves that propagate through the air or through a medium, such as coaxial cable or optical fiber.

- **Receiver System:**

  A receiver system is responsible for receiving the signal that was previously transmitted and to demodulate it and extract the original message signal. It typically consists of the following components:

  - **Antenna:** The antenna receives the transmitted electromagnetic signals and converts it back into electrical signals. It collects the signals from the environment and directs them to the receiver.
  - **RF Amplifier:** The main purpose of an RF amplifier is that it amplifies weak signals that are received through the antenna system in order to make them suitable for processing. This stage helps to overcome any attenuation or loss experienced by the signal during transmission.
  - **Analog Demodulator:** The analog demodulator extracts baseband signal from the modulated RF carrier. This demodulation process extracts the original message signal which was encoded in the carrier signal.
  - **Digital Demodulator:** In digital communication systems, a digital demodulator processes and demodulates the baseband signal to recover the transmitted data. This may involve decoding techniques specific to the modulation scheme that was used in the transmitter, such as QAM demodulation or PSK demodulation.

- **Data Sink:** The data sink receives, shows or displays the data that was previously demodulated. This can also lead to further utilization. Data sinks can be storage memory, image viewers, video viewers, spectrum analyzers or time scope.

2.1 Industrial background

The industrial background of the ADALM Pluto platform and MATLAB Simulink encompasses their respective roles in technological advancements, education sector and research across various industries.

2.1.1 ADALM Pluto:

ADALM Pluto (Analog Devices Active Learning Module Pluto) is a versatile and cost-effective software-defined radio (SDR) platform designed for educational, hobbyist, and professional applications.

Figure 2: ADALM Pluto SDR [10]

With a frequency range spanning from 325 MHz to 3.8 GHz, the Pluto enables users to engage in a wide array of wireless communication experiments, including cellular, Wi-Fi, Bluetooth, and more [9]. Its baseband sample rates of up to 61.44 MSPS (Mega Samples Per Second) allow for high-resolution signal processing and waveform generation, while the RF front-end offers a typical bandwidth of around 20 MHz, facilitating the reception and transmission of wideband signals [1]. The platform supports full-duplex operation, serving as both a transmitter and receiver, which is essential for applications like cognitive radio and spectrum sensing. Equipped with a programmable FPGA (Field-Programmable Gate Array) and an ARM Cortex-A9 processor, the Pluto platform offers computational power for implementing signal processing algorithms, modulation/demodulation schemes, and communication protocols [1].

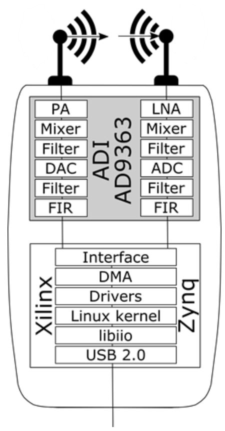

Figure 3: Architecture of ADALM Pluto [1]

It connects to a host computer via USB interface, enabling seamless integration with software tools such as MATLAB, Simulink, and GNU Radio. Additionally, ADALM Pluto is supported by open-source software, fostering community-driven development, experimentation, and customization. Its compact form factor and comprehensive educational resources make it suitable for a diverse range of applications across education, research, and industry in the field of wireless communication and software-defined radio.

- **Wireless Communication Industry**:

  ADALM Pluto has a wide application in wireless communication research and development, particularly in exploring advanced modulation techniques, signal processing methods, and wireless networking protocols. It serves as a cost-effective platform for prototyping and testing new wireless communication technologies, such as 5G and beyond, cognitive radio systems, and IoT devices.

- **Education Sector:**

  ADALM Pluto has a significant impact on engineering education by providing students with hands-on experience in wireless communication systems. It offers a practical platform for teaching concepts such as modulation, demodulation, signal processing, and RF communication. It enhances students' understanding of theoretical concepts through real-world experimentation and practical understanding.

- **Research Institutions:**

  Institutions utilize ADALM Pluto for conducting various experiments, studies in wireless communication, spectrum sensing, software-defined radio (SDR), and related fields. Its programmable nature and wide frequency range make it suitable for exploring new research ideas, validating theoretical models and conducting practical experiments in academic and industrial research settings.

2.1.2 MATLAB Simulink:

MATLAB Simulink is a versatile tool used by engineers and scientists to design, simulate, and analyze complex systems. With Simulink, users create models by connecting graphical blocks that represent system components. It offers a vast library of pre-made blocks for various domains like signal processing and control systems. Simulink integrates seamlessly with MATLAB, allowing for custom algorithms and functions to be incorporated into models. It supports simulation and analysis tools for time and frequency domains, as well as automatic code generation for deploying models to real-world systems [14]. Simulink also facilitates hardware-in-the-loop simulation for testing control systems with physical interfaces. Overall, Simulink is an essential tool for engineers, researchers, and educators across various disciplines.

- **Telecommunications Industry:**

  Simulink is extensively used by telecommunications companies for the design, simulation, and verification of their newly designed communication systems These include wireless, wired and optical networks. It facilitates the modeling of complex communication protocols, modulation schemes, channel coding techniques, and error correction methods that enable engineers to optimize system performance and reliability.

- **Wireless Communication Systems:**

  In the development of wireless communication systems such as 5G, LTE, Wi-Fi and Bluetooth, Simulink serves as a primary tool for modeling and simulating physical layer components such as transmitters, receivers, antennas and communication channels. Engineers use Simulink to design and evaluate advanced modulation schemes (e.g., QAM, PSK), multiple access techniques (e.g., OFDM, CDMA), and signal processing techniques (e.g., channel equalization, synchronization) for wireless communication systems.

- **Digital Signal Processing (DSP) Applications:**

  Simulink is widely employed in DSP applications. This includes audio processing, image processing, radar systems and medical signal processing. It enables engineers to prototype and implement digital filters, FFT algorithms, convolution operations and other signal processing techniques efficiently which provides leverage for built-in blocks and toolboxes for rapid development and testing.

Overall, the ADALM Pluto and MATLAB Simulink have become integral tools in various industries. They contribute to innovation, education, and research endeavors worldwide. They are versatile, easy to use and have a wide range of capabilities that continue to drive advancements in technology and foster collaboration between academia and industry.

2.2 Existing Solution and Drawback

2.2.1 DSBSC Modulation and Demodulation in Simulink

DSBSC (Double Sideband Suppressed Carrier) modulation transmits the message signal with two sidebands, effectively consuming less power compared to DSBFC (Double Sideband Full Carrier) [5]. However, the complexity of the circuit increases with DSBSC. Demodulation of DSBSC always requires the carrier signal in the demodulator, with the frequency and phase matching that of the transmitter's carrier [6] [4]. Failure to match these parameters can result in loss of parts of the message signal. Generating a carrier signal with the exact frequency and phase as the modulated carrier can be costly, potentially driving up the demodulator's cost. Furthermore, the modulation and demodulation processes in Simulink are not applicable to ADLAM Pluto Radio. These operations must be performed on the same laptop, limiting their scope to a single device.

2.2.2 QAM Transmitter and Receiver in Simulink

This solution presents the design of a Quadrature Amplitude Modulation (QAM) transmitter and receiver in Simulink and evaluates the Bit Error Rate (BER) through simulation [9]. The Simulink block "Rectangular QAM Modulator Baseband" processes input log2M bits and outputs QAM symbol coordinates in a 2-D vector space. Received QAM signals, affected by Additive White Gaussian Noise (AWGN), are mapped to points in this space.

Signal trajectories are observed using an oscilloscope. This chapter employs an active learning approach to teach communication systems effectively in a classroom setting.

2.2.3 Image Tx and Rx Using 802.11 Waveform and SDR

This solution demonstrates the encoding and packing of an image file into WLAN packets for transmission, followed by decoding the packets to retrieve the image. It also showcases the utilization of a software-defined radio (SDR) for over-the-air transmission and reception of the WLAN packets [7]. The transmitter input for the Pluto SDR must be complex to avoid potential signal corruption caused by radio hardware IQ imbalance correction when the input transmission signal is real-valued. Specifically, issues arise when:

- The Pluto-SDR is employed in loopback configurations with locked local oscillators (LOs) for both transmission and reception. As a result, a real signal is transmitted [8].
- When two separate radios are used, and the LO frequency offset is almost less than 100Hz [8].

Chapter 3: Design and Implementation

This section delves into the detailed process of designing and implementing the framework of our thesis. This part serves as the foundation upon which our research is built for understanding and combining theoretical knowledge and concepts with practical application. Our focus remains on the Simulink models, the technical parameters and adaptability with a view to attain efficient, reliable and resilient solutions for our given tasks.

The implementation stage brings our designs to life by translating models into functional systems and prototypes. Through rigorous testing, iterations and refinement, we validate our theoretical constructs in real-world scenarios and therefore, ensuring that our solutions meet the expectations.

Throughout this journey, we encounter challenges that demand theoretical knowledge, adaptability and persistence. From optimizing technical parameters to designing complex models, each decision shaped the trajectory of our research, guiding it towards impactful outcomes.

The design and implementation part are distributed according to the scope of the thesis and cover the requirements accordingly.

3.1 Receiving and Analyzing Frequency Spectrum of Various Mobile Network Carriers

The aim is to develop the understanding of frequency spectrum of various network carriers. The task was accomplished by utilizing ADALM Pluto in receiver mode. The requirement is fulfilled by setting up the technical parameters of ADALM Pluto. The center frequency of ADALM Pluto was set to the frequency of various mobile network carriers. The frequency band of each network carrier is as following:

- Zong: 2100 MHz
- Mobilink: 1800 MHz
- Telenor: 850 MHz

3.1.1 Mobile Network Carrier – Zong 4G

Zong mobile network covers a frequency band of 2100MHz. To receive and further carry out analysis of the frequency spectrum, a Simulink model is designed. This model upon implementation aims to understand the bandwidth along with the power spectral density of the frequency spectrum.

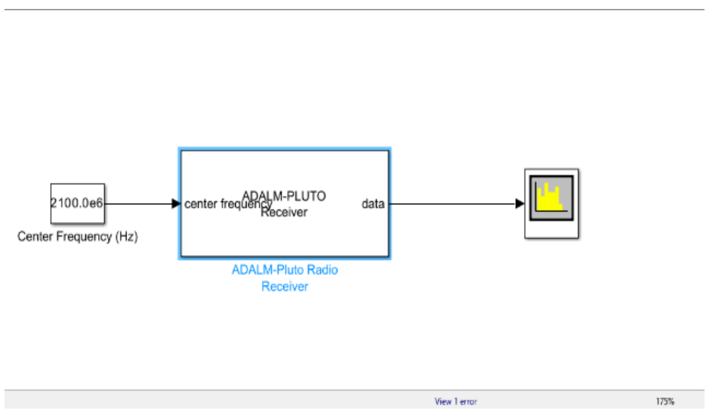

Figure 4: Simulink model encompassing ADALM Pluto Rx Block

In this model, the center frequency of ADALM Pluto (In receiver mode) is set to 2100MHz followed by a Spectrum Analyzer to carry out analysis of receiver frequency spectrum and its power density.

3.1.1.1 Findings

Findings reveal a distinct representation in the spectrum analysis, illustrating that Zong 4G occupies a specific frequency band spanning from 2110MHz to 2120MHz. This observation highlights the spectral coverage of Zong 4G within the broader frequency spectrum under examination.

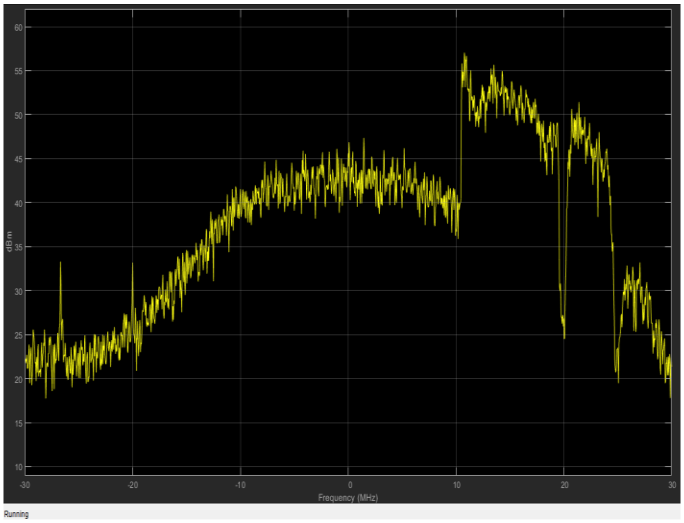

Figure 5: Analysis of Received Frequency Spectrum – Zong 4G.

3.1.2 Mobile Network Carrier – Jazz 4G

Jazz mobile network covers a frequency band of 1800MHz. The design and implementation of the Simulink model is the same as for Zong 4G. However, only the center frequency is set to 1800MHz.

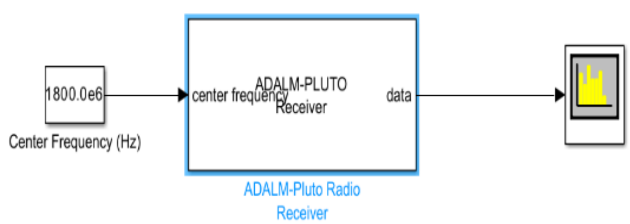

Figure 6: Simulink model encompassing ADALM Pluto Rx Block

In this model, the center frequency of ADALM Pluto (In receiver mode) is set to 1800MHz followed by a Spectrum Analyzer to carry out analysis of receiver frequency spectrum and its power density.

3.1.2.1 Findings

Findings reveal a distinct representation in the spectrum analysis, illustrating that Zong 4G occupies a specific frequency band spanning from 1805MHz to 1820MHz. This observation highlights the spectral coverage of Jazz 4G within the broader frequency spectrum under examination.

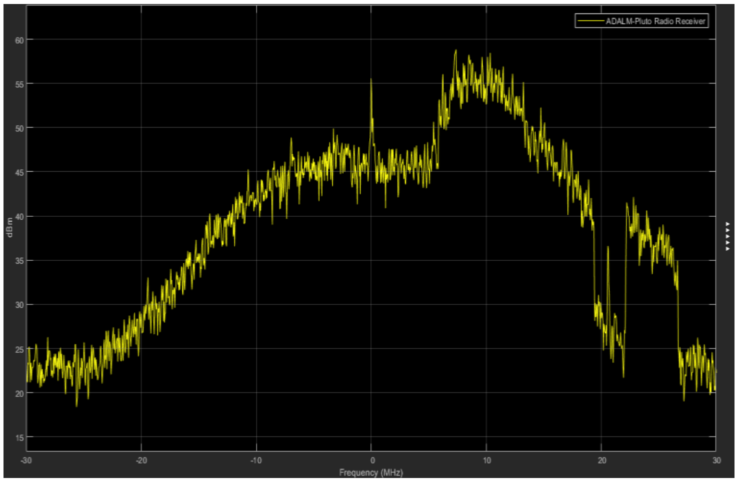

Figure 7: Analysis of Received Frequency Spectrum – Jazz 4G.

3.1.3 Mobile Network Carrier – Telenor 4G

Jazz mobile network covers a frequency band of 850MHz. The design and implementation of Simulink model is the same as for Zong 4G. However, only the center frequency is set to 850MHz.

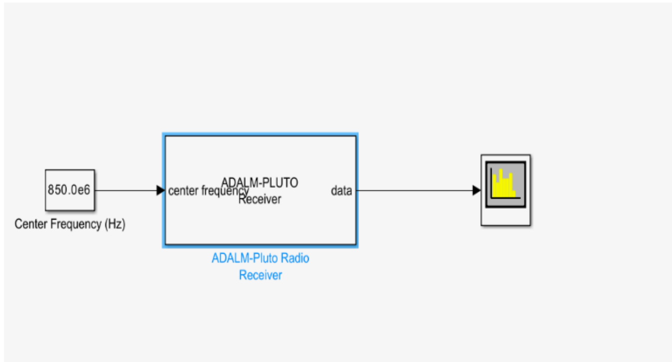

Figure 8: Simulink model encompassing ADALM Pluto Rx Block

In this model, the center frequency of ADALM Pluto (In receiver mode) is set to 850MHz followed by a Spectrum Analyzer to carry out analysis of receiver frequency spectrum and its power density.

3.1.3.1 Findings

Findings reveal a distinct representation in the spectrum analysis, illustrating that Zong 4G occupies a specific frequency band spanning from 870MHz to 880MHz. This observation highlights the spectral coverage of Telenor 4G within the broader frequency spectrum under examination.

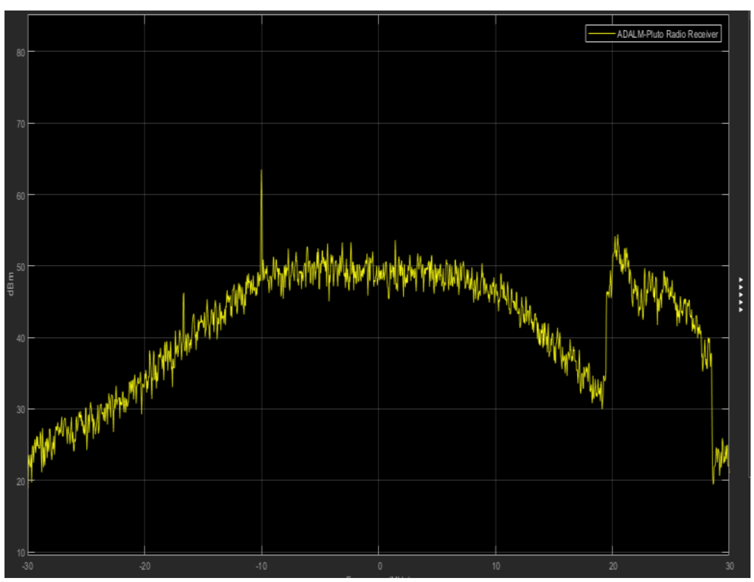

Figure 9: Analysis of Received Frequency Spectrum – Telenor 4G.

3.2 Transceiver System for DSB-SC Modulated Signal

The purpose of designing a DSB-SC modulated signal followed by a transceiver system and to implement it by utilizing ADALM Pluto is to achieve understanding of how modern communication takes place. It also ensures the uniqueness and efficiency of ADALM Pluto that has made this process very user friendly, efficient and inexpensive. The design of the transceiver system comprises of a transmitter that includes a message signal (amplitude modulated) that has been DSB-SC modulated with a carrier signal for transmission using ADALM Pluto and subsequently, a receiver that demodulates the transmitted signal back to the original message.

3.2.1 Implementation and Findings

The implementation and findings are segregated between transmitter and receiver.

3.2.1.1 Transmitter

A Sine-Wave block is converted into a message signal by setting it up to the parameters given below and is amplitude modulated by simple addition. This message signal is modulated (multiplied using a product block) with the carrier signal, also a Sine-Wave block, having the parameters given below. This process is called DSB-SC modulation. The DSB-SC modulated signal is converted to a complex signal by a Real-Imaginary Block. This is done because ADALM Pluto takes the input in complex form in MATLAB Simulink.

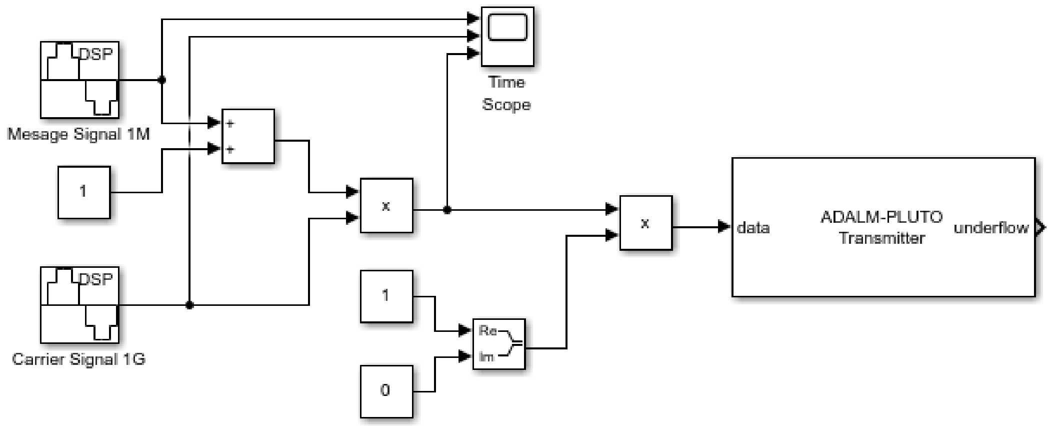

Figure 10: Simulink Model of Transmitter for DSB-SC Modulated Signal

Parameters:

The parameters of message signal and carrier signal are given below:

- **Message Signal:**

  The specifications of message signal are as follows:

  - Frequency: 1MHz
  - Sample Time: 10µs.
  - Samples Per Frame: 100k

- **Carrier Signal:**

  The specifications of Carrier Signal are as follows:

  - Frequency: 1GHz
  - Sample Time: 10µs.
  - Samples Per Frame: 1e5

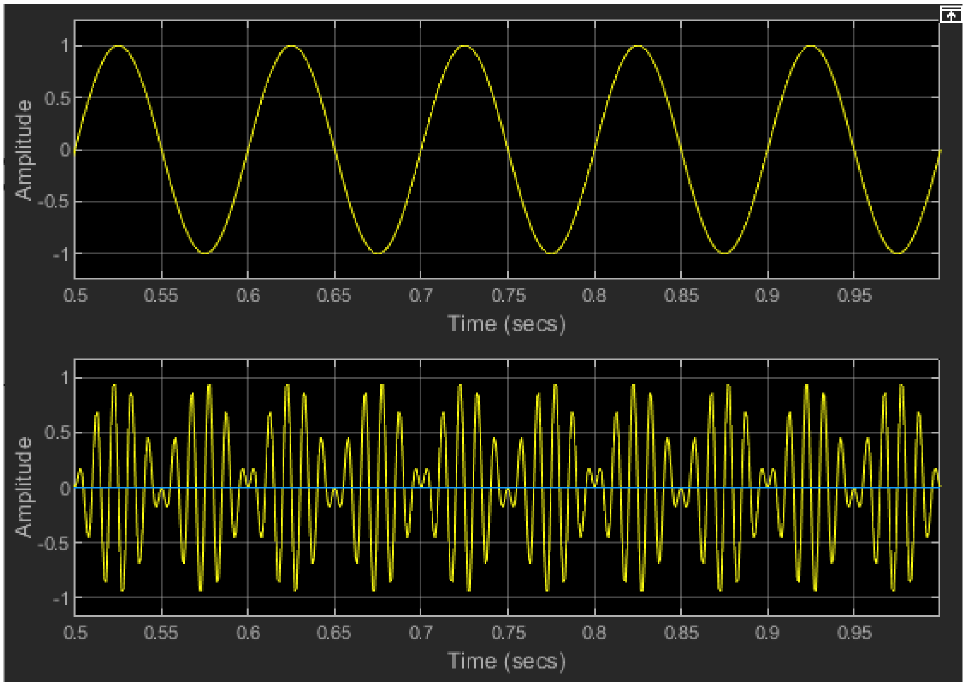

Figure 11: Message Signal (above), DSB-SC Modulated Signal (below)

3.2.1.2 Receiver

After reception of a modulated signal through ADALM Pluto Receiver Block, the received signal is demodulated (multiplied) with the same carrier signal. This signal comprises of Unwanted Signal which is removed through a Low Pass Filter to retrieve the original message signal [12].

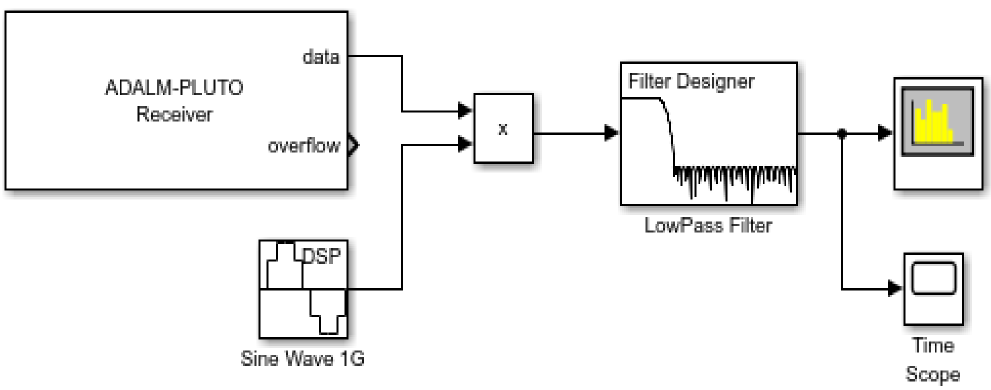

Figure 12: Simulink Model of Receiver for DSB-SC Modulated Signal

The design and parameters for the LPF are as follows:

- Sampling Frequency: 1 MHz
- Pass-Band Edge Frequency: 110 kHz
- Stop-Band Edge Frequency: 150 kHz
- Pass-Band Ripple: 1 dB
- Stop-Band Ripple: 80 dB

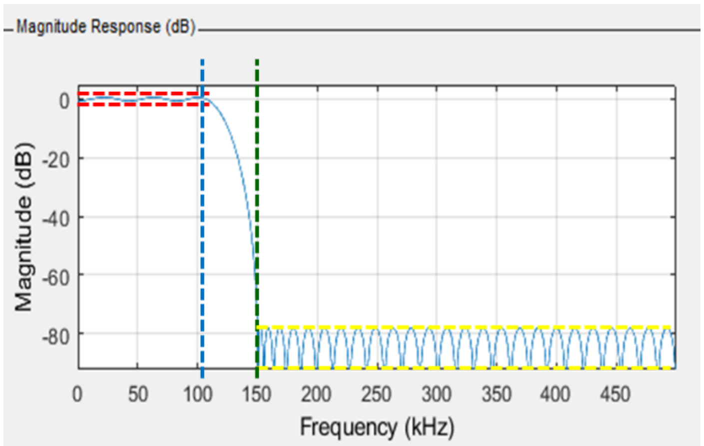

Figure 13: Design of LPF for Receiver

The Output waveform received after LPF is shown in Figure 13.

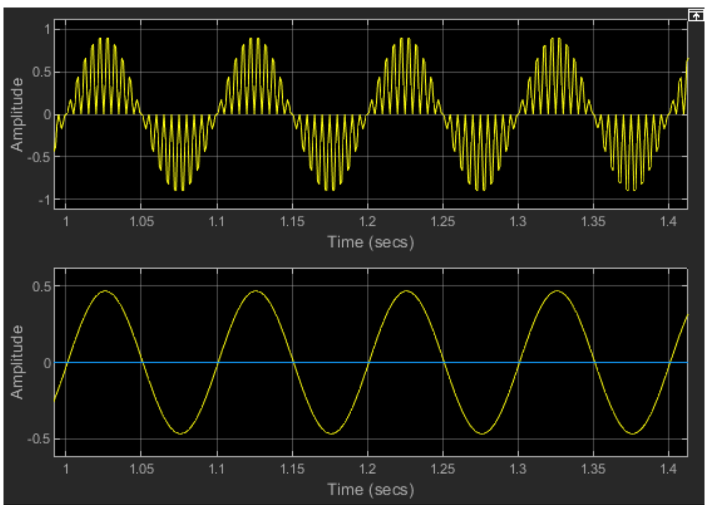

Figure 14: Demodulated Signal (above), Original Message Signal After LPF (below)

3.3 Transceiver System for QAM Modulated Signal

The aim of this requirement is to understand the working of QAM modulated signal. This is carried out by generating a message signal both In-Phase and Quadrature-Phase which is then modulated using Quadrature Amplitude Modulation and transmitted using ADALM Pluto. The modulated signal is received at the receiver end of the system which is then demodulated and after passing through the necessary filter the required message signal (in-phase and quad-phase) is attained.

3.3.1 Implementation and Findings

The implementation and their findings are subsequently segregated into transmitter and receiver end.

3.3.1.1 Transmitter

The designing process of transmitter involves a Sine-Wave block (parameters given below) which is our In-Phase signal and another Sine-Wave block (parameters given below) that is our Quadrature-Phase signal. A Local Oscillator also a sine-wave block with parameters given below is split into its Sine component and Cosine component using a Complex to Real-Imaginary block. The Sine component of LO is modulated (multiplied) with In-Phase message signal and Cosine component of LO is modulated (multiplied) with Quad-Phase signal. The resultant of these two are added using an Addition block and forwarded to transmitter block of ADALM Pluto. The resultant signal is our QAM modulated signal. The Simulink model for transmitter is shown in figure 14.

Parameters:

The parameters for In-phase, Quad-phase and LO are as following:

- **In-Phase Message Signal:**
  - Frequency: 1 MHz
  - Sample time: 10 µs.
  - Samples per frame: 100K
- **Quad-Phase Message Signal:**
  - Frequency: 2 MHz
  - Sample time: 10 µs.
  - Samples per frame: 100K
- **Local Oscillator:**
  - Frequency: 1 GHz
  - Sample time: 10 µs.
  - Samples per frame: 100K

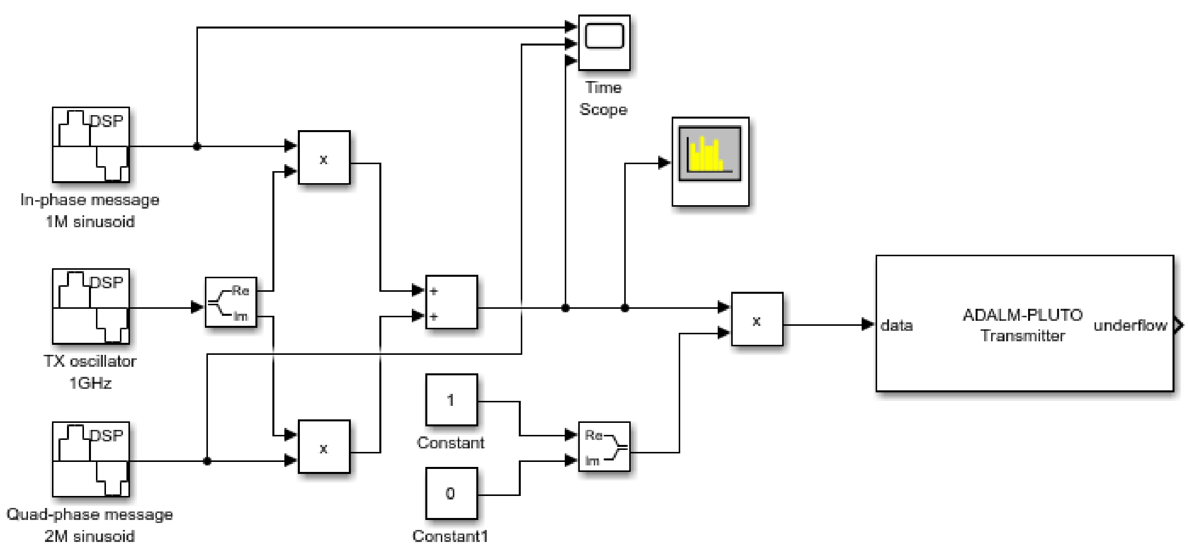

Figure 15: Simulink Model of Transmitter for QAM Modulated Signal

The waveforms for In-phase, Quad-phase after modulating with LO is given below.

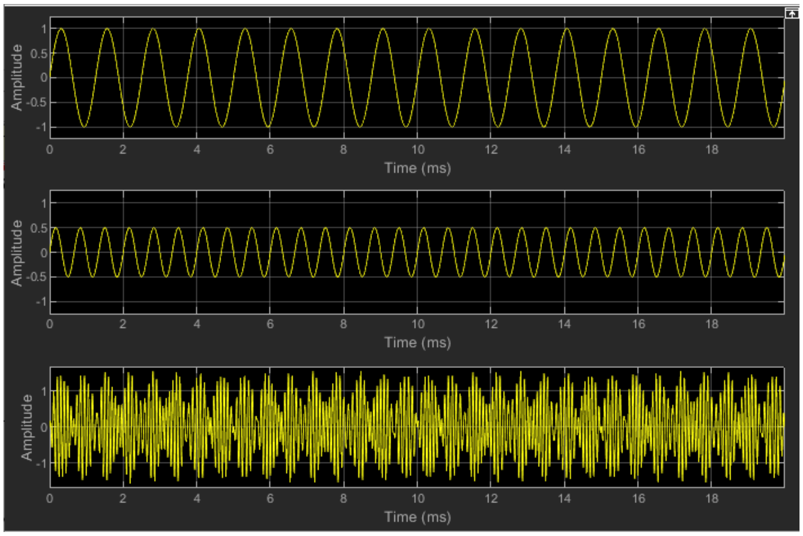

Figure 16: In-Phase Message Signal (top), Quad-Phase Message Signal (middle) and QAM Modulated Signal (below)

3.1.1.2 Receiver

The design of receiver comprises of the Receiver block of ADALM Pluto which receives our modulated signal and demodulates it with a LO of same parameters as that used in the transmitter. The two signals received are passed through the necessary LPF (parameters given below) to attain the In-phase and Quad-phase message signal. The Simulink model of the receiver is shown in figure 16.

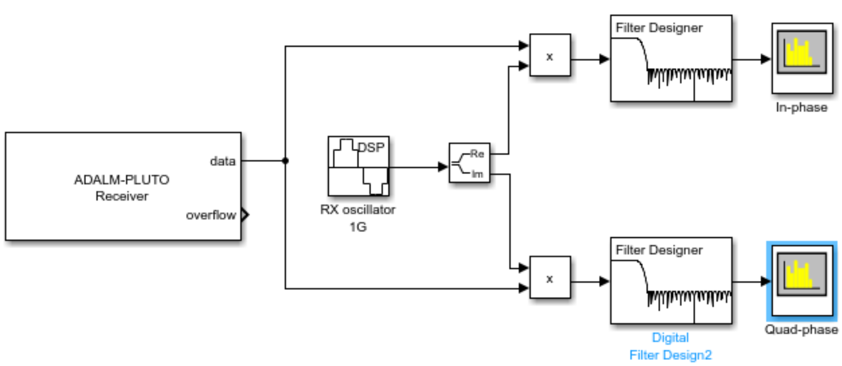

Figure 17: Simulink Model of Receiver for QAM Modulated Signal

Parameters:

The technical parameters of an Equiripple LPF are as following:

- Sampling Frequency: 1 MHz
- Pass-Band Edge Frequency: 110 kHz
- Stop-Band Edge Frequency: 150 kHz
- Pass-Band Ripple: 1 dB
- Stop-Band Ripple: 62 dB

The design characteristics of LPF (equirriple) is as shown in figure 17.

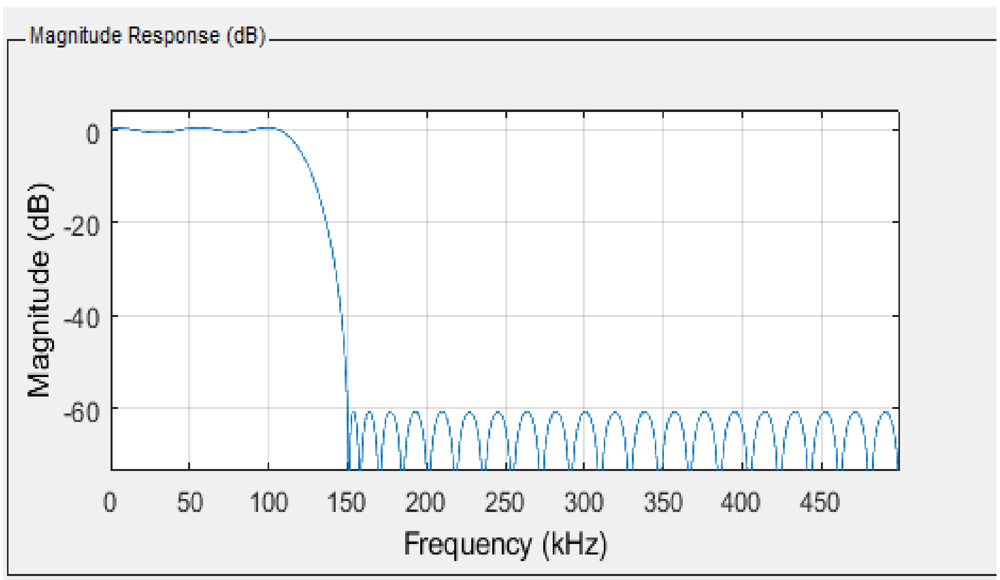

Figure 18: Low Pass Filter (Equiripple)

The demodulated signal after passing through the LPF is free from unwanted signals and clean message signals both In-phase and Quad-phase are received as shown in figure 18.

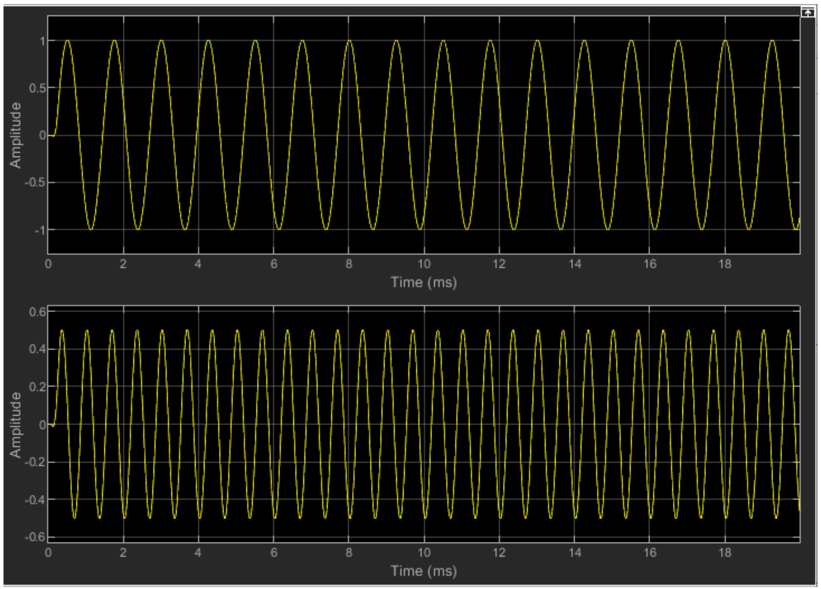

Figure 19: Demodulated and Filtered In-Phase Message Signal (above) and Demodulated and Filtered Message Signal (below)

3.4 Image Transmission and Reception with QAM

The aim of this requirement is to grasp the understanding developed through the previous requirements and tasks and set up a strong foundation necessary for the implementation of Image Transmission. QAM provides image transmission and reception with an efficient and higher transfer rate over various medium and it also offers a robust framework for encoding digital information onto carrier signals. Our target image is color adjusted followed by adjusting the dimensionality then encoded and converted to Binary digit in order to be QAM modulated and transmitted. The received data is then demodulated followed by the same conversions but in reverse order.

3.4.1 Implementation and Findings

The implementation and fundings of this requirement are segregated between transmitter and receiver.

3.4.1.1 Transmitter

The design of the transmitter comprises of an image source block. This block imports image data that needs to be transmitted. The color of the image, if necessary, is adjusted from RGB to Grayscale or any other as per requirement. The resultant data is a 2D vector that needs to be converted into 1D using a 2D to 1D converter. This block helps in converting the image data into a linear array that is required to be converted or encoded into binary digits. This later process is carried out by a Quantization Encoder. This block includes Quantization Partition and Quantization Codebook. Quantization partition is basically the conversion of data into bits using according to the provided parameters/ partitions. This partition looks up for referencing and that is provided by Quantization Codebook. Depending upon the values of partition and codebook, the type of QAM (4, 16, 64 etc.) is applied. For example, if there are 14 values provided for Quantization Codebook, then the type of QAM that can be applied is 16-QAM. It should be such that QAM technique should be greater than the values of codebook. Lastly, the resultant data is mounted to the transmitter block of ADALM Pluto and sent for transmission. The Simulink model for this design is as shown in figure 19.

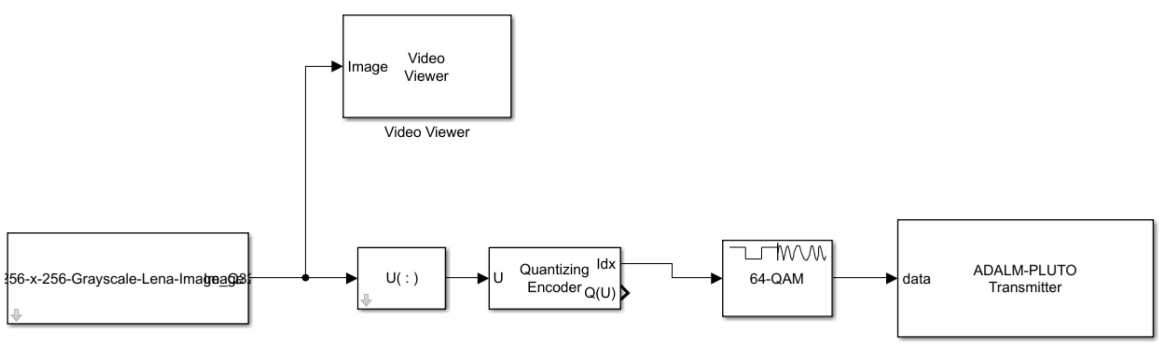

Figure 20: Simulink Model for Image Transmitter Using 64-QAM

After executing the Simulink model, the image to be transmitted is shown for reference.

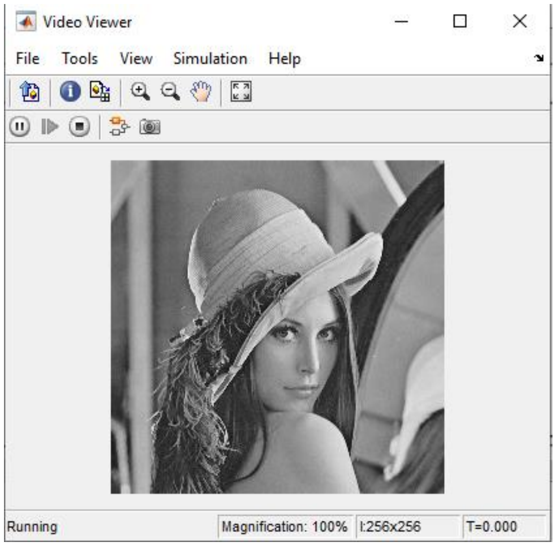

Figure 21: Image to be Transmitted

3.4.1.2 Receiver

The design of the receiver comprises of an ADALM Pluto receiver block. Followed by a QAM demodulator block. Then the demodulated data is decoded using Quantization Decoder. The image is resized to its original dimensions and displayed using Image/ Video Viewer block. The Simulink model of the receiver is as shown in figure 21.

It is to be noted that the parameters of the transmitter and receiver block of ADALM Pluto should be carefully selected so as to make the transmission successful. For example, the samples per frame must be aligned with the image data that is to be sent. Baseband sample rate of transmitter must be aligned with the receiver.

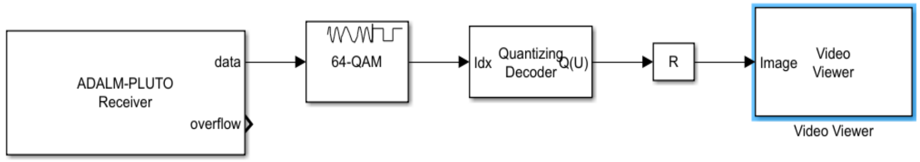

Figure 22: Simulink Model for Image Receiver Using 64-QAM

The image as received from the receiver block is demodulated, decoded and reshaped. The received image is shown in figure 22. A slight distortion in the received image is due to the interference of the communication channel.

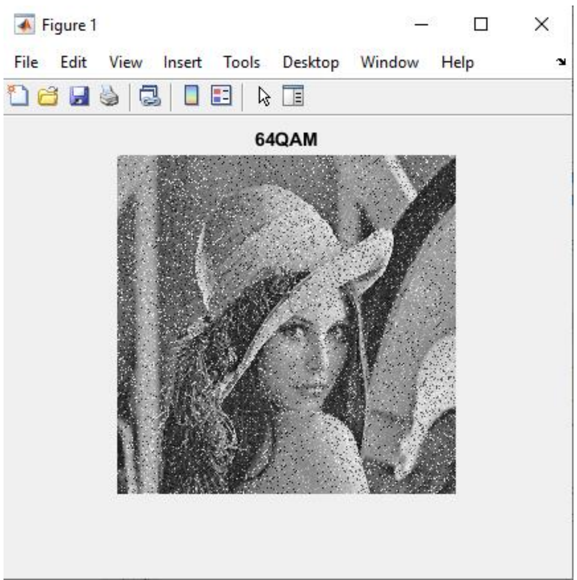

Figure 23: Image Received Using 64-QAM

Chapter 4: Conclusion

This thesis has explored the transformational impact of reduced-cost equipment, illustrated by the emergence of the ADALM-Pluto, on analog and digital communications as well as research and education within electrical engineering. By offering functionality comparable to high-end devices at a fraction of the cost, ADALM-Pluto has provided access to practical experimentation and exploration in this domain to almost everyone who is indulged in this field. This shift towards more accessible equipment not only facilitates hands-on learning experiences but also fosters innovation and creativity among students and researchers.

The design and implementation process outlined in this thesis provides a robust framework for understanding and applying theoretical knowledge in practical scenarios. Through the utilization of Simulink models and its technical parameters, efficient and reliable solutions have been developed for image transmission using Quadrature Amplitude Modulation (QAM). By integrating various processes such as color adjustment, dimensionality adjustment, encoding, and modulation, the design of the transmitter ensures the successful transmission of images over various mediums.

The adoption of ADALM-Pluto is expected to catalyze the advancements of analog and digital communications in curriculum development and research initiatives. By considering the portability, versatility and affordability of these devices, future endeavors in this field are pushed to the boundaries of innovation and drive meaningful progress. As such, this thesis not only contributes to the body of knowledge in analog and digital communications but also lays the groundwork for continued exploration and discovery in this dynamic field.

Chapter 5: Future Work

Future milestones that need to be achieved to commercialize this product are as follows.

5.1 Error Detection and Correction

5.1.1 Objective:

The primary goal of this project is to address and rectify errors that occur during data transmission over communication channels. These errors can significantly impact the integrity and reliability of the data being communicated. The project aims to implement various techniques for both detecting and correcting errors to ensure that the received data is as accurate and complete as possible.

5.1.2 Introduction:

In any communication system, data transmission is prone to errors due to various factors such as noise, interference, signal attenuation, and hardware imperfections. These errors can lead to data corruption, which, if not detected and corrected, can compromise the integrity of the information being communicated. Error detection and correction are crucial for maintaining the accuracy and reliability of data in communication systems.

5.1.3 Types of Errors:

- **Single-bit errors:** Only one bit in the data unit has been altered.
- **Burst errors:** Multiple bits in the data unit have been altered. Burst errors are more challenging to detect and correct due to their complexity.
- **Random errors:** Errors that occur unpredictably across the data stream.
- **Systematic errors:** Errors that occur in a predictable pattern due to issues in the communication system.

5.1.4 Error Detection Techniques:

5.1.4.1 Parity Check:

- Single Parity Bit: Adds a single bit to the data to make the number of 1s either even (even parity) or odd (odd parity).
- Two-dimensional Parity: Uses a matrix of bits to add parity bits for both rows and columns.

5.1.4.2 Checksums:

Involves adding the binary values of the data segments and including the result as a checksum in the data packet. The receiver calculates the checksum to verify data integrity.

5.1.4.3 Cyclic Redundancy Check (CRC):

Uses polynomial division to append a sequence of redundant bits (CRC code) to the data. The receiver performs the same division to check for discrepancies.

5.1.5 Error Correction Techniques:

5.1.5.1 Forward Error Correction (FEC):

Adds redundant data (error-correcting codes) to the transmitted data so that the receiver can detect and correct errors without needing retransmission.

5.1.5.2 Hamming Code:

A specific type of FEC that uses multiple parity bits to detect and correct single-bit errors and detect (but not correct) double-bit errors.

5.1.5.3 Reed-Solomon Code:

Useful for correcting burst errors by dividing the data into blocks and adding redundant symbols.

5.1.6 Implementation:

5.1.6.1 Designing Detection and Correction Algorithms:

- Develop algorithms for parity check, CRC, checksums, and hash functions for error detection.
- Implement FEC codes such as Hamming and Reed-Solomon for error correction.

5.1.6.2 Simulation and Testing:

- Simulate various communication scenarios with different types of noise and error patterns.
- Test the performance of the error detection and correction techniques under varying conditions.

5.1.6.3 Optimization:

- Optimize the algorithms for computational efficiency and minimal redundancy.
- Evaluate the trade-offs between detection/correction capability and resource overhead.

5.1.7 Conclusion:

Error detection and correction are fundamental to reliable communication systems. By implementing a combination of detection and correction techniques, this project aims to enhance data integrity and ensure robust communication across different channels. This not only improves the user experience but also ensures that critical information is transmitted accurately, thereby supporting the overall functionality and reliability of communication systems. The scope of this project is to cater for all sorts of errors that are generated in the communication channel and carry out its correction through various techniques of error correction.

5.2 Live Audio Calls and Video Streaming

5.2.1 Objective:

The primary goal of this project is to develop and implement systems for both live audio calls and live video streaming. These technologies will enable real-time voice and video communication, providing critical support for a wide range of civil and military applications. The project will address the technical requirements and challenges associated with delivering high-quality, low-latency audio and video transmissions.

5.2.2 Introduction:

In modern communication, live audio and video streaming are essential for effective real-time interaction. These capabilities are vital for various applications, from routine civilian communication to complex military operations. This project aims to create robust systems for live audio calls and video streaming, ensuring high quality, reliability and security.

5.2.3 Key Components:

5.2.3.1 Live Audio Calls:

- **Voice Capture and Processing:** Use high-quality microphones, noise reduction, and echo cancellation technologies.
- **Audio Encoding and Compression:** Select and implement efficient audio codecs
- **Network Transmission:** Utilize protocols and ensure QoS and security.
- **Audio Playback:** Implement solutions for low-latency and high-fidelity audio output.

5.2.3.2 Live Video Streaming:

- **Video Capture and Processing:** Use high-definition cameras and video processing techniques.

- **Video Encoding and Compression:** Implement video codecs to balance quality and bandwidth.
- **Network Transmission:** Use protocols like Real-Time Messaging Protocol
- **Video Playback:** Ensure seamless playback on various devices with minimal latency.

5.2.4 Civil Applications:

5.2.4.1 Telecommunications:

- **VoIP Services:** Enhance VoIP services with integrated audio and video capabilities.
- **Customer Support:** Provide richer customer service experiences with video support.

5.2.4.2 Healthcare:

- **Telemedicine:** Enable remote consultations with audio and video, improving patient care.
- **Medical Training:** Stream live surgeries and training sessions for educational purposes.

5.2.4.3 Education:

- Online Learning: Support interactive online classes with live video and audio.
- Virtual Classrooms: Create immersive learning environments with real-time interaction.

5.2.4.4 Business:

- Conference Calls: Improve virtual meetings with live video and audio communication.
- Remote Work: Enhance remote work setups with reliable communication tools.

5.2.5 Military Applications:

5.2.5.1 Field Operations:

- **Command and Control:** Facilitate real-time audio and video communication between command centers and field units.
- **Reconnaissance:** Stream live video feeds from drones and other reconnaissance tools.

5.2.5.2 Training and Simulation:

- **Live Training:** Stream training sessions for personnel in remote locations.
- **Simulation Exercises:** Use live audio and video to enhance realism in simulation exercises.

5.2.5.3 Surveillance and Intelligence:

- **Live Monitoring:** Stream live video feeds for surveillance and intelligence gathering.
- **Interoperability:** Ensure seamless communication between different military branches and allied forces.

5.2.6 Implementation Plan:

5.2.6.1 System Design:

- Develop a comprehensive design for both audio and video communication systems, addressing all technical requirements.
- Ensure scalability and flexibility to adapt to various use cases and network conditions.

5.2.6.2 Development and Integration:

- Implement core functionalities for audio and video capture, processing, encoding, transmission, and playback.

- Integrate security measures to protect communications from eavesdropping and unauthorized access.

5.2.6.3 Testing and Optimization:

- Conduct extensive testing under various conditions to ensure reliability and performance.
- Optimize systems for low latency, high quality, and efficient bandwidth usage.

5.2.6.4 Deployment:

- Roll out the systems for both civil and military users, providing necessary training and support.
- Continuously monitor and maintain the systems, making improvements as needed.

5.2.7 Conclusion:

The development of systems for live audio calls and video streaming is crucial for enhancing real-time communication capabilities. By leveraging advanced technologies in audio and video processing, transmission, and security, this project aims to deliver robust solutions for a wide range of civil and military applications. Successful implementation will improve communication efficiency, support critical operations, and facilitate training and educational activities, ultimately contributing to better connectivity and operational effectiveness.

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