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4G/5G Demonstrator for NI USRP

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Abstract

The purpose of this project is to use the National Instruments Universal Software Radio Peripheral (USRP) to create a 4G and 5G demonstrator to be used in future laboratory projects and design exercises. The demonstrator should show how data is transferred through a 4G/5G network, as well as exhibiting how various impediments can be mitigated against.

A working demonstrator was achieved and utilised OFDM communications to show how 4G and 5G systems operate. In addition to this, various aspects of OFDM communications were investigated such as cyclic prefixing, channel estimation, time synchronisation offset, peak to average power ratio, carrier frequency offset, and filtering.

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Abbreviations

ADC	Analog to Digital Converter
AM	Amplitude Modulation
AWGN	Additive White Gaussian Noise
BER	Bit Error Ratio
BPSK	Binary Phase Shift Keying
CFO	Carrier Frequency Offset
CP	Cyclic Prefix
DAC	Digital to Analog Converter
DBPSK	Differential Binary Phase Shift Keying
eMBB	Enhanced Mobile Broadband
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
f-OFDM	Filtered Orthogonal Frequency Division Multiplexing
GUI	Graphical User Interface
ICI	Inter Carrier Interference
IFFT	Inverse Fast Fourier Transform
IOT	Internet Of Things
ISI	Inter Symbol Interference
LTE	Long-Term Evolution
LS	Least Squares
MIMO	Multiple-Input Multiple-Output
mMTC	Massive Machine-Type Communications
MMSE	Minimum Mean Square Error
NR	New Radio
NGW	Next Generation Wireless
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak to Average Power Ratio
PDR	Pilot to Data Ratio
PLL	Phase Locked Loop
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying

RF	Radio Frequency
SNR	Signal to Noise Ratio
USRP	Universal Software Radio Peripheral

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We would like to thank our project supervisors Mohammed El-Hajjar and Lie-Liang Yang for their guidance and support, and our second examiner Tracy Melvin for her feedback.

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Chapter 1

Introduction

The Next Generation Wireless (NGW) Research Group within the department of Electronics and Computer Science is involved in over ten teaching modules in undergraduate courses [1] as well as the teaching of the MSc Wireless Communications course which has graduated over 600 students [2]. There is scope for supplementing teaching with many practical tasks and the Universal Software Radio Peripheral (USRP) is an ideal tool for this [3][4].

The USRP (Figure 1.1) is a radio frequency transceiver that can be programmed using LabVIEW, a graphical programming environment that contains pre made blocks for key functions such as symbol mapping and pulse shaping [5]. The environment also supports a simple front end GUI which allows the user to define variables and view outputs.

FIGURE 1.1: National Instruments Universal Software Radio Peripheral (USRP).

The resulting Group Design Project is to use the USRP and LabVIEW to demonstrate the transmission and reception of 4G and 5G signals. Once this has been created, the demonstrator should also support hindrances such as frequency or time synchronisation offsets and channel interference whilst also demonstrating the techniques put in place to correct the signal when these hindrances occur.

When completed, the demonstrator will be used by the NGW group in practical laboratory sessions as well as in a future design exercise.

This report explains the objectives of the project followed by the resources available to the team. Then a summary of the background research that has been carried out will be explained, followed by the team's approach to the project, the results, and a section on team management.

Chapter 2

Objectives

After discussing the project with the supervisors, a project specification was defined with a list of technical goals and stretch goals. The technical goals are mandatory and should be completed. The stretch goals were optional and dependant on the progress of the project.

2.1 Technical Goals

1. Build:
    (a) Implement an Orthogonal Frequency Division Multiplexing (OFDM) communications system on the NI USRP device
    (b) Implement 4G standards on the NI USRP device
    (c) Implement 5G standards on the NI USRP device
    (d) Simulate these standards on MATLAB
2. Analyse and Test:
    (a) Effect of Cyclic Prefix (CP) design on the performance of the system
    (b) Channel estimation and channel estimation error on the performance of the system
    (c) Effect of time synchronisation offset on the performance
    (d) Peak to Average Power Ratio (PAPR) issues when increasing the amount of subcarriers
3. Design mitigation techniques for:
    (a) Carrier frequency offset
    (b) Time synchronisation offset
    (c) Filtering

2.2 Stretch Goals

1. Analyse effect of carrier frequency offset on the performance
2. Analyse effect of filtering on the performance
3. Analyse effect of inter-user synchronisation in uplink
4. Create interactive GUI to alter variables in real time

Chapter 3

Resources

The project is mostly software related with some experimentation on hardware.

3.1 Software

MATLAB was used to simulate various systems and LabVIEW Communications System Design Suite was used to program the USRP and analyse the signals. Both programs were provided by the department on an education software license.

3.2 Hardware

The NI USRP 2922 kits were provided by the department for the duration of the project. The kits also contained coaxial cables, 30 dB attenuators, and antennae which allowed us to test our designs over a variety of channel mediums.

Chapter 4

Background Reseach

Both members of the team were required to carry out research on OFDM systems, 4G and 5G standards, and the workings of the USRP in order to complete the project. This research is outlined in the following chapter with supplementary content available in Appendix A.

4.1 OFDM

OFDM is a digital multicarrier modulation scheme that has a greater spectral efficiency [6] [7] than other multicarrier schemes by merging the sub-channels as shown in Figure 4.1. Whilst it would seem that the subcarriers would interfere with other, the key aspect of OFDM systems is that the subcarriers are orthogonal to each other. This means that for any given subcarrier, its adjacent subcarriers have an amplitude of zero at the frequency at which the subcarrier in question has a maximum amplitude. The result of this is that when the signal is sampled at the frequencies corresponding to the centre frequencies of each of the sub-channels there is no interference from neighbouring sub-channels [8]. This property allows the overlapping of subcarriers without Inter Carrier Interference (ICI).

Making the subcarriers orthogonal to each other is achieved by applying the Inverse Discrete Fourier Transform (IDFT) to each set of symbols at the transmitter. At the receiver the Discrete Fourier Transform (DFT) is used to obtain the symbols. The execution of the DFT and IDFT is usually performed using the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) respectively. These functions are simple and cheap to create in hardware [6] which reduces the cost of building OFDM transceivers. The merging of subcarriers brings the benefit of a very high spectral efficiency [7] which allows more data to be sent within the same bandwidth.

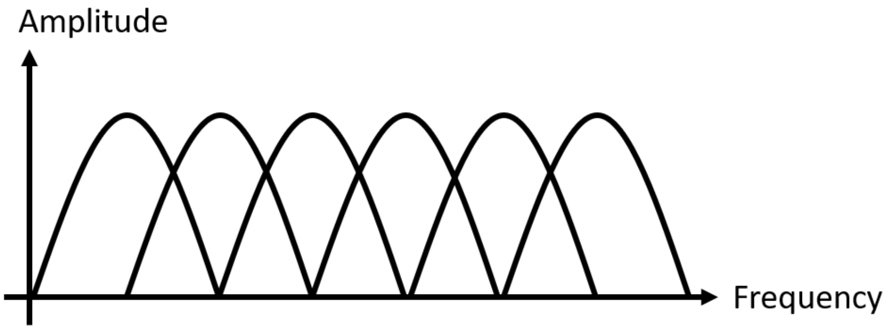


Figure 4.1: A frequency spectrum demonstrating how an OFDM signal overlaps sub-channels to improve spectral efficiency.

An example OFDM transmitter is shown in Figure 4.2. Here the data stream is mapped to Quadrature Amplitude Modulation (QAM) symbols prior to the serial to parallel conversion. After the conversion the symbols undergo the IFFT after which a cyclic prefix is applied. The uses of cyclic prefixing are discussed in Chapter 4.2.1. The data is then converted into a single stream before being converted to an analog signal and modulated using a carrier.

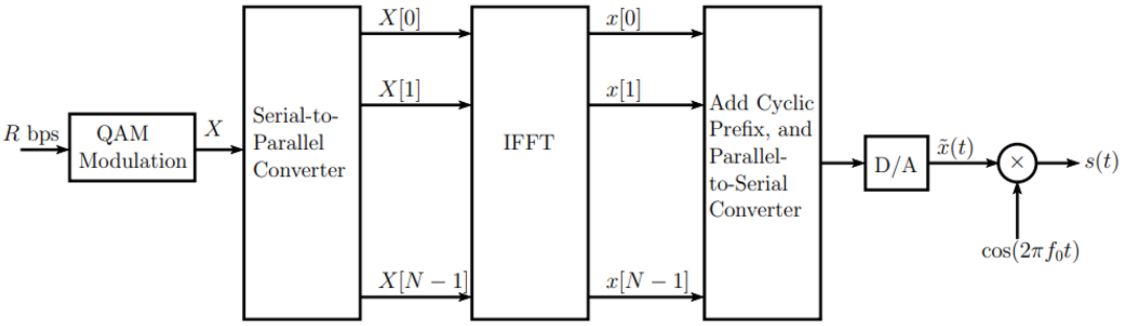


Figure 4.2: A diagram showing the key blocks in an OFDM transmitter, sourced from [9].

An example OFDM receiver is very similar (Figure 4.3). The incoming signal is brought to the baseband by multiplication with the locally produced carrier, low pass filtering, and an analog to digital conversion. The cyclic prefix is removed and the data is split into parallel streams with each stream undergoing an FFT to obtain the QAM symbols. These parallel symbols are then combined into a serial stream before being QAM demodulated.

4.2 4G

In this section we will discuss the main aspects that will be integrated when building a 4G OFDM system both in MATLAB and the USRP.

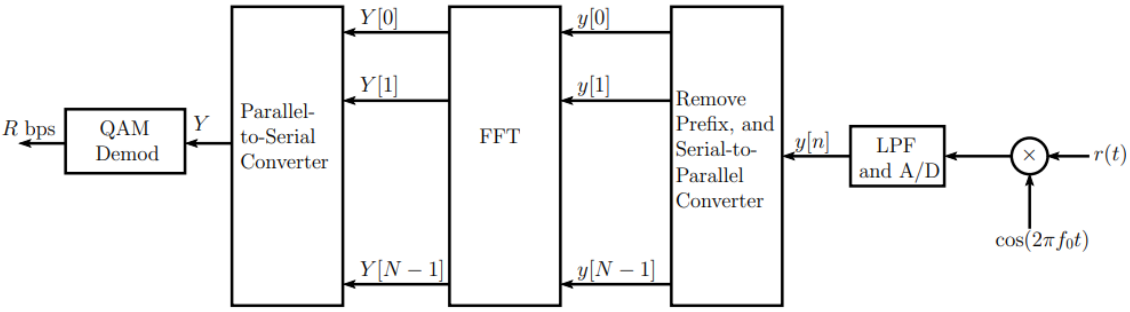


Figure 4.3: A diagram showing the key blocks in an OFDM receiver, sourced from [9].

4.2.1 Cyclic Prefix

The cyclic prefix is used in OFDM as a guard interval. It is an integral part of an OFDM symbol. The OFDM symbol consists of N symbols, corresponding to each signal from the subcarriers. The cyclic prefix is prepended to the OFDM symbol at the transmitter. It consists of the last μ symbols of the OFDM symbol (Figure 4.4). Sending a cyclic prefix that is longer than necessary will lower the efficiency of the system as it carries redundant information. At the receiver the cyclic prefix is removed and the rest of the OFDM symbol is demodulated. The cyclic prefix brings the benefit of making the OFDM system more robust to timing synchronisation errors [7] as well as added resistance to inter-symbol interference.

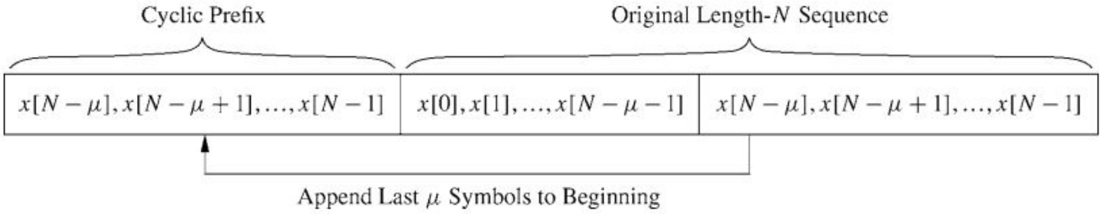


Figure 4.4: An example of a cyclic prefix, sourced from [6].

Although it carries redundant information, the cyclic prefix is essential to build a strong OFDM system. Due to multipath propagation, the signals do not arrive at the same time at the receiver. Some signals that have been scattered, diffracted or refracted are delayed in their arrival at the receiver. If the OFDM symbol did not contain any cyclic prefix, the delayed signals would interfere with the next symbol arriving at the receiver causing ISI. In order to mitigate this, the cyclic prefix is made long enough so that all the delayed signals are removed along with the cyclic prefix to remove all ISI.

In the case where the cyclic prefix is long enough, the received signal Y can be expressed in the following form.

$$Y = HX + n \tag{4.1}$$

In Eq 4.1, H is the circulant matrix containing the time domain channel taps, X represents the transmitted symbols and n is the Additive White Gaussian Noise (AWGN) added onto the channel.

The variable E is the difference in the length of the channel and the length of the CP. When this value is higher than 0, this results in interference in the signals due to ISI.

$$E = L - \mu - 1 \tag{4.2}$$

In Eq 4.2, L is the length of the channel and μ is the length of the CP. From this equation we can deduce that when the channel length is greater than the length of the CP by 1, there is no ISI. This is because the channel taps are the different paths that the message can take. When the message only has one path, there is no delayed arrival of the message and hence there is no ISI.

However, when the channel length is longer than the cyclic prefix length, there is ISI and the resulting received signal can be written in the following form [10].

$$Y = HX_k + H_{ISI}X_{k-1} + n \tag{4.3}$$

In Eq 4.3, X_k is the k^{th} transmitted OFDM symbol and H_{ISI} is the ISI channel matrix defined below [10].

$$H_{ISI} = \begin{bmatrix} 0_{E\times(N-E)} & H_I \\ 0_{(N-E)\times(N-E)} & 0_{(N-E)\times E} \end{bmatrix} \tag{4.4}$$

In Eq 4.4, $0_{M\times N}$ is an M by N size matrix of zeros, E is defined in Eq 4.2 and H_I is the matrix defined below [10].

$$H_I = \begin{bmatrix} h_{L-1} & \cdots & \cdots & h_{\mu+1} \\ 0 & \ddots & & \vdots \\ \cdots & \ddots & \ddots & \cdots \\ 0 & \cdots & 0 & h_{L-1} \end{bmatrix} \tag{4.5}$$

In Eq 4.5, H_I is an E by E matrix built using the channel taps h_n as defined in the background research regarding the channel. The trivial case where $E = 0$ simplifies the Eq 4.3 to Eq 4.1.

4.2.2 Channel

When transmitting data over a medium, it faces interference. The function that transforms the data between the transmitter and the receiver is called a channel. In this project we will be considering two different types of channels.

The first type of channel considered is an AWGN channel. In the communication between the two USRPs using a coaxial cable, we consider the transmission to occur over an AWGN channel. In this case, the noise in the system is due to the thermal noise at the receiver. In our MATLAB simulations however, we add a noise element to the data when it is transmitted from the transmitter to the receiver. By nature, AWGN is random and can be modelled as a random variable with a Gaussian distribution whose average is 0 and variance is the noise power spectral density. In our model the noise is complex. As a result, we generate two random variables like the one that would be generated had the noise been purely real. However the variance of these two random variables is half of the noise power spectral density. One of the random variables is purely real whilst the other is purely imaginary. They are then added together to form a complex normalised noise element.

$$Y = X + n \tag{4.6}$$

Equation 4.6 is the mathematical expression for the received symbols at the receiver with X being the transmitted symbols and n the noise of the channel.

The second type of channel that we will be considering in this project is a Rayleigh fading channel. This type of channel is a frequency selective channel. It is a distortion that stems from the fact that in a wireless transmission, signals can arrive at the transmitter through different paths as seen in Figure 4.5. This is because radio frequency waves can change direction through diffraction, reflection, or scattering. Each path will have different distances but RF waves travel at the same speed which will result in different path losses at the receiver. This path loss variation due to multipath propagation is the reason for fast fading. When there is no major line of sight component between the transmitter and the receiver the channel is modelled by a Rayleigh channel. This phenomenon is described in [11].

Mathematically the channel impulse response can be modelled as a complex random variable with a Gaussian distribution with zero mean (Eq 4.7). For the remainder of the project we will be referring to the length of the channel impulse response as L.

$$Y = HX + n \tag{4.7}$$

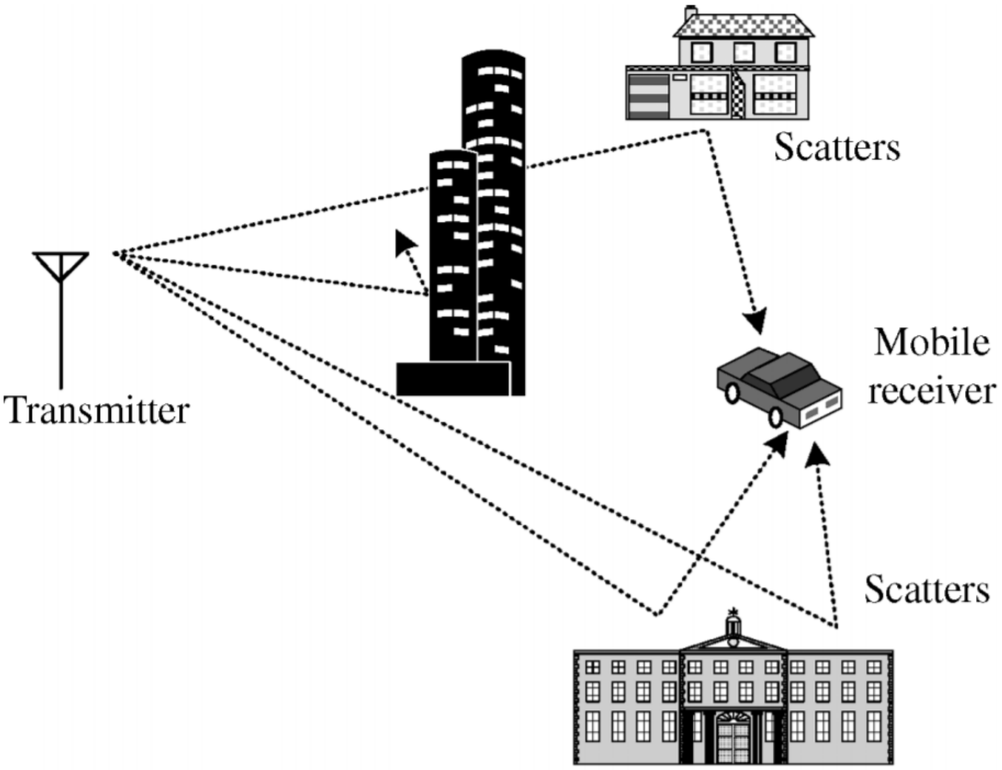


FIGURE 4.5: An example of multipath propagation, sourced from [12].

Where H is the circulant matrix of the channel impulse response h_n with $1 \leq n \leq L$ and n is the AWGN.

4.3 5G

In this project we planned to build a 5G OFDM system based on the Filtered OFDM (f-OFDM) transmission scheme which is a candidate for 5G. The block diagram for an f-OFDM transmitter is shown in Figure 4.6. Compared to standard OFDM, this scheme enables the use of different sub-bands. The advantage of this is to be able to use different specifications for each sub-band but transmit the sub-bands over the same OFDM symbol. This is an important aspect for 5G communications as 5G has to accommodate for different types of communications scenario [13]. The three main scenarios would benefit from being able to use different specifications to send data. For example, the enhanced mobile broadband (eMBB) scenario, would require a higher bandwidth than the massive machine-type communications (mMTC) scenario. In this example a higher bandwidth would allow a higher data rate which benefits an eMBB scenario more than an mMTC scenario.

Another advantage of f-OFDM is the use of filters for each sub-band, reducing the amount of guard bands needed to separate them from each other. This enables better spectral efficiency for the system.

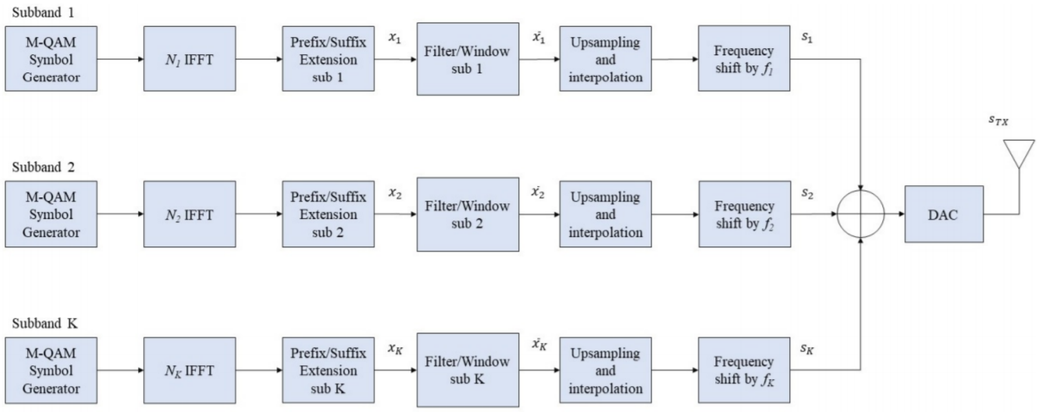


FIGURE 4.6: Block diagram of f-OFDM transmitter, sourced from [14]

In the frequency domain, the output of the transmitter would be the sum of adjacent sub-bands. This method of transmission allows the transmitter to recover the data from each sub-band by shifting the frequency and using a matched filter to eliminate the other sub-bands. The block diagram for the transmitter is outlined in Figure 4.7.

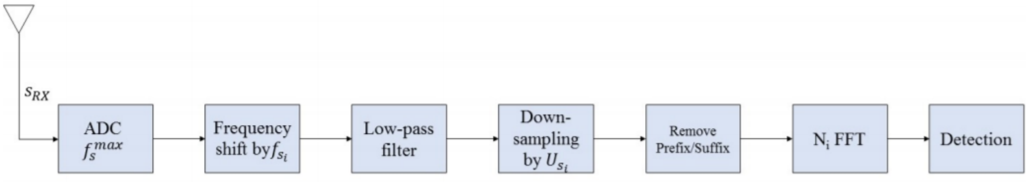


FIGURE 4.7: Block diagram of f-OFDM receiver, sourced from [14]

As seen above the complexity of the receiver in f-OFDM is minimal, making it a strong candidate for 5G [15]. The reason behind this is that 5G is built to allow an exponential increase in the amount of Internet Of Things (IOT) devices that will be used. Energy efficiency is key in IOT devices. Using a simple receiver design such as the f-OFDM's receiver would result in a longer battery life for these devices.

4.4 USRP

The USRP-2922 consists of two coaxial inputs, the first labelled "RX1 TX1" can receive or transmit a signal whilst the second labelled "RX2" can only receive a signal. An Ethernet port is available for programming from a PC and a Multiple-Input Multiple-Output (MIMO) expansion port is available for connecting to another USRP to share clock signals, reroute programming code, and more. The front panel is shown in Figure 4.8.

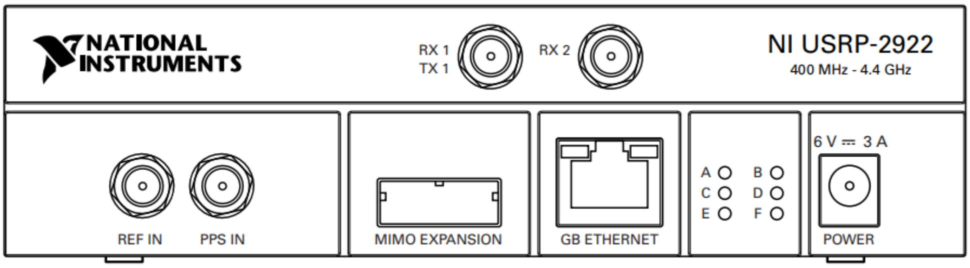


Figure 4.8: The front panel of the USRP-2922, sourced from [16].

The USRP uses a mixture of analog and digital components to create signals ranging from 400 MHz to 4.4 GHz [17]. Data to be transmitted is provided to the USRP from LabVIEW in the form of a complex vector. In the USRP the real and imaginary values are processed separately. Both sets of values go through digital upconverters to bring them to an intermediate frequency before being converted to analog signals using Digital to Analog Converters (DAC). These two signals are then passed through a low pass filter before being mixed up to the specified carrier frequency. As an imaginary signal cannot be transmitted, the signal containing the imaginary values undergoes a 90° phase shift. The two signals, the real signal being the in-phase signal and the imaginary signal being the quadrature phase signal, then combine before being amplified and then transmitted.

The receiver has a similar flow but in reverse. After amplification the signal is split in two with both being mixed with the carrier produced by the receiver's oscillator. This carrier is phase shifted by 90° before being mixed with one of the two signals to obtain the quadrature phase signal. Both in-phase and quadrature phase signals go through low pass filters and ADCs to obtain digital data before being downconverted. The USRP turns this data into packets that can be sent through an ethernet cable to the host PC for further processing in LabVIEW. A diagram explaining both the transmitter and receiver circuitry is shown in Figure 4.9.

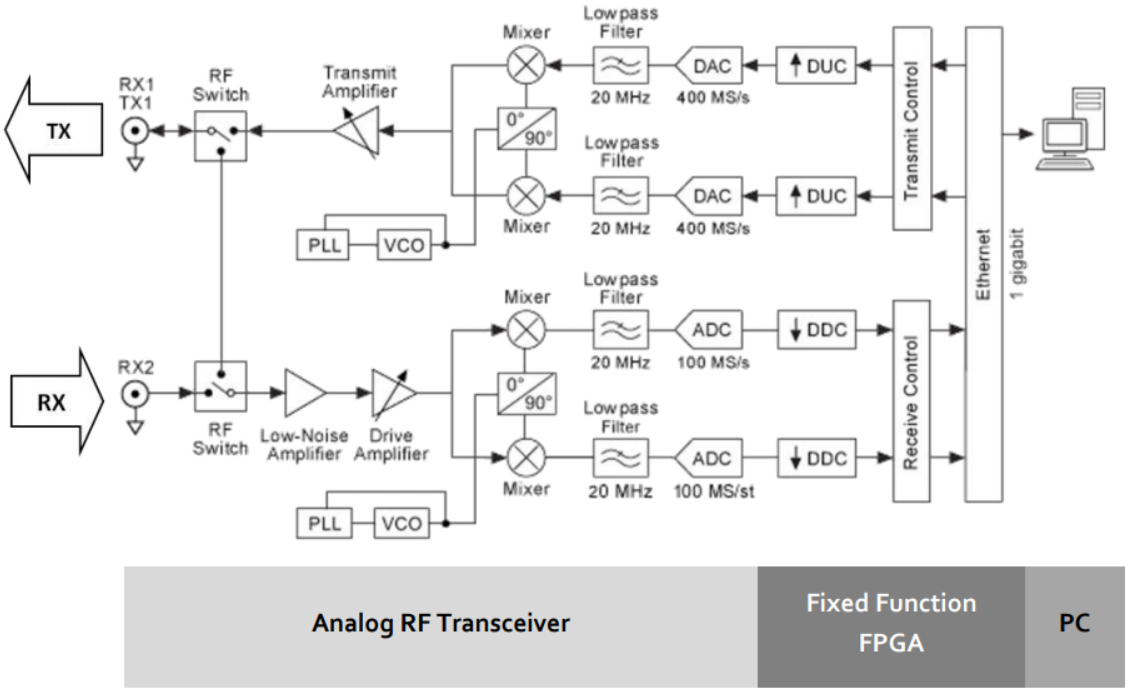


Figure 4.9: A diagram showing the key blocks in the USRP, sourced from [18].

Chapter 5

Approach

The team's approach can be broken down into different subsections. Initially, we designed simulations in order to obtain the required understanding to simulate and test more complex systems. This part of the project was entitled basic design. The next phase of the project was to build an OFDM system. This design would be the precursor to our 4G and 5G systems that would be adapted to Long Term Evolution (LTE) and New Radio (NR) standards respectively. These subsections are split between MATLAB and LabVIEW.

5.1 MATLAB

In this section, we use MATLAB to simulate OFDM, 4G OFDM and 5G f-OFDM systems. The MATLAB code used in this section runs a baseband simulation of each system. This means the system does not upsample/downsample, upconvert/downconvert, or pulse shape. Although this is not a complete radio frequency communications system, this type of simulation allows us to estimate the results of a real system and study its performance.

5.1.1 Basic Design

In order to get a better understanding of the system, the approach was to simulate various scenarios and study their response. The initial simulations on MATLAB were designed to assess different modulation schemes that can be used in OFDM systems. The four modulation schemes used in this report are Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16QAM, and 64QAM.

We were given MATLAB code [19] to simulate a BPSK modulation and plot the resulting BER in terms of the SNR. We used this code as a framework to develop higher bit per symbol modulation schemes such as QPSK, 16QAM, and 64QAM. In order to check the validity of our results we compared the resulting BER plots generated through MATLAB simulations with the theoretical BER plots for these modulation schemes over AWGN channels. We were able to show that the experimental results matched the theoretical results, demonstrating the accurate modulation of each scheme.

The experimental BER results were obtained by running a simulation that transmits data over a channel. The channel distorts the data causing it to be mapped to the wrong symbols. As the effect of the channel is a random process, the simulation runs in a while loop until the receiver reaches a given number of errors. The error limit set by the program is chosen to achieve a smooth BER curve. The values were found using trial and error. Depending on the modulation scheme and the type of channel used (AWGN or frequency selective fading channel), the values ranged from 100 to 500. For smaller values of the SNR we found that adding a lower limit for the amount of bits transmitted resulted in a smoother curve.

5.1.2 OFDM

Using the knowledge that was acquired in the initial phase of the project, we were able to simulate more complex systems. The next phase of the simulation process in MATLAB was to create an OFDM system. Using the simple OFDM block diagram as a model for our system described in Chapter 4.1, we were able to create a working OFDM system. This entailed creating a parallel to serial converter as well as a serial to parallel converter. Additionally, an FFT block and an IFFT block which converts values from the time domain to the frequency domain and vice versa were made. These blocks were normalised by the length of the transform to obtain adequate results.

To model a real world system in MATLAB, such as the over the air transmission done in the USRP, the next phase was to generate a channel for our system. In previous versions we used an AWGN channel, but the channel was enhanced to produce a Rayleigh fading channel coupled with AWGN. A Rayleigh channel is equivalent to a multipath channel with no line of sight component. OFDM is a strong candidate in wireless communications due to its robustness in fading channels [6]. This was tested in MATLAB by simulating the performance of the OFDM system in this context. The BER response in perfect channel detection conditions was compared to the theoretical results for each modulation scheme in a Rayleigh channel in order to verify that the implementation of the OFDM system was performed correctly.

5.1.3 4G

This part of the project comprised of adapting the OFDM system to a 4G OFDM system. In order to pass as a 4G OFDM system, the symbols had to be adapted to frames as specified by the LTE-A standards [20]. We chose to simulate the environment using the 1.4 MHz bandwidth. This bandwidth contains 6 resource blocks which each containing 12 subcarriers. Guard bands were added on either side of the symbol to fit through a standardised FFT block of length 128.

In MATLAB, not all parts of the LTE-A standards were implemented as the simulation was simplified to a baseband simulation. For example, the timing specifications were not considered in the code and neither was the cyclic prefix.

5.1.4 5G

The current preferred option for 5G OFDM system is f-OFDM [14]. It was built using the description in the background research. The design specifications of this filter ensure a flat passband, a high attenuation and a fast transition.

The specifications for the OFDM symbol are described in the NR standards outlined by 3GPP. In order to run simulations that are as close to real world 5G OFDM communication systems, we adapted the code to fit to 5G standards specified in [21]. In MATLAB we simulated our system in the FR1 frequency range with a specified subcarrier spacing of 15 kHz, 10 subframes per symbol, 1 slot per subframe, and 14 OFDM symbols per subframe. One OFDM symbol contains 20 resource blocks each of which contain 12 subcarriers.

Our approach to build this section was to demonstrate the capability of a frequency selective f-OFDM system with multiple sub-bands. The next part of our approach was to adapt the f-OFDM code to one sub-band for simplicity and test the performance as well as other metrics such as PAPR and spectral efficiency. Using this study, we were able to draw conclusions on the 5G f-OFDM transmission scheme.

5.2 LabVIEW

This section outlines the work carried out on LabVIEW and the USRP. Two USRP-2922 radios were set up (Figure 5.1) with one running transmitter code and the other running receiver code. To begin with, a coaxial cable with a 30 dB attenuator was used to connect the two radios to remove the effects a wireless channel would have on the signal. Once the system worked with a cable this was replaced with antennae. The code was ported onto the transmitter radio using an ethernet connection to the PC. A MIMO cable connected the two radios and the receiver radio was programmed by sending the code via the transmitter radio and the MIMO cable. This was done due to the limited number of ethernet sockets on the PC.

Figure 5.1: The setup of two USRP radios. Antennae are connected to both the transmitter (top) and receiver (bottom). A MIMO cable connects the two radios and an ethernet cable connects the transmitter to the PC.

5.2.1 Basic Design

In a similar fashion to the work carried out in Chapter 5.1.1, some basic designs were made in LabVIEW before progressing onto OFDM. The "Introductory Communications Systems" tutorial [18] was worked through to gain familiarity with LabVIEW and the USRP. A basic system using amplitude modulation was created in LabVIEW and worked on the USRP. The next step was to create several systems of increasing complexity that used coherent modulation such as BPSK, QPSK, and 16QAM. However, several problems were encountered when attempting this.

It was discovered that there was an unwanted varying carrier frequency offset affecting the signal at the receiver which was due to the tolerances in the USRP's local oscillators. The accuracy of the USRP's oscillator is 2.5 ppm [17]. The carrier frequency was 915 MHz. When the receiver USRP demodulates the signal, the local oscillator that performs this may not be producing a signal with a frequency of exactly 915 MHz. Due to the 2.5 ppm accuracy the actual frequency can vary by up to ± 2287.5 Hz. Given that both radios have this tolerance, the frequency difference between the transmitted carrier signal and the signal generated at the receiver can vary by up to double this amount at ± 4575 Hz. The effect this has on the received signal is an unwanted sinusoid with a frequency of the difference between the transmitter and receiver carrier signals [22] shown in Figure 5.2.

For coherent modulation schemes such as BPSK or 16QAM this effect can distort the transmitted symbols and result in bit errors. This can easily be observed on a constellation graph (Figure 5.3). The frequency offset causes the constellation points to rotate

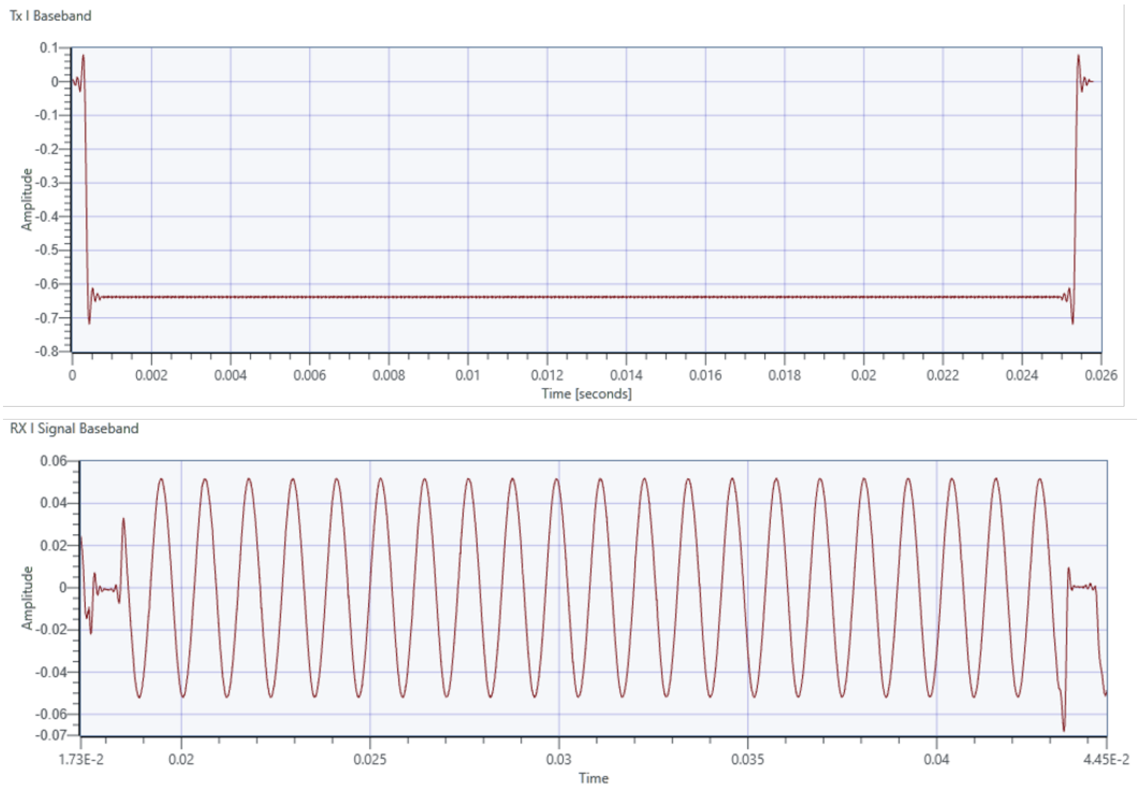


FIGURE 5.2: The transmitted (top) and received (bottom) signal. A flat steady signal is transmitted to show the unwanted sinusoid introduced at the receiver.

around the origin. As the positions of the points are used to determine the encoded data, this results in a loss of information. This is an issue that needed to be solved as QAM is the main modulation technique used in 4G and 5G systems.

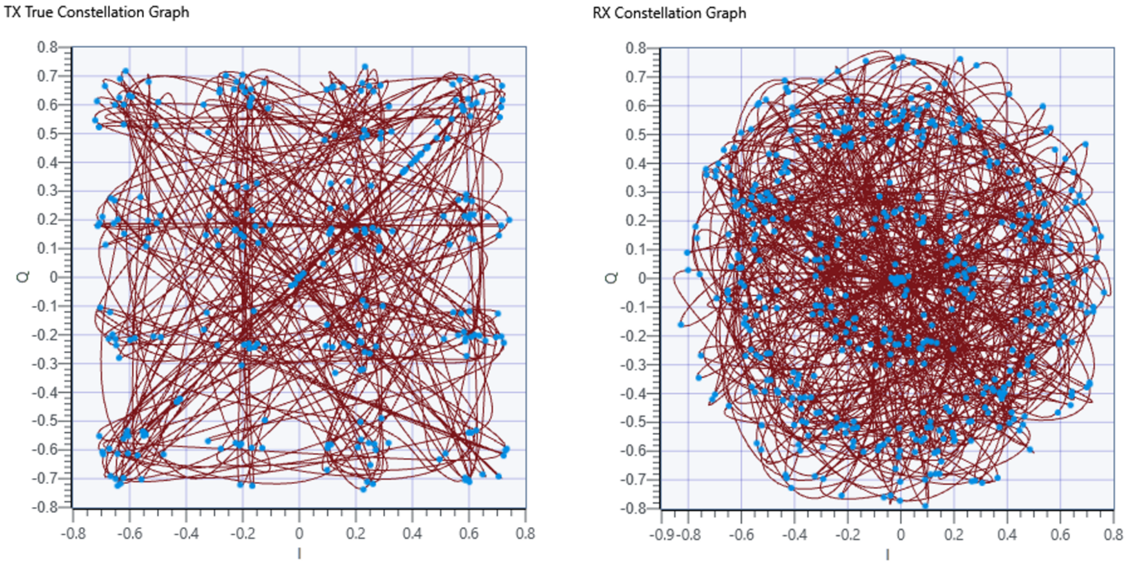


FIGURE 5.3: Constellation graphs of the transmitted (left) and received (right) signal using 16QAM modulation. A frequency offset causes distortion of the received constellation points.

A temporary solution for fixing the frequency offset was to configure the receiver USRP to use the transmitter's local oscillator signal which could be sent through the MIMO cable. This unveiled another problem. The received signal suffered from a fixed phase shift. This can be seen on a constellation graph (Figure 5.4), the points remain in the same position relative to each other but all of the points have rotated about the origin by the same fixed distance.

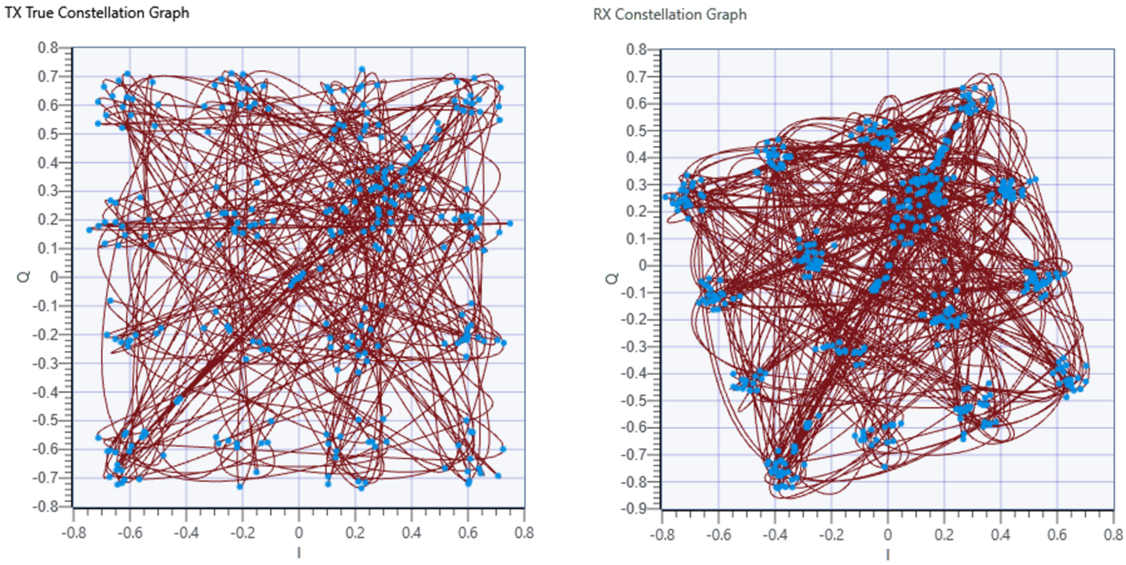


Figure 5.4: Constellation graphs of the transmitted (left) and received (right) signal using 16QAM modulation. A phase offset causes a fixed rotation of the received constellation points.

The effect of signal distortion also made it impossible for the receiver to detect the start of the data frame that was being transmitted. The transmitter was configured to send a repeated sequence of bits with the sequence prefixed with a Barker code. The receiver runs a cross-correlation between the Barker code and the received signal and uses the output to determine the start of the message. When the signal is distorted the cross-correlation does not find a match between the Barker code and the received distorted Barker code and the receiver fails to detect the frame.

The solution to detect the frame was to implement a differential encoding scheme for the Barker code that prefixed the frame. Differential encoding prevents phase and frequency differences in the oscillators from affecting the data. As the Barker code is redundant information, Differential Binary Phase Shift Keying (DBPSK) was the chosen scheme because of its simplicity. Using this, the receiver performs DBPSK decoding on the received signal and performs the cross-correlation until it finds the start of the frame, and then proceeds to use regular decoding on the rest of the message.

The solution to eliminate the effects of frequency and phase offsets was through the use of pilot symbols and channel estimation. By inserting pilot symbols at regular intervals, the receiver could estimate the offsets and recover the data. This approach is supported by [3] and [22] and is explained in further detail in Chapter 5.4.1. With these offsets compensated for, a 16QAM system was successfully made with a BER of 0.003125.

The transmitter and receiver code consisted of multiple MathScipt nodes and a collection of premade `.gvi` blocks found in the LabVIEW libraries. Front panel and diagram views of the 16QAM transmitter and receiver as well as an explanation of the code can be seen in Appendix B.

5.2.2 OFDM

Creating the OFDM transmitter and receiver in LabVIEW involved reusing many of the parts that made up the 16QAM system. The only difference between the 16QAM transmitter and the OFDM transmitter is in the MathScript node that handles the encoding from bits to symbols. In the former, the bits are simply mapped onto symbols and outputted as a vector of symbols. Extra steps are added in the latter. After the mapping, the vector of symbols is then reshaped into a matrix with a number of columns equal to the number of subcarriers specified by the user in the front panel. This is equivalent to doing a serial to parallel conversion. For our testing 64 subcarriers were used. Then the matrix is processed with an IFFT function, the cyclic prefix is determined and added to the start of the matrix, and then the matrix is converted back into a single row vector. The chosen length of the cyclic prefix was 5.

A similar situation occurs when comparing the receivers for the 16QAM and OFDM systems. The 16QAM MathScript node that deals with converting the received symbols into a single row vector of bits is extended to make it work in the OFDM receiver. First the incoming vector of symbols is reshaped into a matrix to allow easy removal of the cyclic prefix. Then the remaining symbols matrix is processed with an FFT block before being reshaped into a single row vector. This vector is then converted into a bit stream using the 16QAM demodulator code previously developed.

Front panel and diagram views of the OFDM transmitter and receiver can be seen in Appendix C.

5.2.3 4G

Adapting the OFDM system to meet a 4G specification involved changing parameters on the front panel. Using OFDM downlink modulation parameters sourced from [23] [24] and the operating bands sourced from [20], suitable parameters were chosen (Table 5.1).

Band 20 was chosen because of its operating frequency of 800 MHz being close to the 915 MHz frequency that was used in the OFDM system. This band is also used in the

Band	20
Frequency (MHz)	800
Bandwidth (MHz)	5
Resource blocks	25
Usable carriers	300
Total carriers (FFT size)	512
Sampling frequency (symbol rate) (MHz)	7.68
I/Q rate (MHz)	15.36
Upsampling factor	2
Bits sent	48,000
16QAM symbols	12,000
OFDM symbols	40

Table 5.1: A table showing the selected parameters for the 4G system.

5G specification [21] which makes the band an ideal choice for demonstrating both a 4G and 5G OFDM system. A bandwidth of 5 MHz was chosen as this is one of the available bandwidths used in both 4G band 20 and 5G band 20. From this bandwidth selection the number of resource blocks, usable carriers, and total carriers are determined.

A change that had to be made in the LabVIEW code was the addition of unused subcarriers. Band 20 has 512 subcarriers when the channel bandwidth is 5 MHz, however only 300 of these subcarriers are used. MathScript nodes were edited to account for unused subcarriers and the IFFT and FFT functions in the transmitter and receiver were adapted to include extra zeros so that the total length of the transform equalled 512 despite there only being 300 useful values.

5.2.4 5G

The transition from a 4G system to a 5G system involved the use of a band pass filter on the transmitter output and receiver input. This is done to increase the attenuation of the frequencies outside of the cut-off frequencies which increases the spectral efficiency and decreases the amount of ICI.

This was implemented on the demonstrator by adding a control signal on the front panel to switch between 4G and 5G. This is connected to a case structure in the diagram that removes or inserts the filter accordingly. The filter was made by producing the filter coefficients in a MathScript node shown in Listing 5.1. By setting the length of the filter and the sharpness of transition band using `toneOffset`, the filter response is defined in Line 7. Then the window is defined in Line 10 before the coefficients are determined in Line 13. These coefficients and the transmitter signal are then provided to a convolution block which performs the filtering. The same front panel parameters used in the 4G system are used here.

```
% F channel
length = 1025
n = -(floor(length/2)):(floor(length/2))

% Sinc function prototype
toneOffset = 2.5
pb = sinc( (ncarriers + (2*toneOffset)) .* (n./ntotalcarriers) )

% Sinc truncation window
w = (0.5 * (1 + cos(2*pi .* (n/(length-1)) ) )) .^ 0.6

% Normalized lowpass filter coefficients
fcoeff = (pb .* w) / sum(pb .* w)
```

Listing 5.1: Creation of the sinc filter coefficients using techniques sourced from [14].

5.3 Analysis and Testing

In this section we will be discussing the simulations that were run on MATLAB and the USRP to analyse the effect of cyclic prefix design, channel estimation, time synchronisation offset, and PAPR issues on the performance of the system.

Each simulation was designed to highlight the effect of each parameter's impact on the system in order to be able to draw suitable conclusions.

5.3.1 Cyclic Prefixing

In order to test and analyse the effect of cyclic prefix on the performance, we compare the performance of the system when the cyclic prefix is longer than the channel to the performance when the cyclic prefix is shorter than the channel.

When the cyclic prefix is shorter than the channel, a variable E in Eq 4.2 measures how much the cyclic prefix deviates from the channel. When E is equal to 0, the cyclic prefix is able to prevent ISI completely. On the other hand when E is more than 0, the value E corresponds to the difference between the length of the channel and the length of the cyclic prefix.

5.3.2 Channel Estimation

As was mentioned in previous subsections, the message is affected by multipath propagation which is modelled by sending the message through a channel. In order to retrieve the correct symbols from the message, this channel has to be estimated. This process is called channel estimation. Initially, perfect detection was used to be able to test the validity of our system. Once the correct results were obtained using perfect detection, we were able to estimate the channel using various techniques including Least Squares (LS), Minimum Mean Square Error (MMSE), and time-domain channel estimation.

The three variables that effect the channel estimation are the number of subcarriers, the channel length and the pilot to data ratio. The number of subcarriers and the channel length affect the fading of the channel. While the number of subcarriers is invariant, the longer the channel length, the faster the fading. As a result a higher pilot to data ratio is required in order to obtain accurate values of channel gains through interpolation. On the other hand when the channel length is fixed, a higher number of subcarriers will pass through the same channel. As a result, a smaller pilot to data ratio is needed to estimate the channel as the subcarriers are closer together.

An investigation on how the pilot to data ratio affects the accuracy of the estimated channel and subsequently the BER is carried out on the OFDM system on the USRP. Due to the random amount of carrier frequency offset described in Chapter 5.2.1 it was decided that the MIMO cable is used to correct this frequency offset and that an fixed offset is introduced in the software at the receiver. As mentioned the maximum offset between the two USRPs is 4575 Hz when considering a carrier frequency of 915 MHz. A Phase Locked Loop (PLL) was used in the receiver to find out the real offset between the USRPs and the value varied between 600 Hz and 950 Hz. A fixed frequency offset of 775 Hz was selected, tests were carried out with pilot to data ratio ranging from 1/2 to 1/6. The LS approach was chosen due to its simplicity.

5.3.3 Time Synchronisation Offset

In order to highlight the effect of time synchronisation offset we focused our approach on symbol timing offset which assumes the time synchronisation is offset by an entire symbol. This assumption relies on the fact that the clock is correctly sampling but the timing of the frame is incorrectly synchronised with the rest of the system. This is an accurate representation of time synchronisation offset.

Our approach in this section was to demonstrate the difference between case 1 and case 2 outlined in Appendix A.2. We decided to neglect cases 3 and 4 as they are extreme cases of time synchronisation offset and the induced ICI would have been similar to the effects studied in the frequency carrier offset section.

5.3.4 PAPR

In Appendix A.1 it is mentioned that the high PAPR in multi carrier modulation and OFDM is a disadvantage. This effect is amplified in f-OFDM where the sidebands are reduced which in turn reduces the average power, causing a rise in the PAPR. One way to reduce the PAPR in OFDM is to introduce clipping to the time domain signal. This solution reduces the peaks of the message without drastically changing the average of the signal causing the PAPR to drop. However, clipping the message signal will result in the loss of data which in turn will affect the performance of the system.

The approach to analyse this aspect in OFDM and f-OFDM is divided in two steps. Firstly, we will show the PAPR values for OFDM and f-OFDM compared to the results of the same messages clipped at different percentages of the maximum value of the message. Secondly, we will highlight the performance of the system when the symbol is clipped. This approach will demonstrate the benefits of clipping in order to reduce the PAPR while showing the limitations of clipping with regard to performance.

In order to clip the message, we will treat the in-phase and quadrature phase parts of the message as two separate messages that we will clip independently.

Other techniques to reduce the PAPR include additional coding at the transmitter to reduce the likelihood of constructive interference, and peak cancellation schemes [9]. These approaches have not been investigated and are suitable for future work.

5.4 Mitigation

In this section we will discuss the approach that we developed to design mitigation techniques for carrier frequency offset, time synchronisation offset, and filtering.

5.4.1 Carrier Frequency Offset

Before designing a mitigation technique for a carrier frequency offset (CFO), we have to introduce the frequency offset in the simulation. We treat the CFO as a diagonal matrix defined by Λ_{CF}. This matrix a function of $\Delta F_s'$, which is equal to the frequency offset over the bandwidth.

$$\Lambda_{CF} = diag[1, e^{-j2\pi\Delta F_s'}, ..., e^{-j2\pi(N-1)\Delta F_s'}] \tag{5.1}$$

The diagonal matrix in Eq 5.1 is introduced at the receiver, when the signal would be downconverted. The resulting received data is given in the equation below.

$$Y = \Lambda_{CF} H X + n \tag{5.2}$$

Due to the two unknowns in Eq 5.2, Λ_{CF} and H, we cannot estimate the frequency and cancel out the effect that it has on the symbols. In order to retrieve the symbols, we made the assumption that when we take the FFT of the received symbols, the first part of the equation simplifies to a diagonal matrix. We then use a pilot based correction method like the one we used for channel estimation to estimate the combined effect of the channel and the frequency offset. However due to ICI, the first part of the equation will not be a diagonal matrix and hence, the pilot based estimation will not be able to recover the symbols perfectly. Although this method will enable the system to be more robust to CFO, the performance will deviate from the theoretical values of the BER as the interference due to CFO increases.

Investigating how well pilot based channel estimation can mitigate against a carrier frequency offset can be done on the USRP by having a fixed pilot to data ratio, varying the frequency offset, and observing the resulting BER. A pilot to data ratio of 1/2 was selected and the frequency offset was varied from 0 Hz to 2000 Hz.

5.4.2 Time Synchronisation Offset

In this section our approach was to use the results from the analysis and testing of time synchronisation offset to get a better understanding of the problem. With the results in mind, we then proceeded to design a mitigation technique that would rectify the error induced by the time synchronisation offset.

The two methods tested in this section were to use the length of the CP to mitigate against extreme time synchronisation offset and to use pilot based correction to correct the error induced in the system.

5.4.3 Filtering

Previous sections mention the important characteristics needed for f-OFDM which are a flat passband, high attenuation and fast transition. In this section, our approach was to analyse the frequency response of multiple filters and find the right fit for this particular application.

The different filters that we considered are the Butterworth filter, the Chebyshev type 1 filter, the Chebyshev type 2 filter, the Bessel filter, and the elliptic filter. Their performance was compared to the windowed sinc filter and truncated sinc filter.

The sinc function is a function whose frequency response is the rectangular function. The sinc filter is an ideal filter as it has an infinite inpulse response but it can be approximated using the truncated sinc filter which takes a finite subset of values from the sinc function. Windowing the truncated sinc filter renders a smoother frequency response [25].

Chapter 6

Results

This section outlines the results of the testing carried out on both MATLAB and the USRP.

6.1 OFDM

The results from the simulations of the OFDM system over a Rayleigh fading channel are shown below in Figure 6.1. The results demonstrate that the performance of OFDM systems increases as the SNR increases. The comparison between the simulated results and the theoretical results are very similar which led us to conclude that the design of our system was correct.

The graph in Figure 6.1 shows that the bit error rates of BPSK and QPSK are the same. This leads us to believe that QPSK is much more efficient in this scenario because the same frequency of errors is achieved in the two modulation schemes but the data rate of QPSK is twice that of BPSK.

On the other hand, 16QAM and 64QAM have a higher probability of error for a given SNR than BPSK and QPSK. The use of a larger number of constellation points makes these modulation schemes more sensitive to noise. As a result, the higher data rates achieved by higher modulation schemes is a trade-off for higher probability of error. This highlights the need to have a flexible transmitter capable of transmitting higher order modulation schemes in good channel conditions and lower modulation schemes in bad channel conditions.

To acquire these results, the receiver uses perfect detection. This means the receiver has full knowledge of the frequency gains for each subcarrier. This allowed us to simulate over a Rayleigh fading channel without requiring channel estimation.

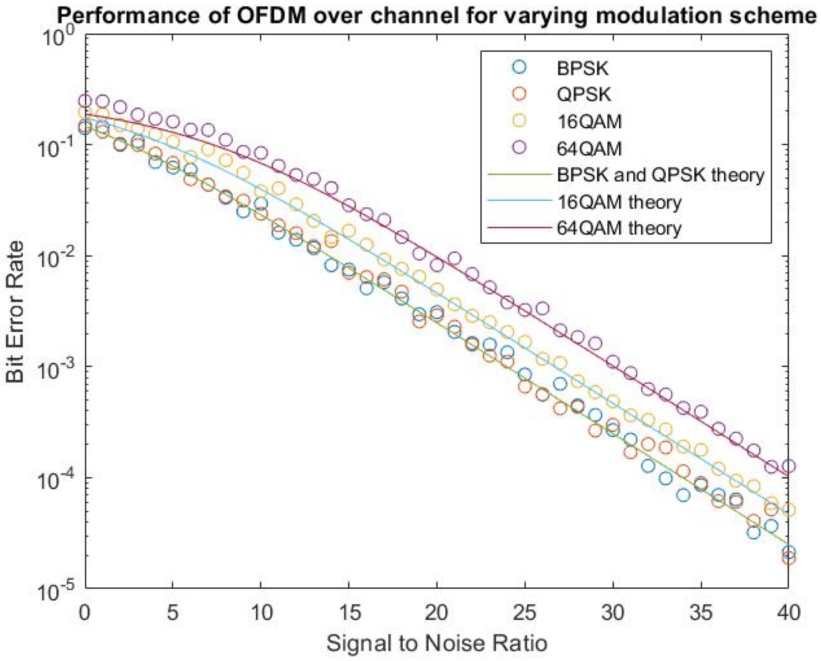


Figure 6.1: Graph of the bit error rate in terms of the signal to noise ratio for varying modulation schemes over a Rayleigh fading channel.

The results from the USRP approach in Chapter 5.2.2 were successful and outlined in Table 6.1. A pilot to data ratio of 1/2 was used.

Test number	Bits sent	Incorrect bits	BER
1	1024	1	0.0009765
2	1024	0	0
3	1024	0	0
4	1024	0	0
5	1024	0	0

Table 6.1: A table showing five test runs of the OFDM system and the resulting BER.

The explanation behind test run 1 having a non-zero BER is down to the frequency offset between the transmitter and receiver not being constant. A higher frequency offset can result in errors being introduced as the channel estimator is pushed to its limits. This is analysed in Chapter 6.8.

The correctly working channel estimation can be seen in the following figures. Figure 6.2 shows the constellation diagram of the transmitted signal after the 16QAM symbols undergo the IFFT function. Compare this to the received signal in Figure 6.3 and the effects of the carrier frequency offset can be seen as the points have been rotated. Figure 6.4 shows the received signal after it has been corrected using channel estimation and it bares a strong resemblance to Figure 6.2 minus the pilot symbol constellation points. This signal is then sent through an FFT function to recover the 16QAM symbols shown in Figure 6.5.

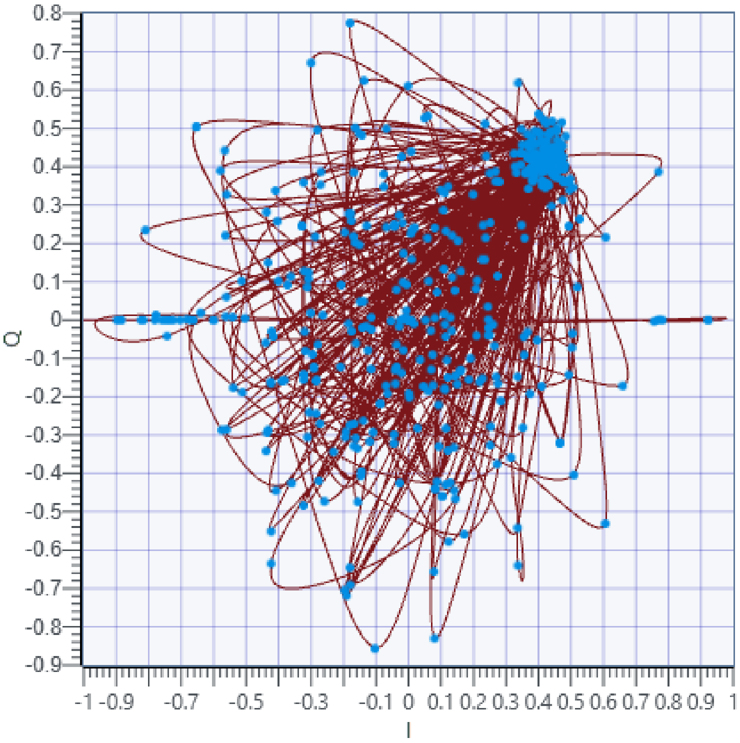


Figure 6.2: Constellation graph of the transmitted 16QAM OFDM signal. The large collection of points in the top right are the pilot symbols.

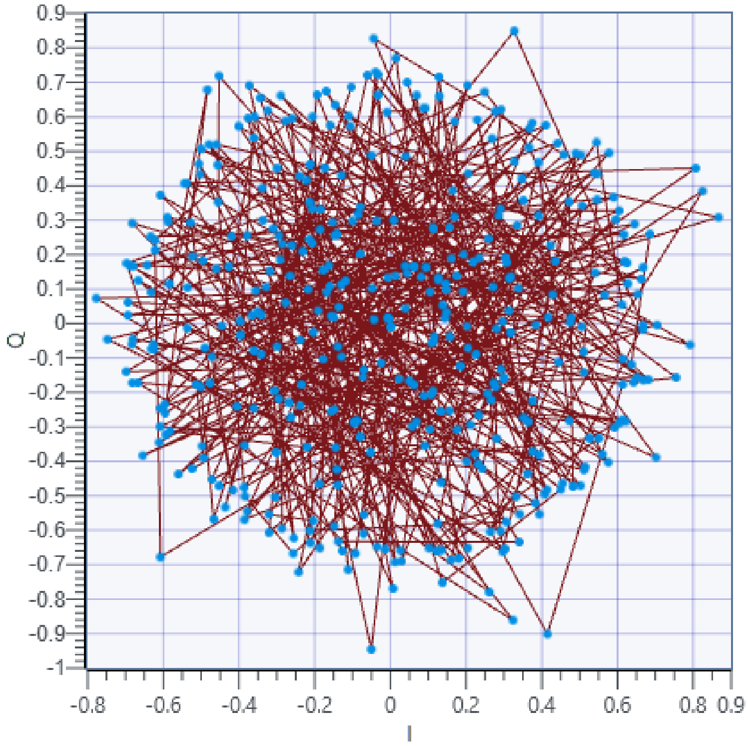


Figure 6.3: Constellation graph of the received 16QAM OFDM signal.

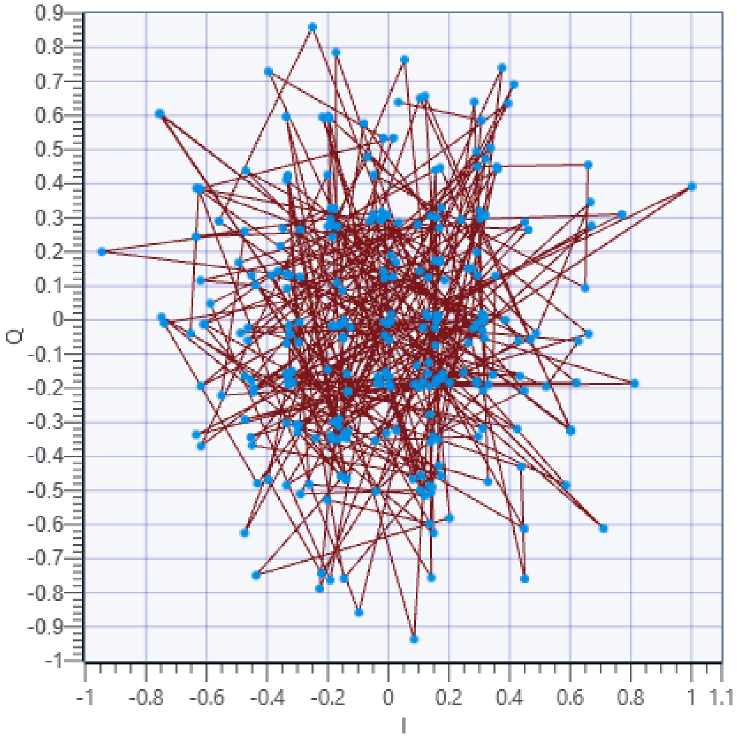


FIGURE 6.4: Constellation graph of the received 16QAM OFDM signal after correction using pilot based channel estimation. The pilot symbols have been removed.

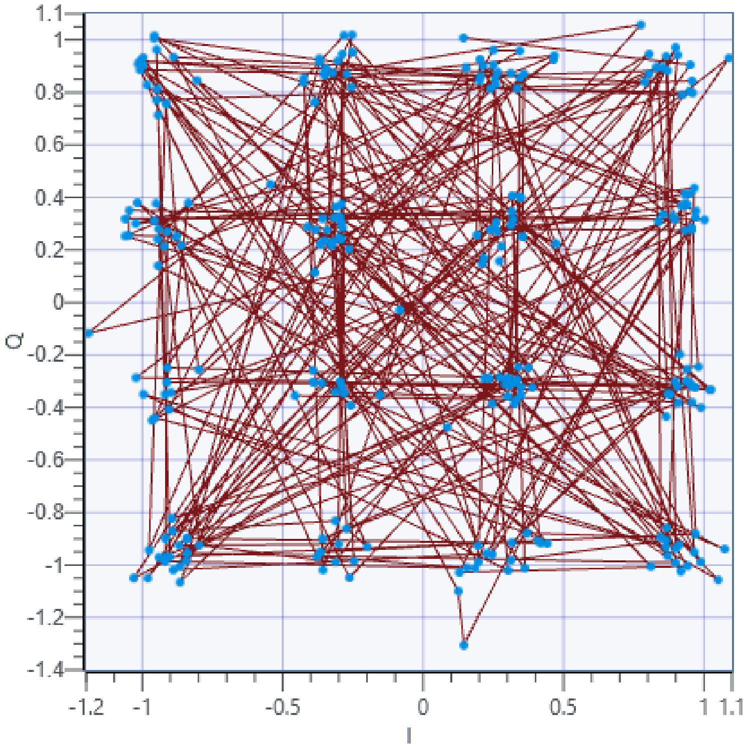


FIGURE 6.5: Constellation graph of the received 16QAM OFDM signal after correction and FFT.

6.2 4G

The results of the 4G approach in Chapter 5.2.3 produced errors in LabVIEW. The first error was due to a transmit buffer underflow in which the USRP requested data at a faster rate at which it was produced. There are three solutions to this:

- Reduce the I/Q rate - this reduces the rate of upsampled samples taken by the USRP.
- Increase the write rate - this is equivalent to increasing the sample rate and is different to the I/Q rate.
- Increase the number of samples per write - this is equivalent to writing more data to the USRP in each iteration so that the transmit buffer is occupied for a longer amount of time.

The first solution was not possible due to the constraints imposed on the upsampling factor which include being a non-zero value and even. The upsampling factor is related to the I/Q rate given by Eq 6.1. Given that the upsampling factor was 2, this could not be decreased therefore the I/Q rate could not be decreased.

$$upsampling\, factor = \frac{IQ\, rate}{sampling\, rate} \tag{6.1}$$

The second solution was not possible as the sample rate was fixed at 7.68 MHz as per the 4G specification. The final solution was attempted as the amount of data written can be changed by changing the number of OFDM symbols sent to the USRP on each write. 4, 40, 400, and 4000 symbols were sent with the expectation that the larger amount of symbols would solve the error, however this was not the case. Sending a large amount of symbols on each write caused another error to do with LabVIEW running out of memory.

These limitations prevented the creation of a 4G system that was true to the standard. As a compromise, the sampling rate and I/Q rate were decreased which in turn reduces the bandwidth from the specified value of 5 MHz. The number of OFDM symbols sent per write was also reduced from 40 to 4 to reduce memory usage. A summary of the changes is outlined in Table 6.2.

This configuration was successful, with a recorded BER of 0. Whilst the system doesn't use the required bandwidth, it has the same carrier frequency and subcarrier count as that seen in 4G LTE band 20.

Parameter	Old value	New value
Sampling frequency (symbol rate) (kHz)	7,680	10
I/Q rate (kHz)	15,360	200
Upsampling factor	2	20
Bits sent	48,000	4,800
16QAM symbols	12,000	1,200
OFDM symbols	40	4

Table 6.2: A table showing the selected parameters for the 4G system.

6.3 5G

In this section we cover the results achieved while building the 5G f-OFDM system.

The original MATLAB design for 5G f-OFDM is a configurable k sub-band system as outlined in Chapter [4.3]. The results (Figure 6.6) show that the sub-bands do not need a lot of guard bands in order to avoid interference between bands as the filter for each band reduces the side lobes significantly. Each sub-band is independent from its neighbour and can be designed to fit the scenario specification.

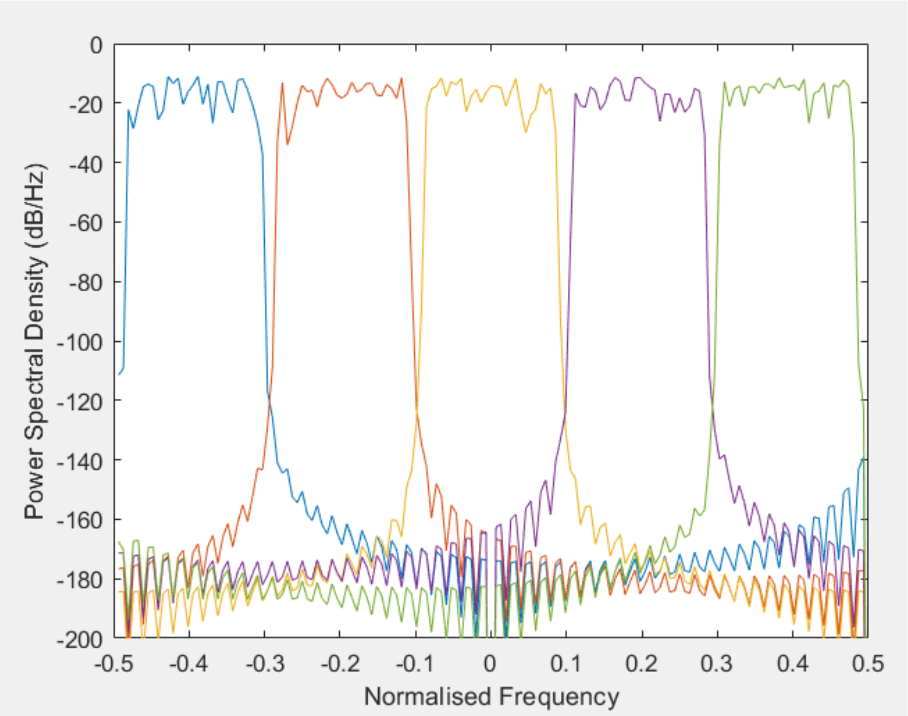


Figure 6.6: Frequency domain plot of the sub-bands of the 5G f-OFDM system.

A second system was built to simplify the overall design. This system also follows the traditional 5G f-OFDM structure but it contains a fixed amount of sub-bands set to 1. The comparison of 4G OFDM and 5G OFDM (Figure 6.7) shows how the filter attenuates the side lobes in f-OFDM without compromising the signal in the pass band. This demonstrates the higher spectral efficiency achieved in f-OFDM.

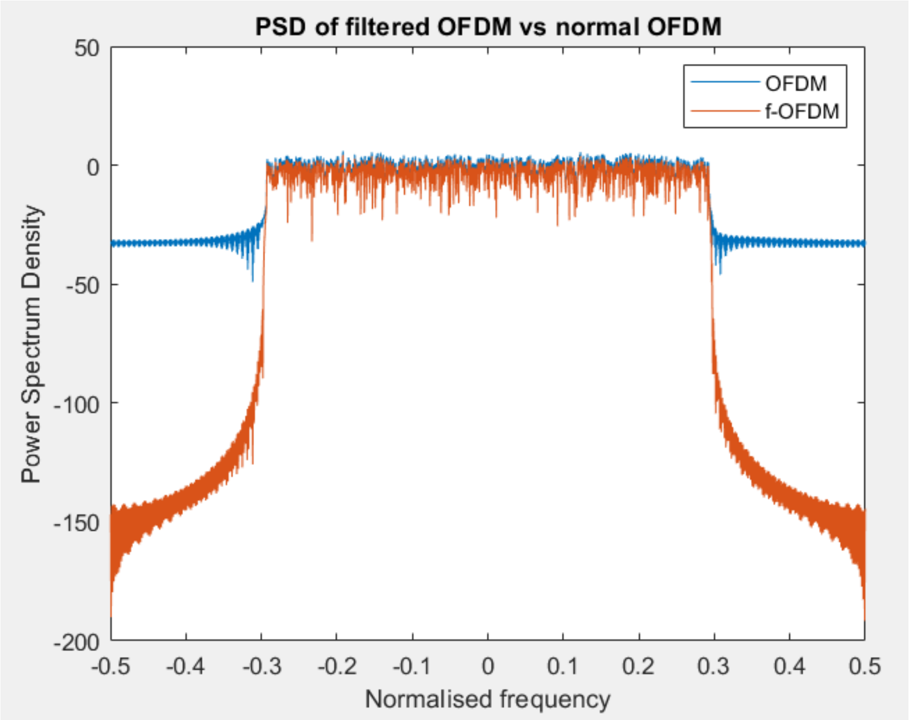


FIGURE 6.7: Frequency domain plot of the one sub-band 5G f-OFDM system compared to the 4G OFDM.

The results from testing the 5G OFDM system on the USRP were mixed. The filter successfully attenuated frequencies outside of the passband with a difference in amplitude of 140 dB. However, the cut-off frequencies did not match the bandwidth of the transmitted signal, the passband can be made smaller to allow for more frequency attenuation without affecting the message. This is done by adding an extra coefficient in Line 7 of Listing 5.1 which affects the frequency response of the sinc filter. A comparison of these different frequency spectra is shown in Figure 6.8. These tests worked with a BER of 0. A front panel view of the demonstrator can be seen in Appendix E. This system has the same limited bandwidth issues seen in the 4G system in Chapter 6.2, finding a solution to this problem is a suggestion for further work.

6.4 Cyclic Prefixing

In this section, we demonstrate how the length of the cyclic prefix affects the performance of the system. The results demonstrate the performance when E ranges from 0 to 5 (Figure 6.9). The results show that when the channel length starts exceeding the length of the cyclic prefix, the resulting performance is much lower as the BER reaches a high error floor. The BER error floor increases as the difference between the channel length and the cyclic prefix length increases.

The results show the importance of having a sufficiently long cyclic prefix to ensure the performance of the system remains ideal.

6.5 Channel Estimation

The relationship between how well the channel is estimated and the resulting BER is clear to see when testing this on the USRP. Taking the approach from Chapter 5.3.2, the resulting BER for a given pilot to data ratio is displayed in Table 6.3.

Pilot to data ratio	Bits sent	Average BER
1/2	1024	0.0009766
1/3	1024	0.0089844
1/4	1024	0.0576172
1/5	1280	1
1/6	1024	1

Table 6.3: A table showing how the average BER varies with the pilot to data ratio (PDR). A different number of bits were sent where PDR = 1/5 so that there were enough symbols for the OFDM transmitter to work correctly.

From these results it can be seen that the smaller the pilot to data ratio, the larger the BER. The BER calculator fails for a PDR of 1/5 or smaller which can be explained by analysing the output of the channel estimation. The applied frequency offset was 775 Hz so we can expect the channel estimation output to be a sine wave of this frequency. The estimated channel with a PDR of 1/2 is shown in Figure 6.10. The channel estimate is very accurate which means most of the channel effects are removed, resulting in the low BER. Better channel estimation with a smaller PDR is achievable through methods more complex than the LS technique used on the USRP, these are discussed in Chapter 5.3.2 and are the suggested methods for future work.

Compare this to the estimated channel with a PDR of 1/5 shown in Figure 6.11. The estimated channel is less accurate and does not resemble a sine wave. This results in some distortion still present in the received signal which leads to errors when decoding.

The reason why a higher PDR leads to a better estimated channel is due to there being more data points available for the interpolation to produce a better estimate of the channel. The pilot symbols can be seen as being samples of the channel, when the frequency of these pilot symbols is greater than twice the maximum frequency of the channel, the channel can be estimated with great accuracy. When the PDR decreases, the frequency of pilot symbols decreases and the remaining data points are not enough for the interpolation to succeed.

In MATLAB, we had more knowledge of the parameters at play and hence an in depth analysis was performed. The simulations that we ran allowed us to develop our understanding of transmitting data over a Rayleigh fading channel.

The PDR has the most impact on the performance of the transmission. The results for the performance of a transmission over a channel containing 5 taps is shown in 6.12. For this type of channel, a PDR of 1/2 shows suitable performance as it follows the curve for the theoretical 16QAM over a Rayleigh fading channel. However when the PDR is reduced the performance is hindered. In the case of a PDR of 1/4 the BER reaches an error floor at an SNR of 25dB. In the case where the PDR is 1/8, the resulting BER indicates that the system cannot correctly estimate the channel. This highlights the limits channel estimation as it can require a large amount of subcarriers to transmit pilot symbols which causes a loss of efficiency in the system.

The following simulations are performed to understand the limits of the channel estimation when the PDR is reduced. In order to better understand the decrease in performance in the channel estimation we compared the actual channel parameters with the estimated channel parameters. In Figure 6.13 the channel is perfectly detected as the result of the interpolated values estimated from the channel match with the values of the channel. However when the PDR is reduced the interpolation worsens as seen in Figure 6.14, when the PDR is 1/4. Although the estimated channel is very close to the real channel it does not match completely and therefore the performance is hindered. This observation shows how a small error in the estimation of the channel causes an error floor in the BER. In Figure 6.15, there are not enough values to build an accurate interpolation of the channel resulting in poor performance.

Calculating the error in the estimated channel and the interpolated channel shows how noise affects channel estimation. In Figure 6.16, as the SNR increases the error in the estimation of the channel decreases and converges to zero. The interpolated error when the PDR is 1/2 converges to zero as the SNR increases whereas the interpolated error when the PDR is 1/4 (Figure 6.17) does not converge to zero which is indicative of the error floor reached by the BER.

In Figure 6.12, even when the PDR is 1/2, the BER is a fraction higher than the theoretical BER. This is due to the error in the channel estimation due to the noise. A mitigation technique for this is to send pilots with a higher energy than other symbols so that the SNR for the pilots is reduced and hence the channel estimation is less error prone. This effect is seen in Figure 6.18 where the pilots are sent with an energy ten times higher than the data symbols. Although this is not a realistic number by which the pilots would be amplified in real world applications, it is the best way to show the impact of this technique. The resulting error in the channel estimation is ten times smaller.

From the results obtained in this section, it can be deduced that OFDM systems are very sensitive to errors in channel estimation. Further analysis demonstrates that if the interpolated channel gain's errors do not converge to zero, the equivalent BER will reach an error floor resulting in inferior performance.

6.6 Time Synchronisation Offset

In this section we demonstrate the results from our analysis of time synchronisation offset and mention the mitigation techniques to avoid this in our system.

In the first case, the OFDM symbol is sampled correctly. The resulting constellation diagram across a perfect channel is an ideal 16QAM constellation diagram Figure 6.19. In this case there is no need for any mitigation as the transmission is ideal.

In the second case, the OFDM symbol is sampled too early. The resulting constellation diagram is distorted as seen in Figure 6.20. The equation 6.2 [12] for the output of the FFT block at the receiver in a perfect channel shows that a timing offset such as the one in the second case induces a phase offset at the receiver. This effect is demonstrated in the results shown in Figure 6.20 where each constellation point is rotated by a constant phase offset in relation with the previous constellation point resulting in three rings corresponding to the three different magnitudes used in 16QAM.

$$Z(k) = X(k)e^{j2\pi k\delta/N} \tag{6.2}$$

In Eq 6.2, $Z(k)$ denotes the k^{th} output of the FFT block at the receiver, $X(k)$ is the symbol of the k^{th} subcarrier and δ is the symbol offset. The symbol offset in the second case will be negative as we are sampling the OFDM symbol early.

In this case, a mitigation technique needs to be implemented in order to recover the data. In this project we use a pilot based technique to recover the data. In the second case, the pilot based correction is able to account for the phase shift and the resulting performance of the system is ideal.

The mitigation technique to avoid the ISI in time synchronisation offset is to have a long CP in order to reduce the probability of sampling a part of the CP that is affected by ISI. On the USRP we use a frame synchronisation block described in Chapter 5.2.1 to ensure the correct frame is sampled at the receiver as a result there is no time synchronisation offset.

6.7 PAPR

This section will showcase the results obtained when executing the approach outlined in Chapter 5.3.4. The clipped message in Figure 6.21 demonstrates the effect of clipping on an OFDM symbol when the message is clipped at 60% of its maximum value. The maximum value is calculated independently for the real and imaginary parts of the signal, it corresponds to the maximum magnitude of the signal.

The plot in Figure 6.22 demonstrates the high difference between the PAPR for an f-OFDM system and an OFDM system. This is because there is a higher number of subcarriers in the f-OFDM system and the PAPR increases linearly in terms of the number of subcarriers in the system [9]. The results show that in both systems, clipping the message reduces the PAPR. The decrease in the PAPR due to clipping increases the more the message is clipped.

The results from this section indicate that when the message is clipped at 50% of its maximum value (Figure 6.23) the performance is poor. This performance is greatly improved when the message is clipped at 60% of its maximum value (Figure 6.24). When the message is clipped above 70% (Figure 6.25) of its maximum value, the performance is close to ideal. Clipping the signal causes the BER to reach an error floor. When the message is highly clipped, the error floor is at a higher BER and arises at a lower SNR than when the message is less clipped.

The analysis of the results led to the conclusion that clipping a message is a simple method of improving the PAPR for a signal which maintains good performance if values above 70% of the maximum value of the original message are clipped.

6.8 Carrier Frequency Offset

The approach to test how an increasing carrier frequency offset affects the BER described in Chapter 5.4.1 was carried out with the results shown in Figure 6.26. The results show that the system has a BER of 0 for frequency offsets up to 600 Hz. The system is resistant to a carrier frequency offset of up to 1200 Hz before the BER starts to dramatically rise. The increase in BER is due to the frequency offset becoming larger in relation to the number of samples used to estimate the channel as explained in Chapter 6.5.

The impact the carrier frequency offset has on the BER can also be seen in the constellation diagrams of Figure 6.27. At an offset of 1200 Hz, the constellation points start to drift as the channel estimation starts to fail. At 1500 Hz many of the symbols have not been corrected.

Additional analysis on MATLAB can be found in Appendix F.

6.9 Filtering

The approach outlined in Chapter 5.4.3 describes the method used to get the result portrayed in this section.

The frequency response plot for the low pass filter (Figure 6.28) shows the characteristics of the filters. For our system, the characteristics that are needed include a flat passband, a sharp transition, and a high attenuation. Each filter's characteristics are qualified in Table 6.4. None of the filters in the table fit to the desired characteristics.

Characteristics	Passband	Transition	Attenuation
Desired	Flat	Sharp	High
Butterworth	Flat	Slow	High
Chebyshev type 1	Ripple	Sharp	High
Chebyshev type 2	Flat	Sharp	Low
Elliptic	Ripple	Sharp	Low

TABLE 6.4: Table classifying the characteristics of the filters in Figure 6.28.

As the previous filters do not fit to the desired specifications, we used a sinc based filter. The two sinc based filters that are tested in this section are the windowed truncated sinc filter and the truncated sinc filter. The finite impulse response for both these filters are shown in Figure 6.29. The windowed filter is smaller as it has been normalised. The windowed sinc filter's ripple is faded on the edges whereas the ripple in the truncated sinc filter does not fade.

The resulting frequency response for the sinc based filters is shown in Figure 6.31. The results show that both the truncated sinc filters do not have a high enough attenuation for our application. On the other hand, the windowed sinc filter's characteristics match the ones needed for this application. The Hamming window changes the finite impulse response of the filter which in turn translates in better performance in the frequency response. As the filter length increases the performance of the truncated filter converges towards that of the windowed sinc filter.

For our 5G f-OFDM system, the windowed sinc filter is the optimal fit for this application.

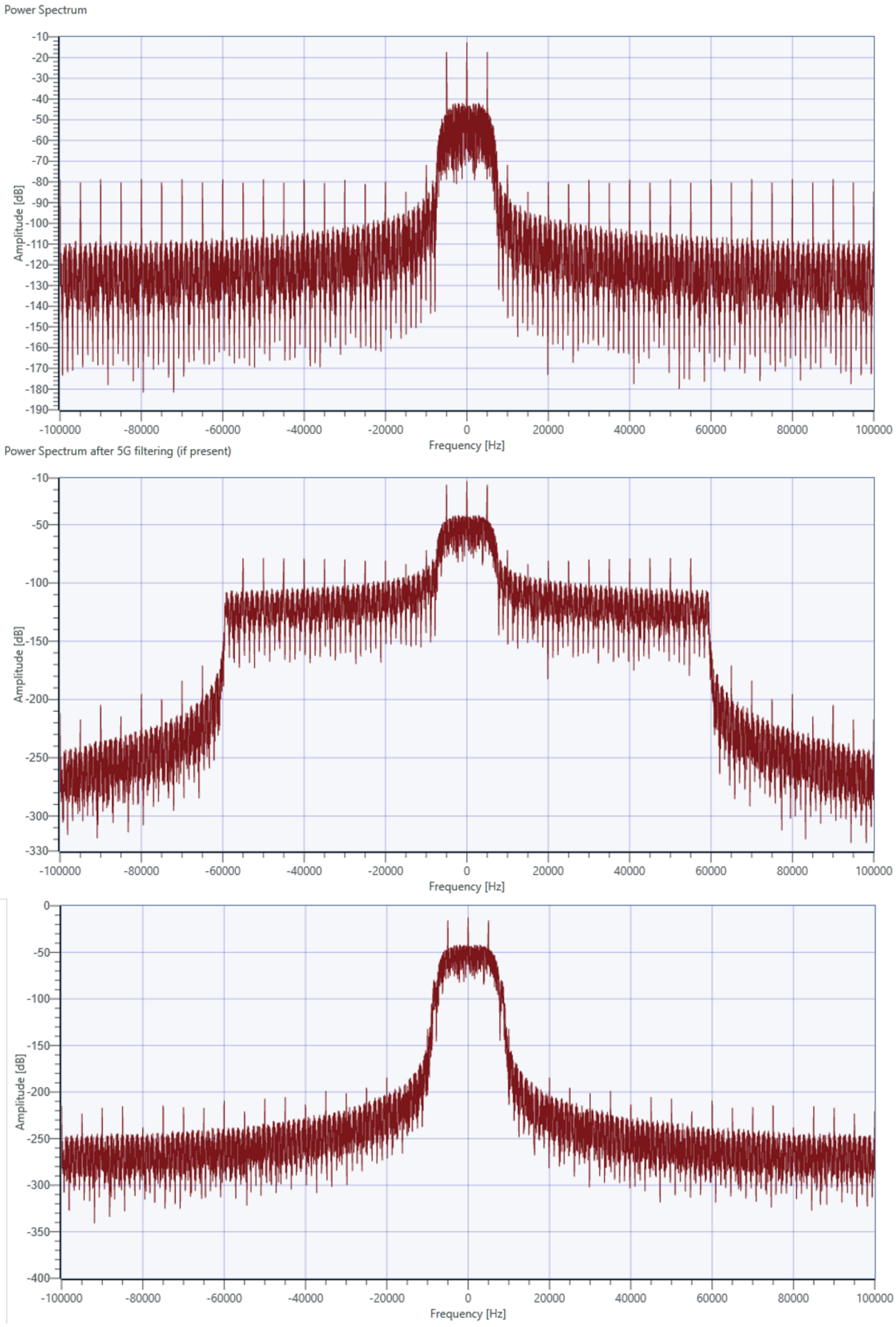


FIGURE 6.8: Frequency domain plot of the transmitted signal before (top) and after (middle) the filter. The filter frequency response was adjusted to match the message to provide a better output (bottom).

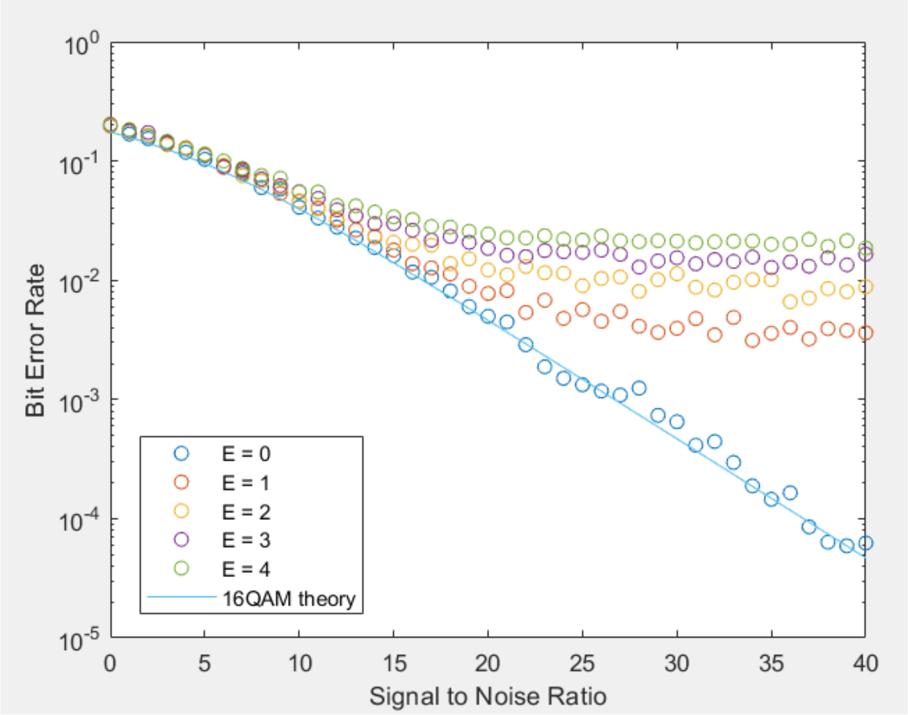


Figure 6.9: Performance of system when cyclic prefix is lower than channel length.

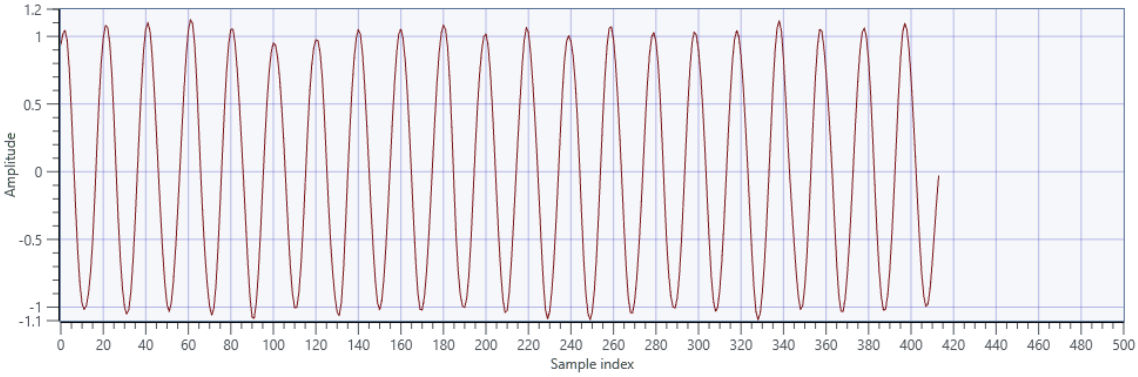


Figure 6.10: Estimated channel with a pilot to data ratio of 1/2.

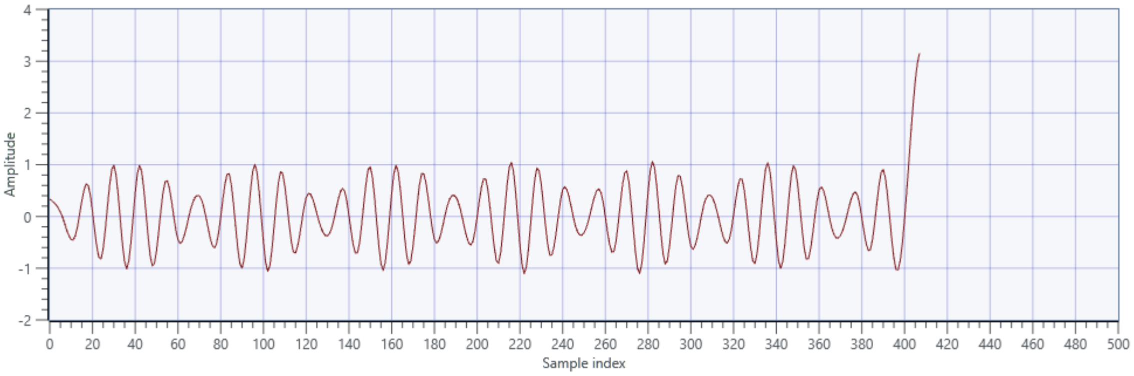


Figure 6.11: Estimated channel with a pilot to data ratio of 1/5.

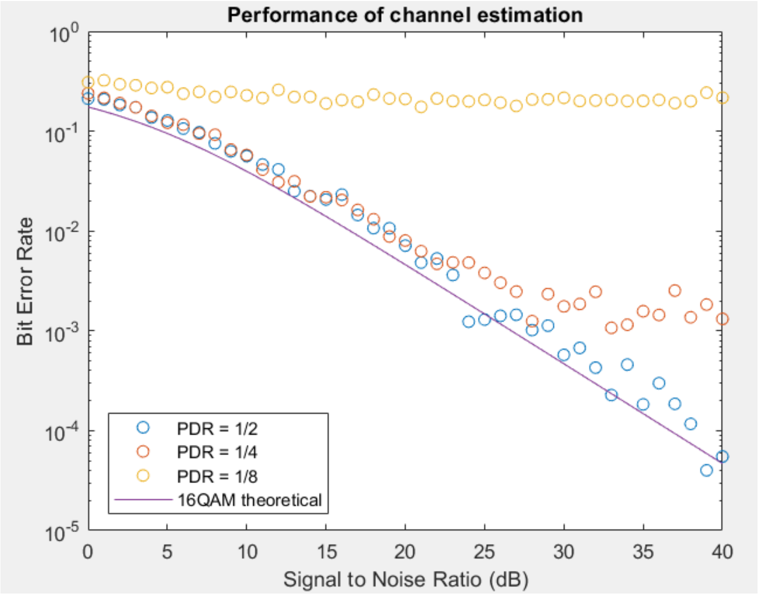


FIGURE 6.12: BER in terms of SNR for channel estimation with varying PDR.

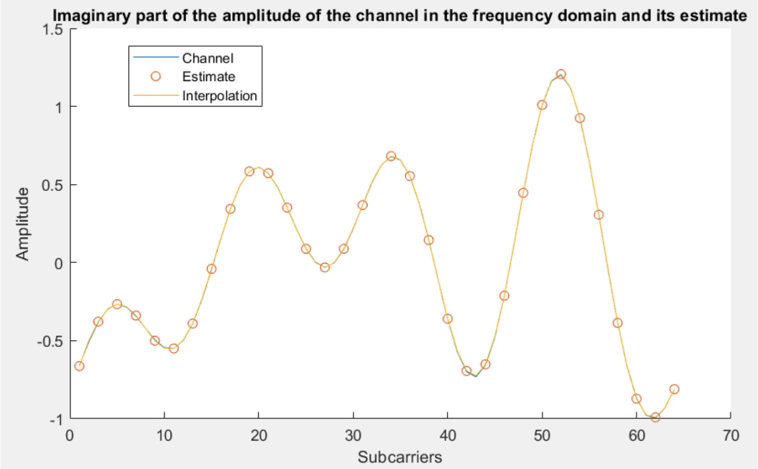


FIGURE 6.13: Frequency domain fading gain for each subcarrier with a PDR of 1/2.

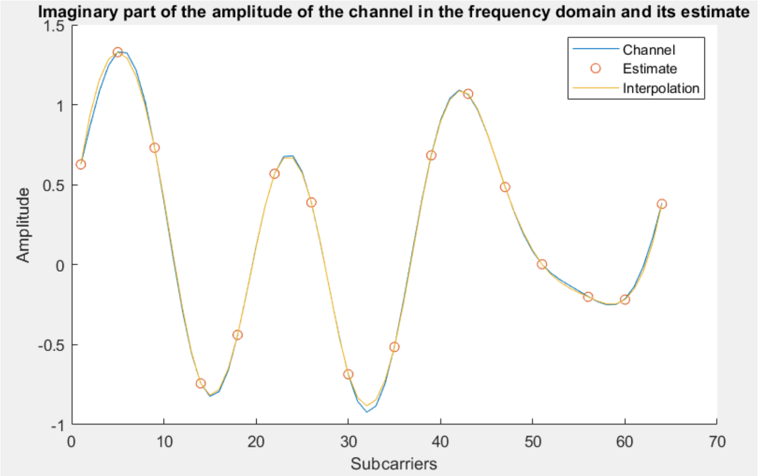


FIGURE 6.14: Frequency domain fading gain for each subcarrier with a PDR of 1/4.

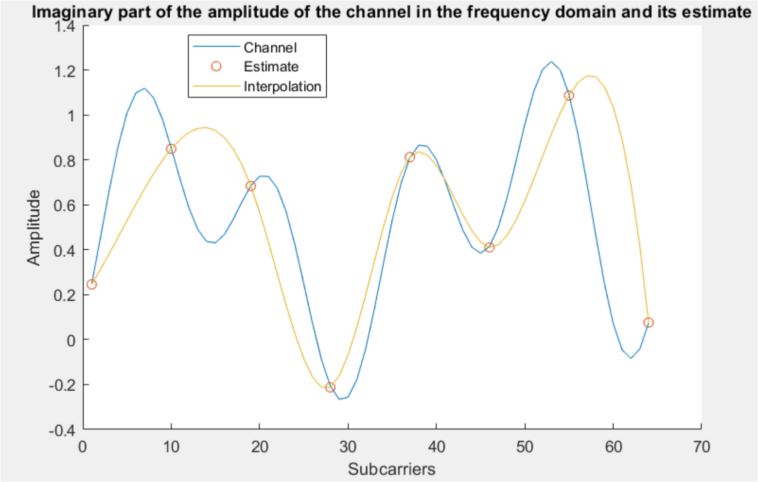


FIGURE 6.15: Frequency domain fading gain for each subcarrier with a PDR of 1/8.

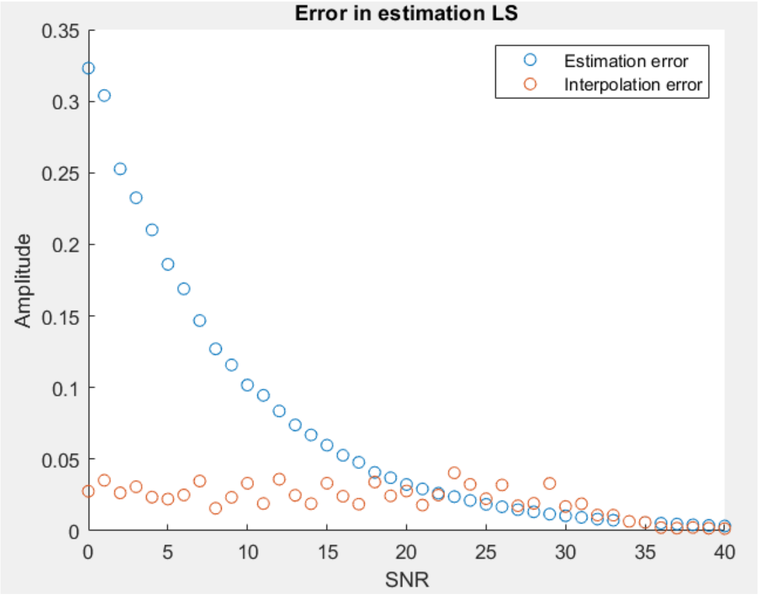


FIGURE 6.16: Error in channel estimation with a PDR of 1/2.

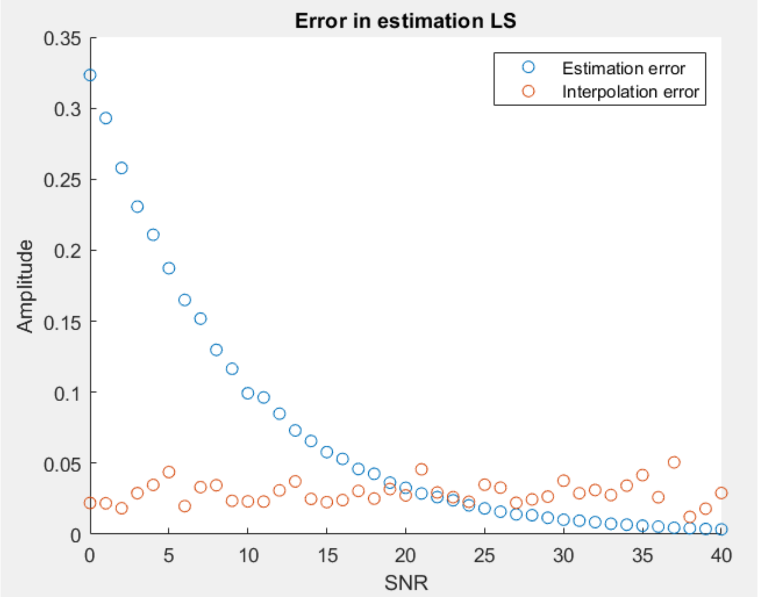


FIGURE 6.17: Error in channel estimation with a PDR of 1/4.

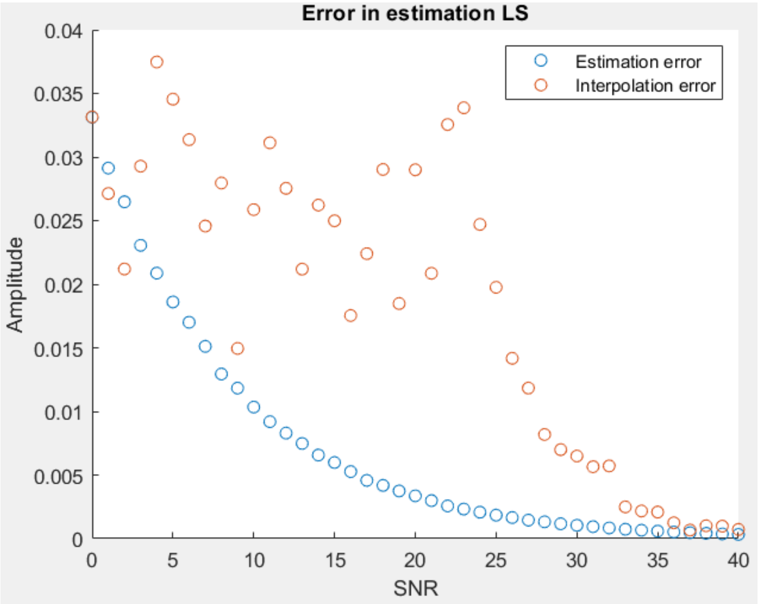


FIGURE 6.18: Error in channel estimation with a PDR of 1/2 and a pilot energy ten times higher than data energy.

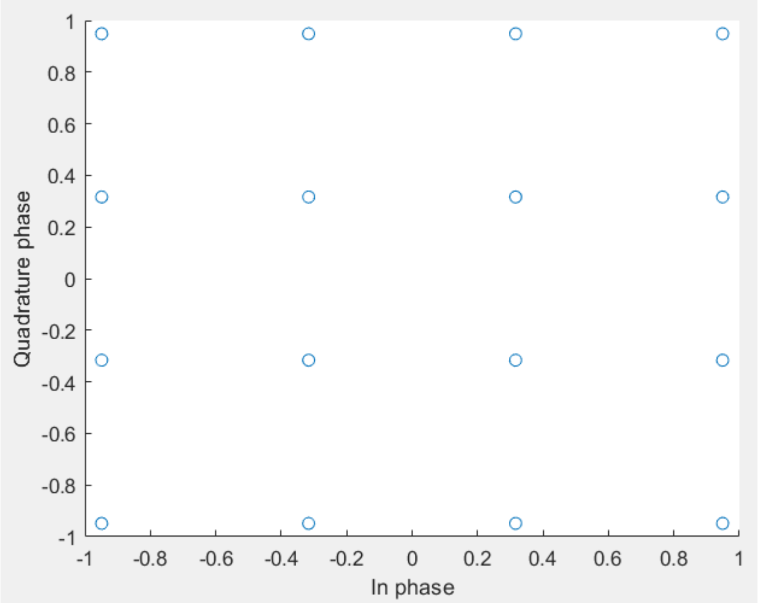


Figure 6.19: Constellation diagram of time synchronisation offset in case 1.

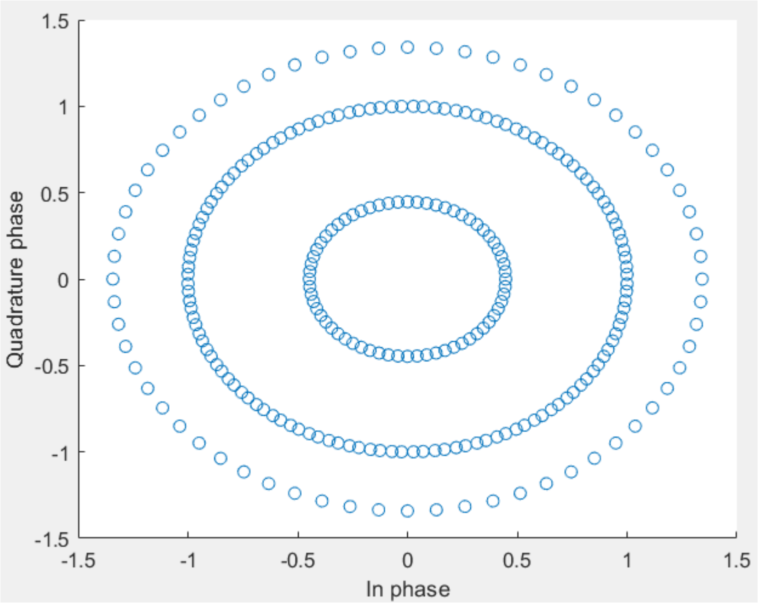


Figure 6.20: Constellation diagram of time synchronisation offset in case 2, $\delta = -3$.

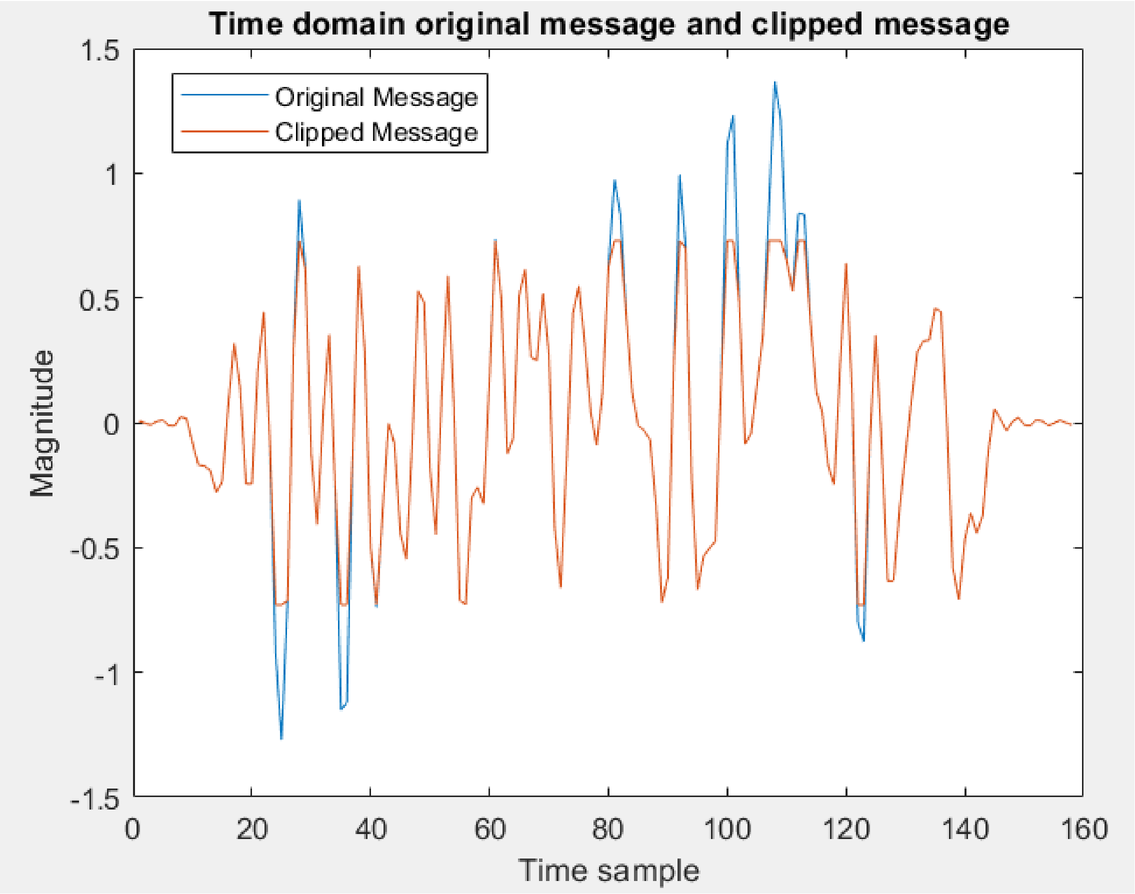


FIGURE 6.21: Plot of clipped and original messages in time domain.

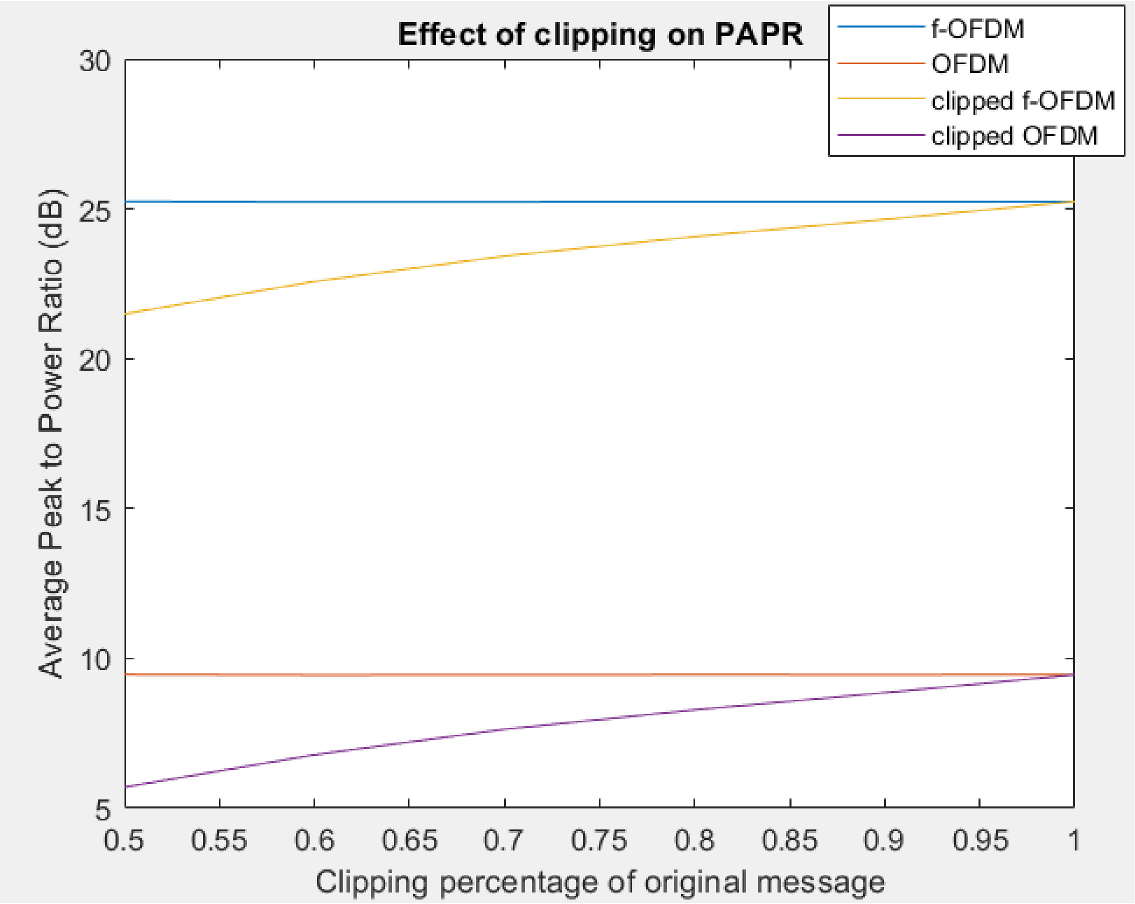


FIGURE 6.22: Graph of PAPR in terms of the the percentage the original message is clipped by.

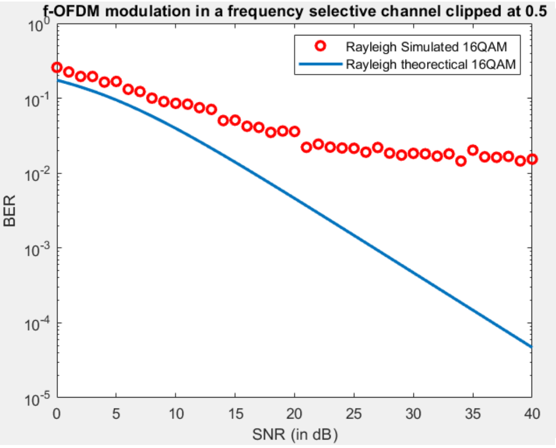


FIGURE 6.23: Performance of f-OFDM system affected by clipping at 50% of maximum value of the message.

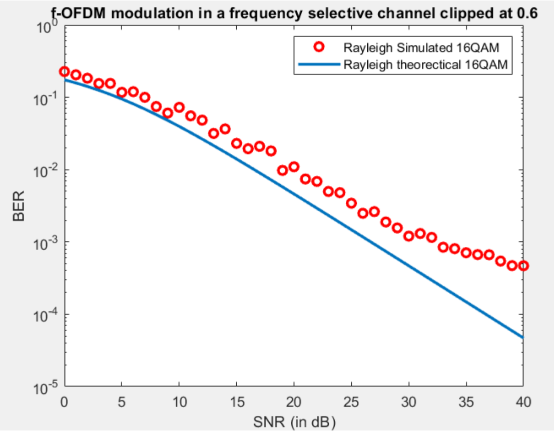


FIGURE 6.24: Performance of f-OFDM system affected by clipping at 60% of maximum value of the message.

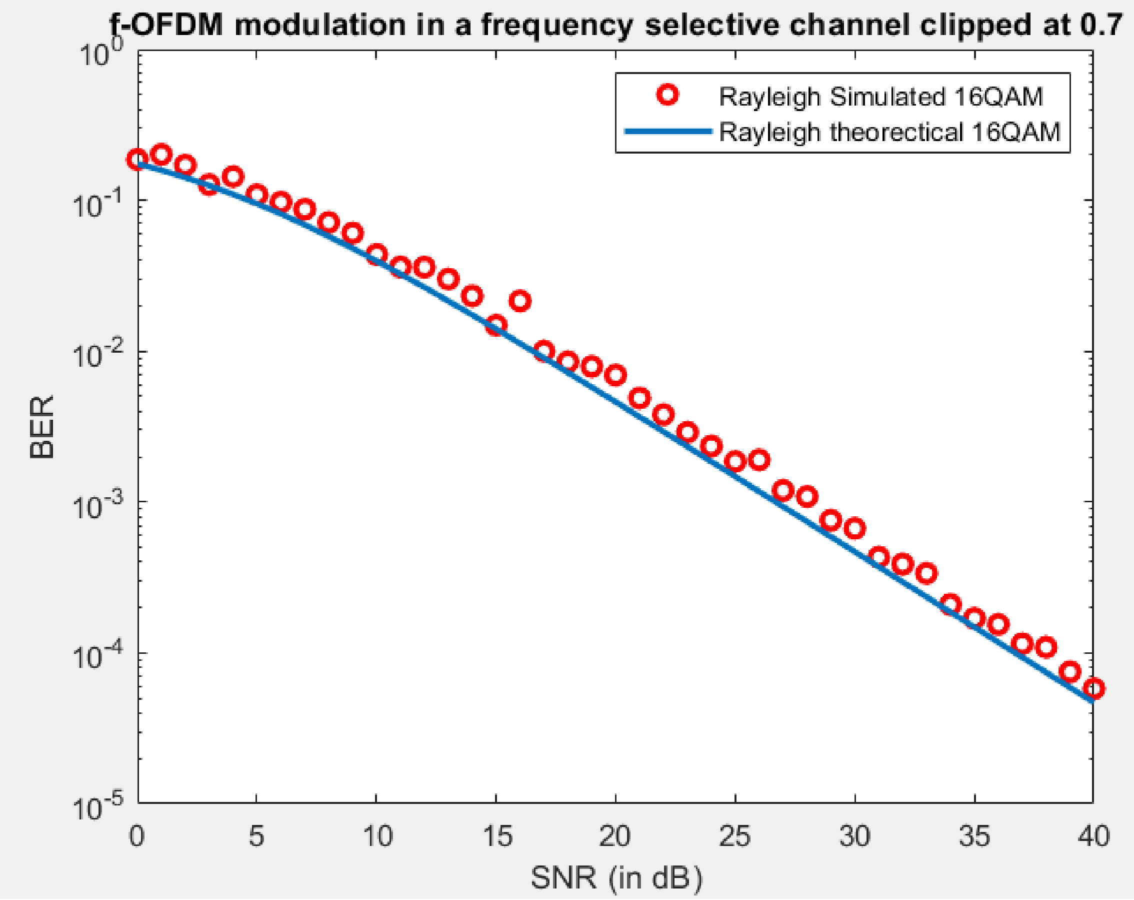


FIGURE 6.25: Bit Error Rate in terms of Signal to Noise Ratio for f-OFDM symbol clipped at 70% of its maximum value.

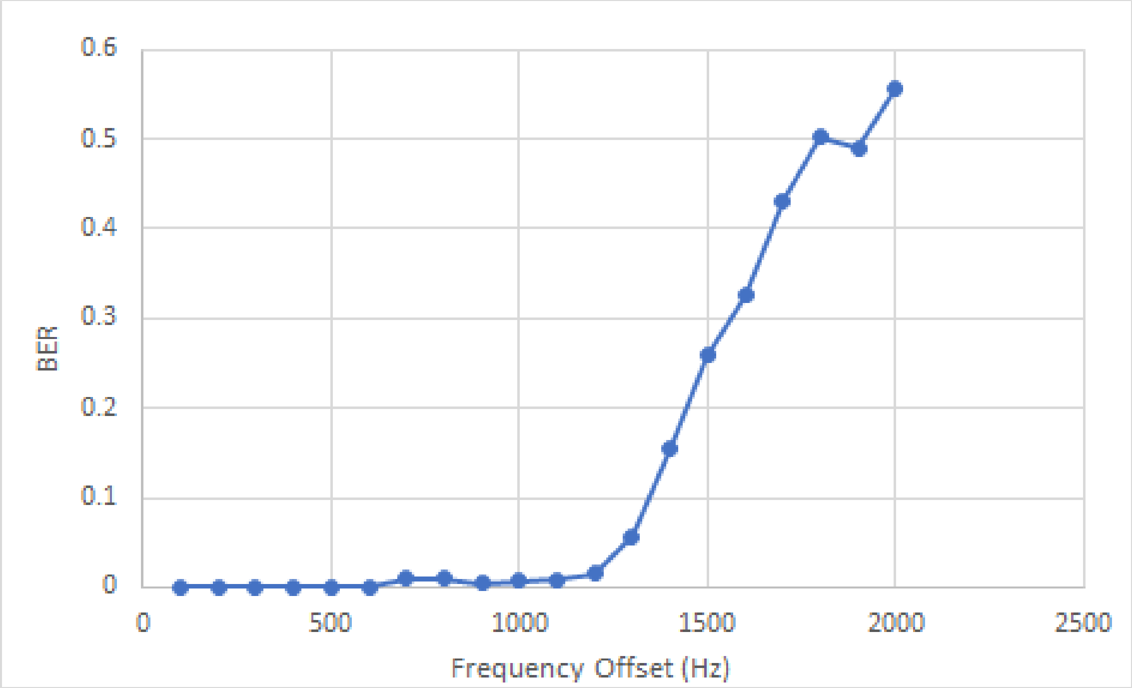


FIGURE 6.26: Graph of BER against carrier frequency offset for a fixed pilot to data ratio of 1/2.

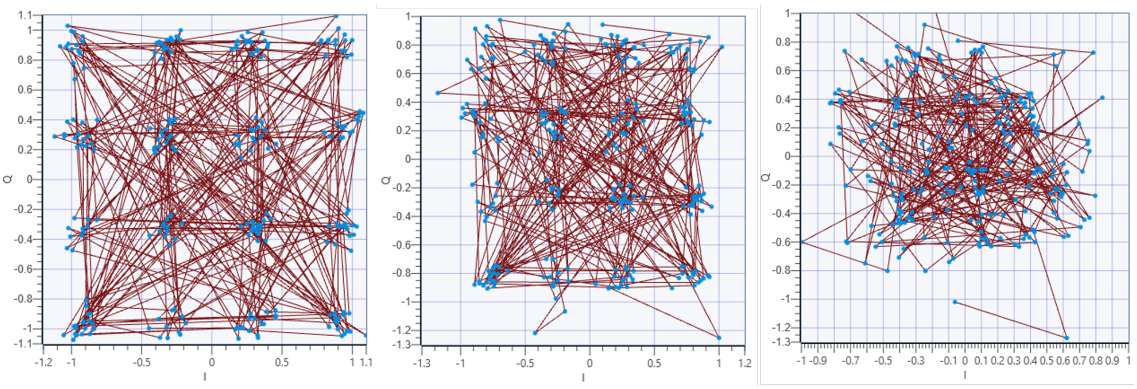


FIGURE 6.27: Constellation diagrams of a received 16QAM OFDM decoded signal with a carrier frequency offset of 100 Hz (left), 1200 Hz (center) and 1500 Hz (right).

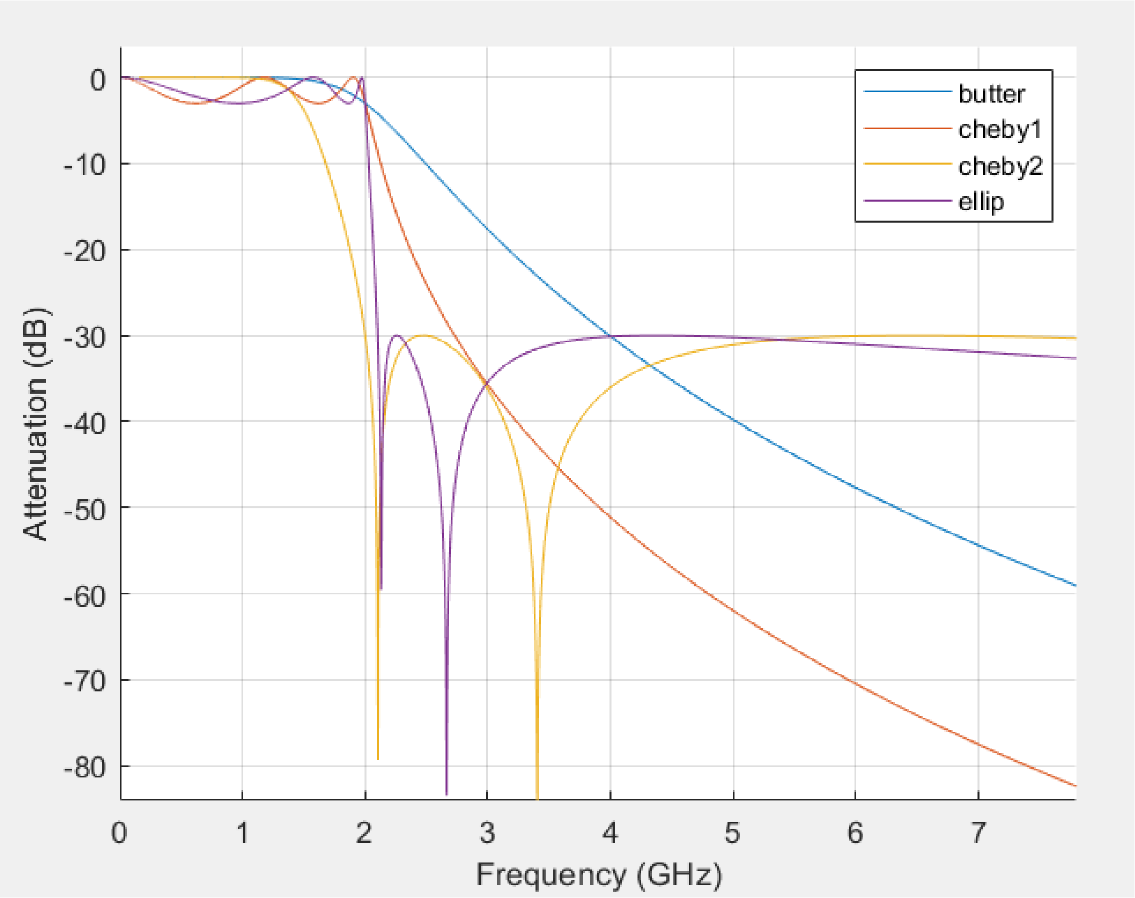


FIGURE 6.28: Frequency response of various low pass filters with a cut-off frequency of 2Ghz.

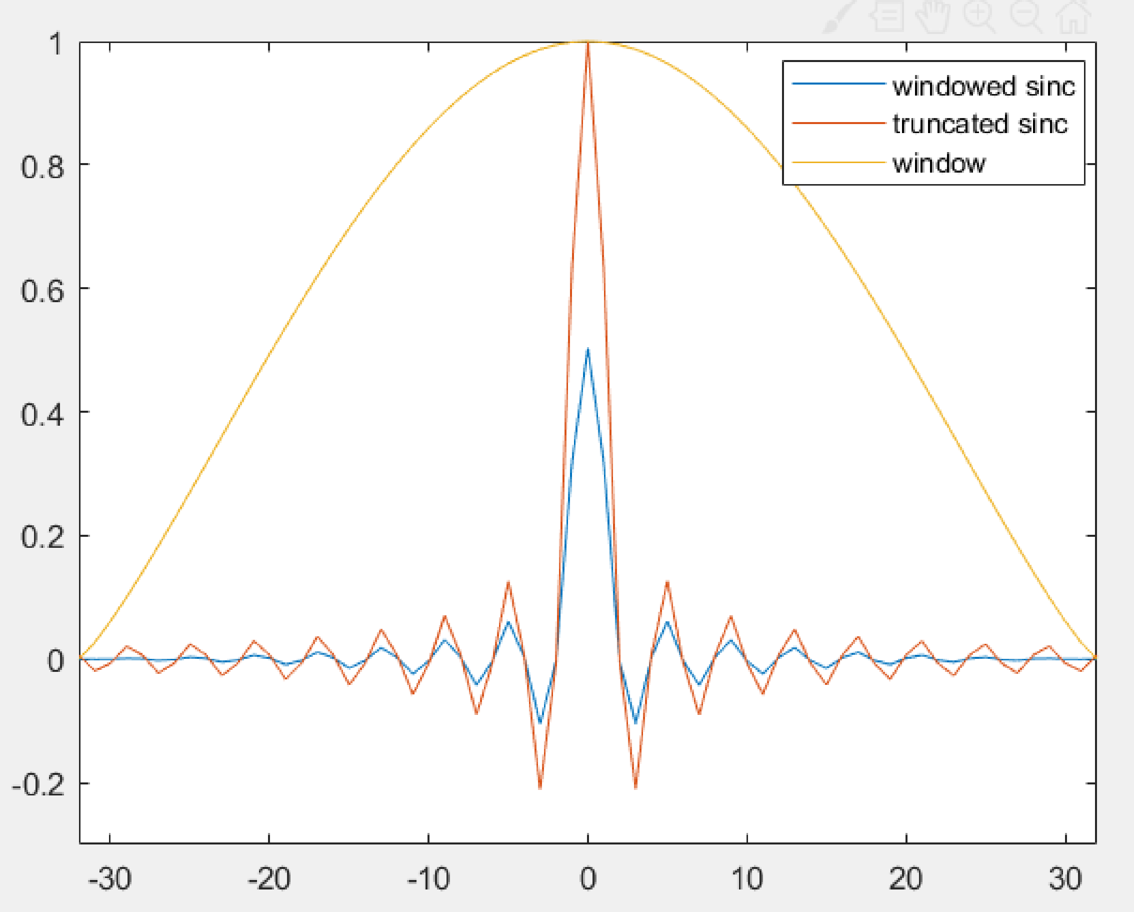


FIGURE 6.29: Plot of the finite impulse response of the Hamming window, the truncated sinc filter and the windowed sinc filter, sourced from [26].

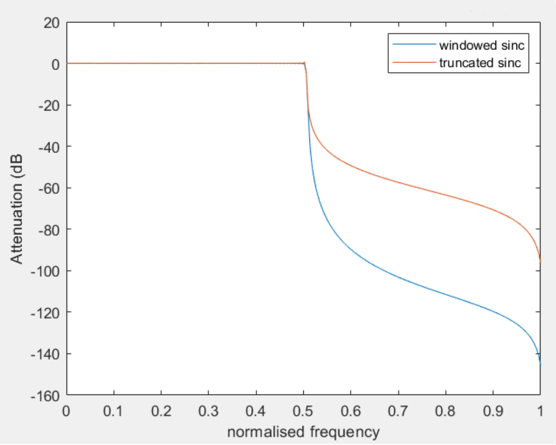


FIGURE 6.30: Frequency response for windowed sinc and truncated sinc filters (dB).

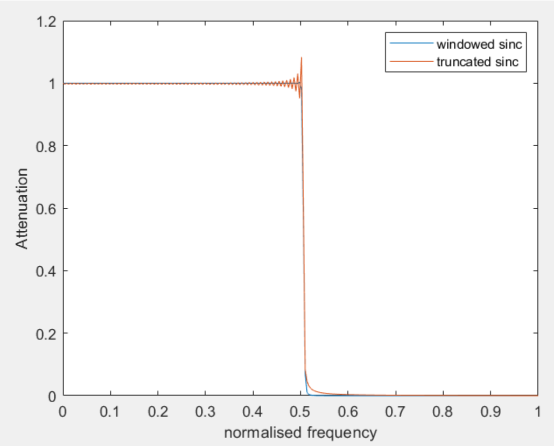


FIGURE 6.31: Frequency response for windowed sinc and truncated sinc filters.

Chapter 7

Management

Many procedures were put in place to ensure the smooth running and the completion of the project.

7.1 Project Management

The majority of work was completed in the Building 16 Projects Lab with every team member present. After comparing the timetables of team members it was decided that Monday to Wednesday inclusive were the days allocated to this project; working continuously for three days a week reduced the amount of disruptions to work flow and increased momentum. In the second half of the project duration this was supplemented by extra work done throughout the week in order to stay on track.

Southampton University's GitLab was used to securely store all of the files associated with the project. The version control properties of Git allowed the team to work simultaneously on their contributions and merge all changes into the repository, this increased productivity. Git also allows easy restoration of past work which helped when mistakes were made and pieces of code had to be reverted to a stable version. A log of the commit history can be found in Appendix I.

A weekly appointment was arranged with the project supervisors to discuss recent progress and problems encountered. This helped the team overcome challenges faced throughout the week and gave an opportunity to ask for guidance. A record of the meeting minutes was created each week by the Project Manager Ricki Tura and is available in Appendix J.

As the project does not involve the collection, storing, or sending of personal data, there were no breaches of GDPR compliance. The project also does involve any interactions with humans or animals, therefore an ethical review was not required.

A Gantt chart was created at the start of the project to track progress and was continuously updated (Appendix K). It can be seen from the Gantt chart that progress on the USRP was severely delayed. This was due to issues that caused severe setbacks such as identifying and fixing the frequency offset between the local oscillators in the two USRPs. This is explained in further detail in Chapter 5.2.1. The original time estimates for each of the USRP tasks described in the Gantt chart were very short and in practice took much longer to complete.

During the project there were some changes to the work required without the need to change the original specification outlined in Chapter 2. It was thought the objectives under the categories “Analyse and Test” and “Design mitigation techniques for” had to be fulfilled in both MATLAB and LabVIEW. This was amended in Week 7 after a discussion with the project supervisors and acting customer so that these objectives only had to be fulfilled on one of the platforms. For example, the objective of analysing the effect of PAPR issues was investigated on MATLAB only.

A summary of the completed objectives and where they are explained in this report is shown in Table 7.1. The completion of each of these objectives were considered as a major milestone. Some of the stretch objectives were completed with the remaining objectives suitable for further work, and are shown in Table 7.2. An email of support from the project’s supervisor and acting customer can be seen in Appendix L and highlighted the team’s good progress, communication, and planning.

Goal category	Goal letter	Completed?	Chapter(s) found
Build	a	Yes	6.1
	b	Yes	6.2
	c	Yes	6.3
	d	Yes	6.1, 6.2, 6.3
Analyse and Test	a	Yes	6.4
	b	Yes	6.5
	c	Yes	6.6
	d	Yes	6.7
Design mitigation techniques	a	Yes	6.8
	b	Yes	6.6
	c	Yes	6.9

Table 7.1: A table showing the different objectives and where they have been addressed in this report. Objectives can be found in Chapter 2.

Goal	Completed?	Chapter(s) found
1	Yes	6.8
2	Yes	6.9
3	No	
4	No	

Table 7.2: A table showing the different stretch objectives and where they have been addressed in this report. Objectives can be found in Chapter 2.

A PERT chart was also created to identify the critical path and determine which tasks should be prioritised (Appendix N).

The project was loosely split between designing and testing simulations on MATLAB and LabVIEW respectively. A skills audit was carried out to identify the individual strengths in the team and assign tasks accordingly (Appendix M). Paul Dampierre was in charge of the MATLAB simulations whilst Ricki Tura was in charge of the LabVIEW simulations.

The ownership of report chapters is outlined in Table 7.3. LaTeX was used to create the report as it works well with Git source control and the template provided by ECS saved the group a lot of time. Mendeley was used to extract, format, and store sources from web pages and also saved the group time. The project poster was a joint effort, with Paul Dampierre creating the MATLAB half and Ricki Tura creating the LabVIEW half. The presentation slides followed a similar ownership, with Paul and Ricki creating the MATLAB and LabVIEW slides respectively.

Another aspect of the project was the teams dialogue with NI Customer Support. The LabVIEW Communications System Design Suite software was notoriously slow throughout the project and would regularly crash, fail to respond, and close down unexpectedly. Our liaising with Customer Support involved sending over sections of code to help identify areas that may be responsible for the slow performance. After a few weeks of discussion, it was concluded that the easiest way to solve the issue was to convert the code so that it was compatible with the newer LabVIEW NXG software that can better handle large projects. Given the time constraints of this project, this was not possible. However, this is a valuable and worthwhile suggestion for further work on this project.

7.2 Risk Management

At the start of the project, a risk assessment was carried out by Paul Dampierre to identify points of concern. These risks were divided into three categories: Technical, Personnel, and External. Technical risks included software crashes and the loss of files, which can be mitigated against through frequent code commits and uploads to the team's Git repository.

Personnel risks involved illness which was identified as a high risk. Due to the team consisting of only two members, the scenario of one of the team falling ill would temporarily reduce the effective team size to just one person. This would have a large impact on the project's progress, and was mitigated against by having detailed minutes from supervisor meetings as well as regular transfers of knowledge between the team. This was helped by the team's decision to work together for most of the project.

Section			**Author**
Introduction			R
Objectives	Technical Goals		R + P
	Stretch Goals		R + P
Resources	Software		R
	Hardware		R
Background Research	Multicarrier Modulation		R
	OFDM		R
	4G	Cyclic Prefix	P
		Channel	P
		Pilots	P
	5G		P
	USRP		R
Approach	MATLAB	Basic Design	P
		OFDM	P
		4G	P
		5G	P
	LabVIEW	Basic Design	R
		OFDM	R
		4G	R
		5G	R
	Analysis and Testing	Cyclic Prefixing	P
		Channel Estimation	P
		Time Synchronisation Offset	P
		PAPR	P
	Mitigation	Carrier Frequency Offset	P
		Time Synchronisation Offset	P
		Filtering	P
Results	OFDM		R + P
	4G		R + P
	5G		R + P
	Cyclic Prefixing		P
	Channel Estimation		R + P
	Time Synchronisation Offset		P
	PAPR		P
	Carrier Frequency Offset		R
	Filtering		P
Management	Project Management		R
	Risk Management		P
Conclusion			R + P

Table 7.3: A table showing the authors of the different chapters of this report. “R” stands for Ricki Tura and “P” Stands for Paul Dampierre.

The main external risk was the unavailability of the project's supervisors. The project has no external partner/customer, as it is the project supervisors who will be using the project after completion. If the supervisors are unavailable it would leave the team without guidance. However, both supervisors have assured the team that they will be present throughout the duration of the project. More details on mitigating risks can be seen in Appendix O.

Chapter 8

Conclusions

Over the course of this project an OFDM demonstrator on the NI USRP has been made that can successfully transmit data with a BER of 0. Various aspects of 4G and 5G OFDM transmission have been investigated both in MATLAB simulations and on the USRP. These aspects include cyclic prefixing, channel estimation using pilot symbols, time synchronisation offsets, carrier frequency offsets, PAPR reduction, and filtering.

Further work that has been proposed throughout this report include: the porting of USRP code from LabVIEW Communications to LabVIEW NXG to improve performance; enhancement of the 4G and 5G transmitters to support higher bandwidths to meet specifications; better channel estimation through the use of different methods to allow for a smaller PDR; and the investigation of different methods of reducing the PAPR such as peak cancellation. Two of the four stretch goals have also been proposed as further work.

Overall, the project's customer is satisfied with the amount achieved in this project and the team worked effectively to achieve these goals.

Bibliography

[1] "MEng Electronic Engineering with Wireless Communications — University of Southampton." [Online]. Available: https://www.southampton.ac.uk/courses/electronic-engineering-with-wireless-communications-degree-meng?tab-course=modules{#}modules

[2] Next Generation Wireless (NGW), "Master of Science (MSc) Wireless Communications," 2018. [Online]. Available: https://www.wireless.ecs.soton.ac.uk/msc

[3] M. El-Hajjar, Q. A. Nguyen, R. G. Maunder, and S. X. Ng, "Demonstrating the Practical Challenges of Wireless Communications Using USRP," Tech. Rep., 2014. [Online]. Available: https://www.southampton.ac.uk/~sxn/paper/usrp-mag.pdf

[4] R. G. Maunder, "University of Southampton Uses the USRP and LabVIEW to Change the Way It Teaches Wireless Communications - National Instruments." [Online]. Available: http://www.ni.com/en-gb/innovations/case-studies/19/university-of-southampton-uses-the-usrp-and-labview-to-change-the-way-it-teaches-wireless-communications.html

[5] "What Is NI USRP Hardware? - National Instruments," 2019. [Online]. Available: https://www.ni.com/en-gb/innovations/white-papers/11/what-is-ni-usrp-hardware-.html

[6] A. Goldsmith, "Multicarrier Modulation," in *Wireless Communications*. Cambridge University Press, Mar 2013, pp. 374–402.

[7] A. A. Zaidi, R. Baldemair, H. Tullberg, H. k. Björkegren, L. Sundström, J. Medbo, C. Kilinc, and I. Da Silva, "Waveform and Numerology to Support 5G Services and Requirements," Tech. Rep., 2017. [Online]. Available: https://www.ericsson.com/assets/local/publications/conference-papers/waveform-and-numerology-to-support-5g-services-and-requirements.pdf

[8] Y. Wu and W. Y. Zou, "Orthogonal frequency division multiplexing: A multicarrier modulation scheme," *IEEE Transactions on Consumer Electronics*, vol. 41, no. 3, pp. 392–399, 1995.

[9] L.-L. Yang, "ELEC3204-Part II: Principles of Multicarrier Modulation and OFDM," Tech. Rep., 2019. [Online]. Available: https://secure.ecs.soton.ac.uk/notes/elec3204/lly/ELEC3204-MC-OFDM-principles18.pdf

[10] M. D. Nisar, W. Utschick, H. Nottensteiner, and T. Hindelang, "On channel estimation and equalization of OFDM systems with insufficient cyclic prefix," in *IEEE Vehicular Technology Conference*, 2007, pp. 1445–1449.

[11] M. Schwartz, *Mobile Wireless Communications.* Cambridge University Press, 2004. [Online]. Available: http://ee.sharif.edu/~pr.wireless.comm/references/Schwartz.pdf

[12] Y. S. Cho, J. Kim, and W. Y. Yang, *MIMO-OFDM Wireless Communications with MATLAB.* John Wiley & Sons, 2010.

[13] L. Zhang, A. Ijaz, P. Xiao, M. M. Molu, and R. Tafazolli, "Filtered OFDM systems, algorithms, and performance analysis for 5G and beyond," *IEEE Transactions on Communications*, vol. 66, no. 3, pp. 1205–1218, Mar. 2018.

[14] F. D. Stasio, M. Mondin, and F. Daneshgaran, *Multirate 5G Downlink Performance Comparison for f-OFDM and w-OFDM Schemes with Different Numerologies*, 2018. [Online]. Available: https://arxiv.org/pdf/1807.10371.pdf

[15] A. Zaidi, J. Luo, R. Gerzaguet, A. Wolfgang, R. Weiler, J. Vihril, T. Svensson, Y. Qi, H. Halbauer, Z. Zhao, P. Zetterberg, and H. Miao, "A preliminary study on waveform candidates for 5g mobile radio communications above 6 ghz," 05 2016, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7504096

[16] National Instruments, "NI USRP-2920/2921/2922 GETTING STARTED GUIDE," 2015. [Online]. Available: http://www.ni.com/pdf/manuals/376358a.pdf

[17] "Specifications USRP-2922," 2017. [Online]. Available: http://www.ni.com/pdf/manuals/375868c.pdf

[18] National Instruments and B. Black, "Introductory Communications Systems." [Online]. Available: https://learn.ni.com/teach/resources/16/introductory-communications-systems

[19] M. El-Hajjar, "main.m," 2019. [Online]. Available: https://secure.ecs.soton.ac.uk/people/meh

[20] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception." [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2411

[21] ——, "NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone." [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3283

[22] C. R. Johnson and W. A. Sethares, *Telecommunication Breakdown: Concepts of Communication Transmitted Via Software-defined Radio, Volume 1*, 2004. [Online]. Available: http://books.google.fr/books/about/Telecommunication_Breakdown.html?id=gw0fAQAAIAAJ&pgis=1

[23] T. Ali-Yahiya, *Understanding LTE and Its Performance*, 1st ed. Springer Publishing Company, Incorporated, 2011.

[24] T. Innovations, "Telesystem Innovations LTE in a Nutshell: The Physical Layer," Tech. Rep., 2010. [Online]. Available: https://home.zhaw.ch/kunr/NTM1/literatur/LTEinaNutshell-PhysicalLayer.pdf

[25] S. W. Smith, *The scientist and engineer's guide to digital signal processing.* California Technical Pub, 1997.

[26] MathWorks, "Butterworth filter design - MATLAB butter - MathWorks United Kingdom." [Online]. Available: https://uk.mathworks.com/help/signal/ref/butter.html

[27] M. Ng and S. Chen, "Wireless Environment Wave Propagation," 2019. [Online]. Available: https://secure.ecs.soton.ac.uk/notes/elec6245/lectures/WirelessPropagation.pdf

[28] A. M. Khan, V. Jeoti, and M. A. Zakariya, "Improved pilot-based LS and MMSE channel estimation using DFT for DVB-T OFDM systems," in *IEEE Symposium on Wireless Technology and Applications, ISWTA*. IEEE Computer Society, 2013, pp. 120–124.

[29] M. S. A. Hassan and R. B. Ahmad, "Variable pilot channels estimation based on blocktype and comb-type pilot arrangement in OFDM system," in *2016 3rd International Conference on Electronic Design, ICED 2016*. Institute of Electrical and Electronics Engineers Inc., Jan. 2017, pp. 99–102.

Appendix A

Additional Background Research

This appendix contains background research supplementary to the main background research section in 4.

A.1 Multicarrier Modulation

Multicarrier modulation is a technique in which the data is split up into sub-streams and the available bandwidth is split up into equal sections known as sub-channels [6]. Each data sub-stream is then modulated and transmitted with the data occupying one of the sub-channels (Figure A.1). The rationale behind this is that each sub-channel will occupy a bandwidth narrower than the coherence bandwidth [6]. The coherence bandwidth is defined as the "range of frequencies over which the channel gain is flat" [27], therefore each of the sub-channels will undergo flat fading [11]. A benefit of this flat fading is that multicarrier systems are resilient to Inter Symbol Interference (ISI) [6].

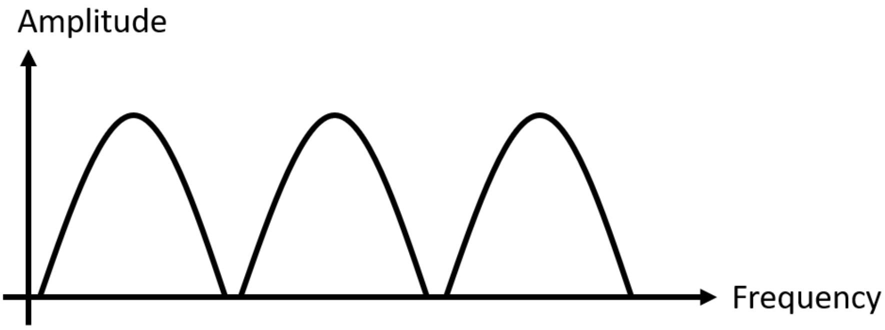


FIGURE A.1: A frequency spectrum demonstrating how a multicarrier signal contains multiple sub-channels.

However, one disadvantage is that when the signals for each sub-channel are combined for transmission and viewed in the time domain they can constructively interfere. This results in an output signal with higher maximum peaks as shown in Figure A.2. This is a disadvantage as it relates to the PAPR of the signal which is typically high in multicarrier systems [15]. A signal with a high PAPR results in greater requirements of the transmitter and receiver. A high PAPR requires the transmitter to have a more complex amplifier which has a greater linear region [6]. The receiver will require an Analog to Digital Converter (ADC) with a high resolution in order to accurately convert the signal due to the signal having a greater dynamic range. A high resolution conversion increases the complexity and power usage of the receiver [6].

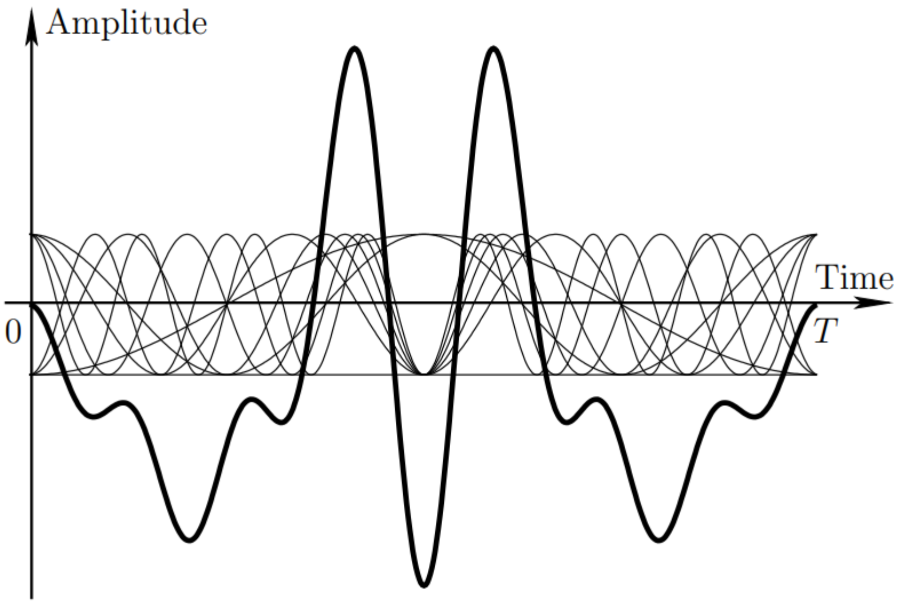


FIGURE A.2: A graph showing the combination of sub-channel signals in the time domain to show the effects of interference, sourced from [9].

An example transmitter is shown in Figure A.3. The serial to parallel converter creates the data sub-streams with the number of sub-streams determining the number of sub-channels. Each sub-stream is converted into symbols and processed with a pulse shaping filter before being modulated with a carrier. Note that each carrier has a different frequency denoted by f_0, f_1, and f_{N-1} which represents the centre frequency of each of the subcarriers. Lastly, the signals are combined before being transmitted.

An example receiver is shown in Figure A.4. The signal is split in parallel with the number of signals equalling the number of subcarriers. Each subcarrier signal is processed separately. Each signal goes through a bandpass filter with a centre frequency equalling that of the sub-channel in question to remove the signals from other sub-channels. Next, the signals are demodulated before being sent through a parallel to serial converter to produce the output.

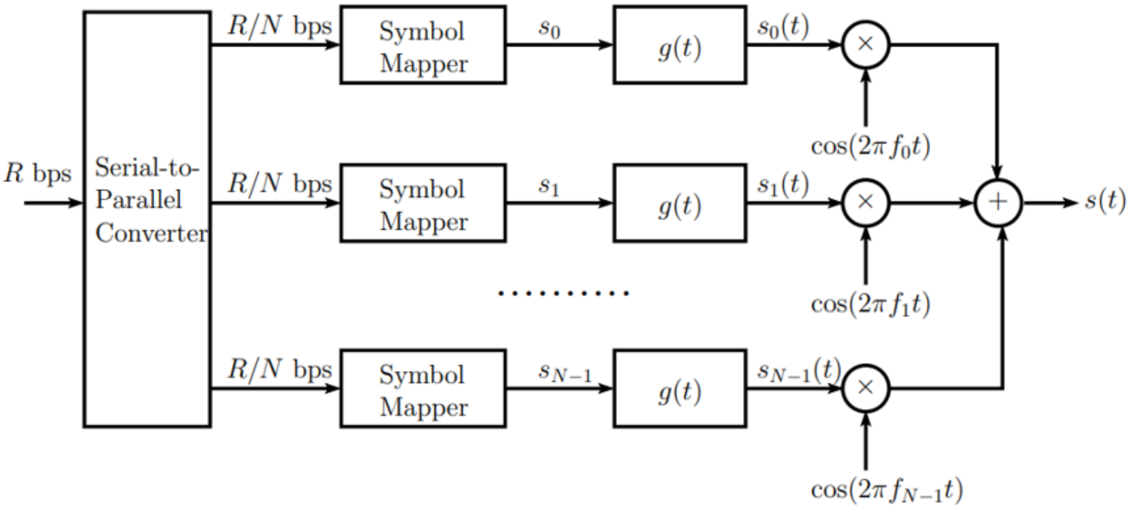


FIGURE A.3: A diagram showing the key blocks in a multicarrier transmitter, sourced from [6].

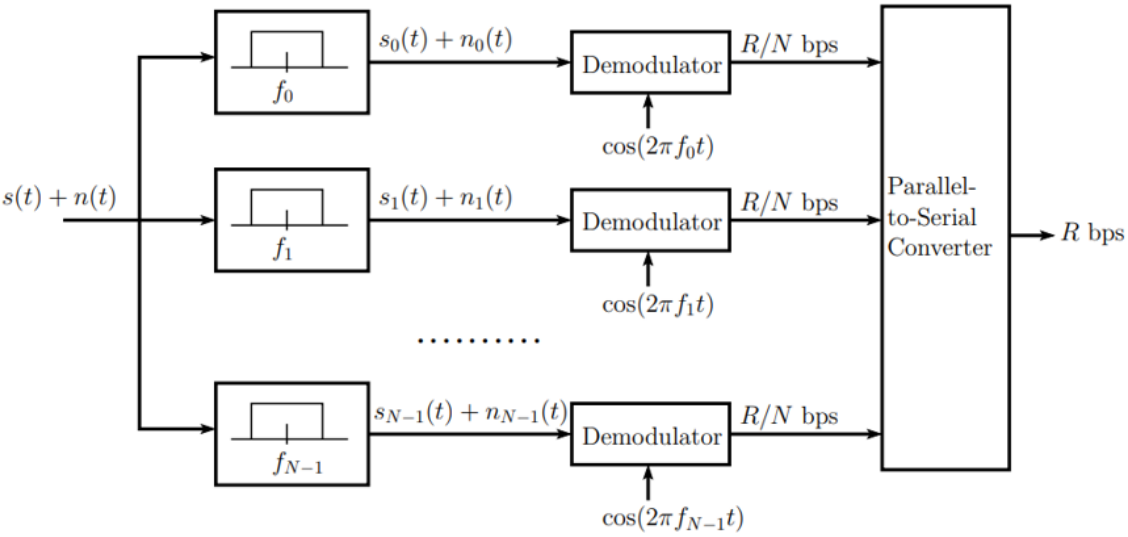


FIGURE A.4: A diagram showing the key blocks in a multicarrier receiver, sourced from [6].

A.2 Time Synchronisation

Synchronisation is very important in OFDM systems. There are several types of synchronisation that need to occur in order to ensure that the modulation scheme performs in ideal condition. In this section we will introduce the concept of time synchronisation offset.

In [12], Cho outlines four ways to sample an OFDM symbol. The first case is the ideal case, the signal is sampled from the first symbol of the OFDM symbol transmitted. The second case is when the symbol is sampled too early, as a result the sample includes a part of the cyclic prefix. In this case, the part of the cyclic prefix sampled does not

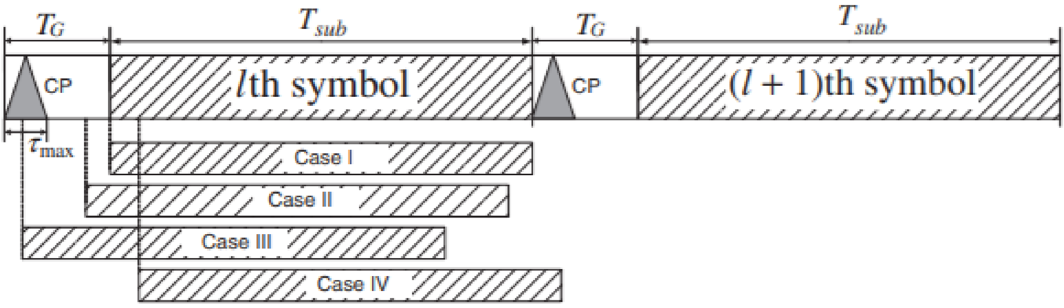


FIGURE A.5: Description of time synchronisation offset, sourced from [12].

contain ISI. The third case samples the OFDM symbol early. The part of the CP that is sampled with the rest of the OFDM system does contain ISI from the previously sent symbol. The last case samples the symbol past the ideal first sample and therefore contains part of the next symbol sent and does contain ISI. When the symbols contain the ISI the FFT block is not able to maintain perfect orthogonality and therefore the cases 3 and 4 induce ICI as well ISI in the system.

A.3 Bit Error Rate

The Bit Error Rate (BER) is the metric used throughout this process in order to test the performance of the system. It is the quotient of total number of received bits, after demodulation, that differ from the original bit sequence, before modulation, over the total number of bits transmitted. It generally varies depending on the Signal to Noise Ratio (SNR) which why the BER in terms of the SNR is a graph that indicates the performance level of the system.

A.3.1 Channel Estimation

The techniques for channel estimation addressed rely on having known symbols at the receiver to be able to reduce the number of unknowns and estimate the channel. These symbols are called pilots. These pilots are modulated onto a subcarrier and sent through the channel. Hence the pilots are sent instead of data which reduces the efficiency of the system. In order to maximise the efficiency of the system it is optimal to only send the amount of pilots necessary to accurately estimate the channel. The pilot to data ratio is the amount of pilots that is sent relative to amount of data sent.

These techniques are based on comb type pilot arrangement specified in Chapter A.4.

LS is a channel estimation technique in which the receiver uses the pilot and the received data to estimate the frequency domain channel gain for all the subcarriers.

$$H_{LS} = X_p^{-1} Y_p \tag{A.1}$$

In Eq A.1 [28], H_{LS} are the LS channel gain estimations, X_p are the pilot symbols and Y_p are the received pilot symbols.

This technique only generates estimates of channel gains for the pilot subcarriers but the remaining channel gains can be obtained through interpolation. MATLAB has different interpolation techniques including step, linear, cubic, and spline. Spline interpolation provides the best results as it allows the estimation to better fit to the original channel.

The second technique used is MMSE. This technique assumes that the variance of the noise is a known variable at the receiver. Like the LS channel estimation technique, the MMSE channel estimation technique uses interpolation to find the channel gains for the data subcarriers. The MMSE takes in consideration the noise variance in order to achieve better results when the SNR is low and the noise has a high impact on the estimation values.

$$H_{MMSE} = (|X_p|^2 + \sigma^2)^{-1} Y_p X_p^* \tag{A.2}$$

In Eq A.2 the H_{MMSE} are the channel gains for the pilot subcarriers, X_p are the pilot symbols, σ is the noise variance, Y_p are the received pilot symbols and X_p^* is the complex conjugate of X_p [28].

The final channel estimation technique used in this report is time domain channel estimation. This is achieved using the derivation described in Appendix D. The contrast between this technique and the previous ones are that instead of using interpolation to find the channel gains, the pilot subcarrier channel gains are used to estimate the time domain channel taps. The frequency domain channel gains for every subcarrier are derived using the time domain channel taps estimated. The issue with this technique is that the error in estimation of the time domain channel taps propagates to all the frequency channel gain.

A.4 Pilots

Pilots are symbols that are transmitted from the transmitter to the receiver whose expected values are known at the transmitter. The comparison of the expected values and the received values of the pilots can be used to deduce the effect of the channel on the transmitted data.

There are two main types of ways to transmit pilots in OFDM systems as described in Chapter 6 of [12]. The first method of transmitting pilots in OFDM system is a block-type pilot. In this method the pilots are sent over all the subcarriers at the same interval S_t. In this case we would achieve full knowledge of the channel for the frame in which the pilots are sent, but no knowledge of the channel would be available for the remaining frames. The values of the channel could be interpolated in time to find the values for the adjacent frames.

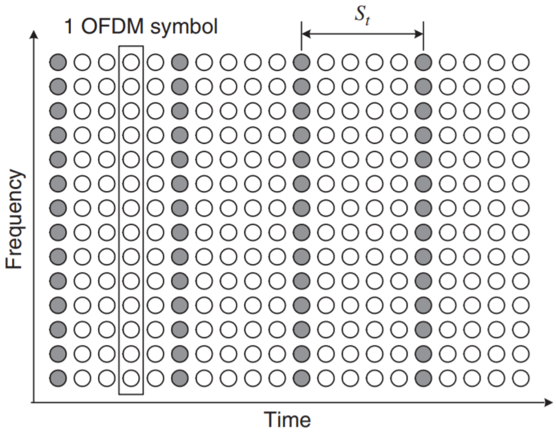


FIGURE A.6: An example of block-type pilot transmission, sourced from [12].

In order to correctly interpolate the values of the channel in time, the distance in time between two pilots has to be less or equal to the coherence time defined by the inverse of the doppler frequency as shown in Eq A.3 [12].

$$S_t \leq \frac{1}{f_{doppler}} \tag{A.3}$$

The second method of transmitting pilots in multi carrier systems is a comb-type pilot transmission. In this type of pilot transmission, pilots are sent in the same subcarrier every frame. The pilots are evenly spaced across the data subcarriers at an interval S_f. The pilot to data ratio indicates how many pilot are being sent relative to the amount of data. The channel is found by interpolation of the values of the channel that can be deduced from the pilots.

In a similar way to the block type pilots, the distance between the two pilots has to be less or equal to coherence bandwidth which is equal to the inverse of the delay spread. This relationship is seen in Eq A.4 [12].

$$S_f \leq \frac{1}{\sigma_{max}} \tag{A.4}$$

Pilots are very useful to deduce the unknown effects of the channel but they render the system less efficient. As the pilots do not transmit any data, they reduce the spectral efficiency and the data rate of the system by taking the bandwidth that could be allocated to a data carrier. As a result, research is being made to render this process more efficient

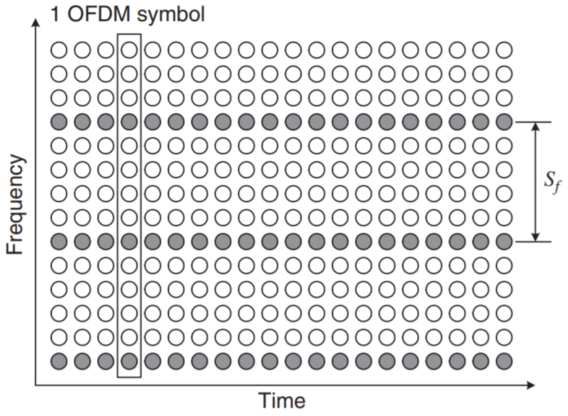


Figure A.7: An example of comb-type pilot transmission, sourced from [12].

such as Hassan et al [29], who suggest varying the amount of pilot to data ratio in terms of the complexity of the channel would improve the overall efficiency of OFDM transmission.

A.5 Normalisation in MATLAB

To make sure the result obtained matched the resulting theoretical values of the BER, normalisation had to occur at different stages in the modulation. Firstly, the average power of the modulation scheme had to be normalised to 1. Secondly, the noise had to be normalised. As the noise in the AWGN channel was complex, the variance of the noise, σ^2, was equal to the noise power spectral density, N_0, divided by 2. The noise power spectral density was defined in terms of the linear SNR which is a function of the bit per symbol. As a result this value was not fixed between different modulation schemes.

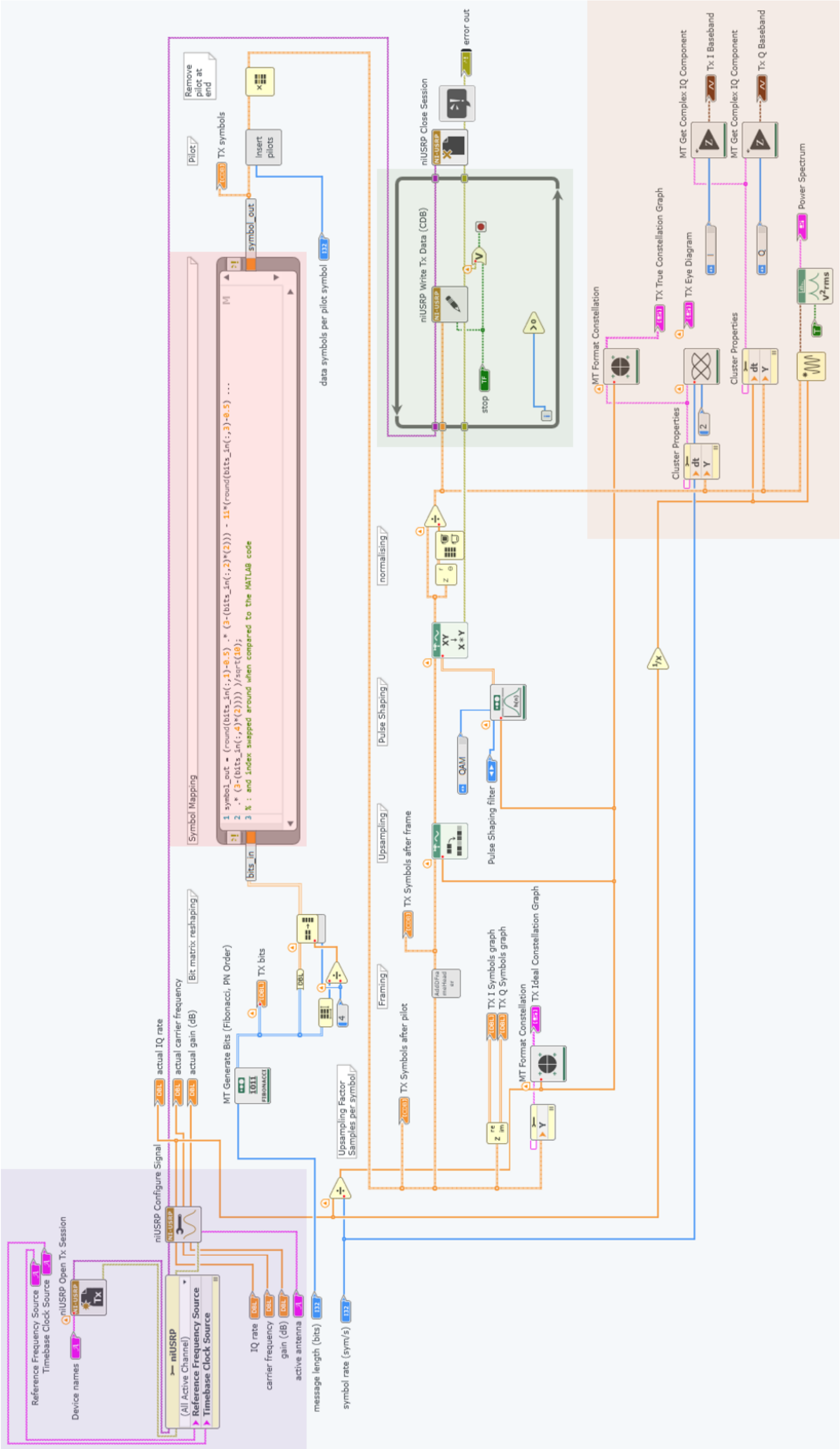
Appendix B

16QAM system in LabVIEW

All blocks mentioned have been sourced from the standard libraries unless stated otherwise. In the transmitter code, USRP blocks were used to configure the USRP with the parameters defined by the user such as carrier frequency, output gain, and sampling rate. Next, a “Generate Bits” block is used to produce a bit stream of the Fibonacci sequence, this is the data that will be transmitted. The bit stream is reshaped from a single row vector to a matrix with four columns and a number of rows dependant of the size of the bit stream. A MathScript node then performs 16QAM encoding on each row of the reshaped bit stream, converting each row of four bits into an encoded symbol. This is then fed into an “Insert Pilots” block made by the team which adds pilot symbols of `0.5 + 0.5i` at regular intervals, the ratio of data symbols to pilot symbols is determined on the front panel by the user. The 26 symbol DBPSK encoded Barker code is then prefixed to the vector of symbols before the entire vector is upsampled. This is then routed to the input of a convolution block with the other input being the coefficients of root a raised cosine filter. This convolution shapes the output into pulses which have a more rapid falloff in the frequency domain than square waves. This is done to reduce the bandwidth of the signal. This output is then normalised before being sent to the “Write Tx Data” block which handles the upsampling, modulation, and transmission using the USRP.

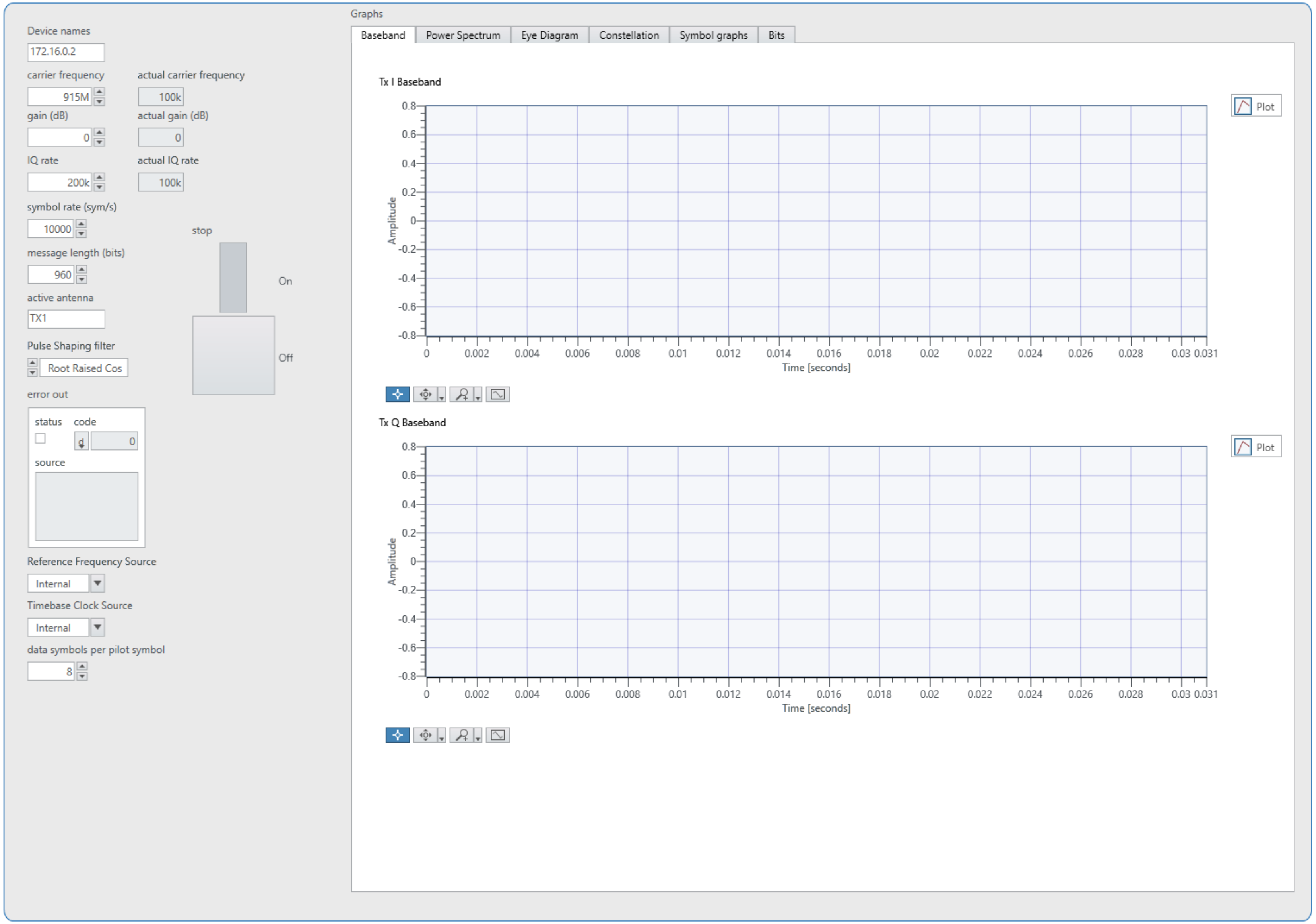
The receiver code contained the same USRP set up blocks found in the transmitter. A `while` loop continuously fetches data from the USRP and runs the data through a convolution block with the coefficients of a filter matched to the one in the transmitter. The data is then passed through a “Pulse align” block which finds the ideal point to obtain the samples. The signal is then sampled, normalised, and fed to an edited “Frame sync” block which was enhanced from the original to perform differential DBPSK decoding of the signal. This is then cross-correlated with the Barker code to obtain the start of the message frame. When this is obtained the code exits the `while` loop and the message data is passed to a MathScript node. This node contains MathScript code written by the team to analyse the received pilot symbols and estimate the effects of the channel. The estimated channel values are then fed into interpolation blocks to obtain the channel estimate across all received samples. This is fed into another MathScript node written to use the estimated channel to recover the data symbols. The final MathScript node takes these 16QAM symbols and converts them into a single bit stream which is then sent to a BER calculator block which compares the bits against the original data.

The diagram figures have been formatted to fit on an A4 page. To view these diagrams in more detail, please see the files in the electronic appendix H.



```
symbol_out = (round(bits_in(:,1)-0.5) .* (3-(bits_in(:,2)*(2))) - 1i*(round(bits_in(:,3)-0.5) ...
 .* (3-(bits_in(:,4)*(2)))) )/sqrt(10);
% : and index swapped around when compared to the MATLAB code
```

FIGURE B.1: A diagram showing the blocks in the 16QAM transmitter. The diagram is made of three rows. The purple area in the first row contains the set up of the USRP, the red area contains the MathScript node that handles the symbol mapping. The second row contains blocks to handle the message framing, upsampling, pulse shaping, normalising, and a "while" loop highlighted in green which sends the data to the USRP to be transmitted. The third and final row highlighted in orange contains the blocks that handle graph creation.



Device names: 172.16.0.2

carrier frequency: 915M

actual carrier frequency: 100k

gain (dB): 0

actual gain (dB): 0

IQ rate: 200k

actual IQ rate: 100k

symbol rate (sym/s): 10000

message length (bits): 960

active antenna: TX1

Pulse Shaping filter: Root Raised Cos

error out

status ☐ code 0

source

Reference Frequency Source: Internal

Timebase Clock Source: Internal

data symbols per pilot symbol: 8

Figure B.2: A diagram showing the front panel of the 16QAM transmitter. The left hand side contains parameters for the user to enter to configure the USRP. The main section of the panel contains graphs and diagrams.

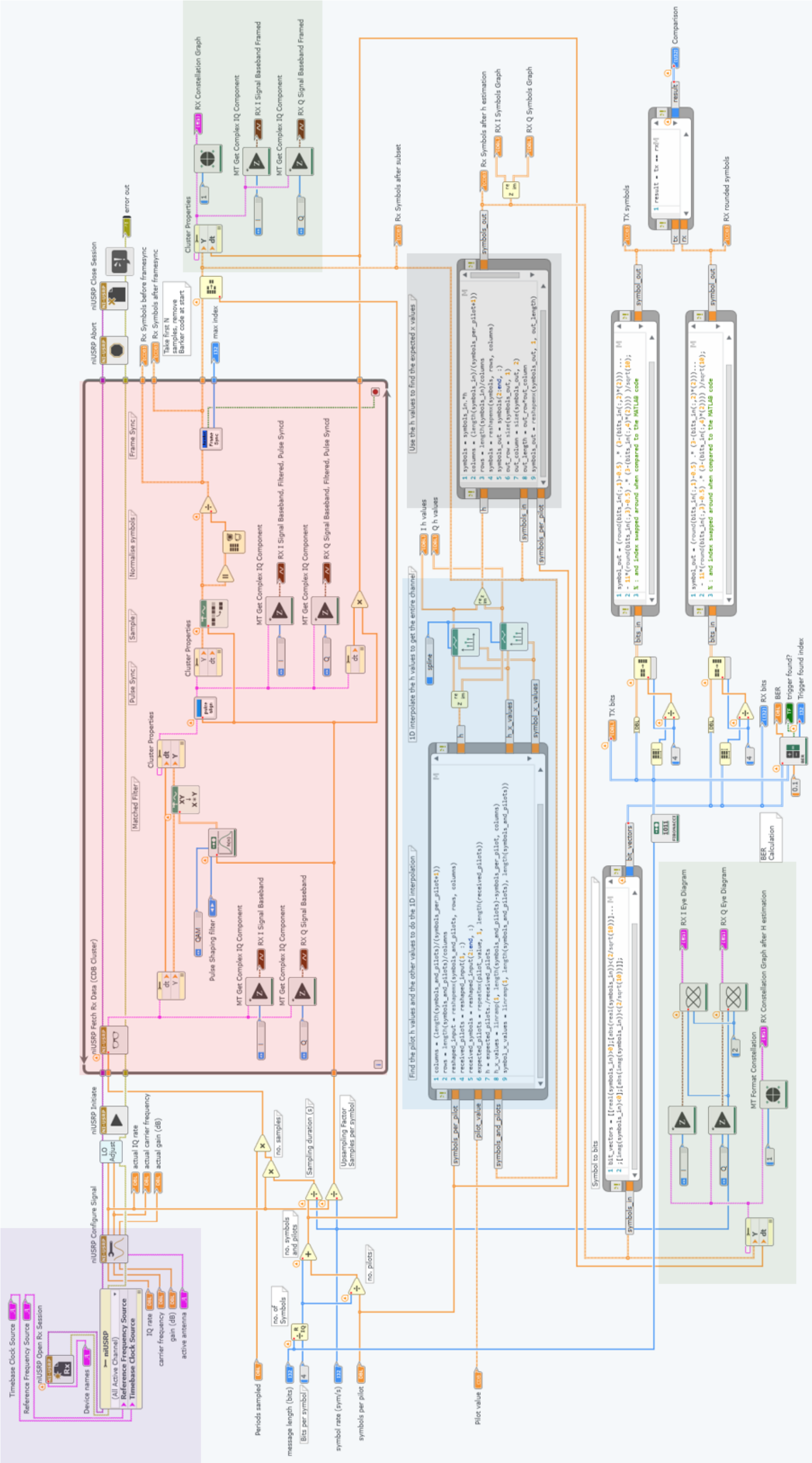
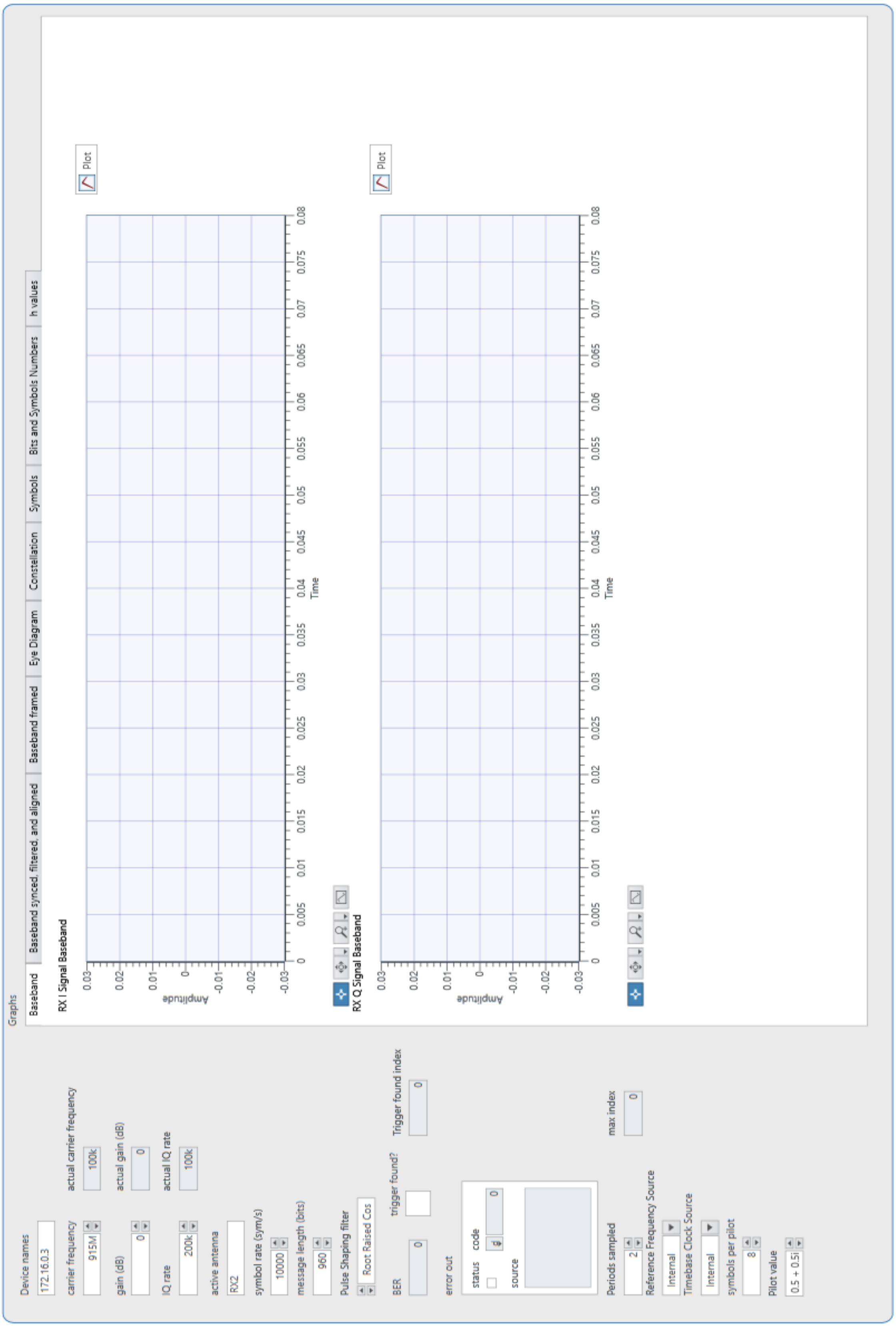


FIGURE B.3: A diagram showing the blocks in the 16QAM receiver. The diagram is made of three rows. The purple area in the first row contains the set up of the USRP, the red area contains a “while” loop that matched filters, aligns, samples, normalises, and DBPSK decodes the signal to find the start of the message. The blue area in the second row uses the pilot symbols and interpolation to estimate the channel. The grey area in the second row uses the estimated channel to recover the data. The third row decodes the symbols to bits, and compares this with the original bit stream calculate the BER. The green areas in the first and third row set up the output graphs on the front panel.



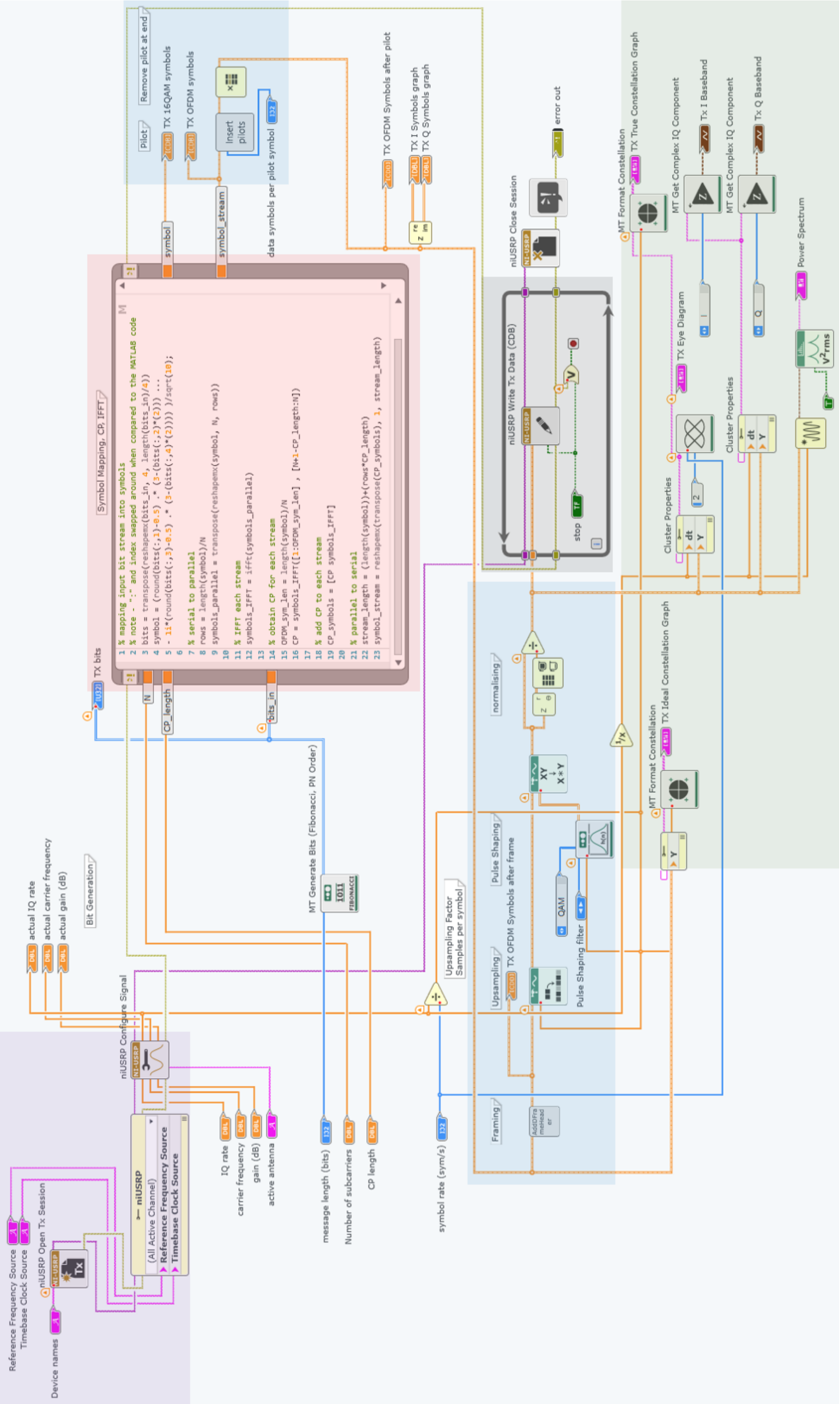
Device names: 172.16.0.3
carrier frequency: 915M
actual carrier frequency: 100k
gain (dB): 0
actual gain (dB): 0
IQ rate: 200k
actual IQ rate: 100k
active antenna: RX2
symbol rate (sym/s): 10000
message length (bits): 960
Pulse Shaping filter: Root Raised Cos
trigger found?
Trigger found index: 0
BER: 0
code: 0
Periods sampled: 2
max index: 0
Reference Frequency Source: Internal
Timebase Clock Source: Internal
symbols per pilot: 8
Pilot value: 0.5 + 0.5i

FIGURE B.4: A diagram showing the front panel of the 16QAM receiver. The left hand side contains parameters for the user to enter to configure the USRP. The main section of the panel contains graphs and diagrams.

Appendix C

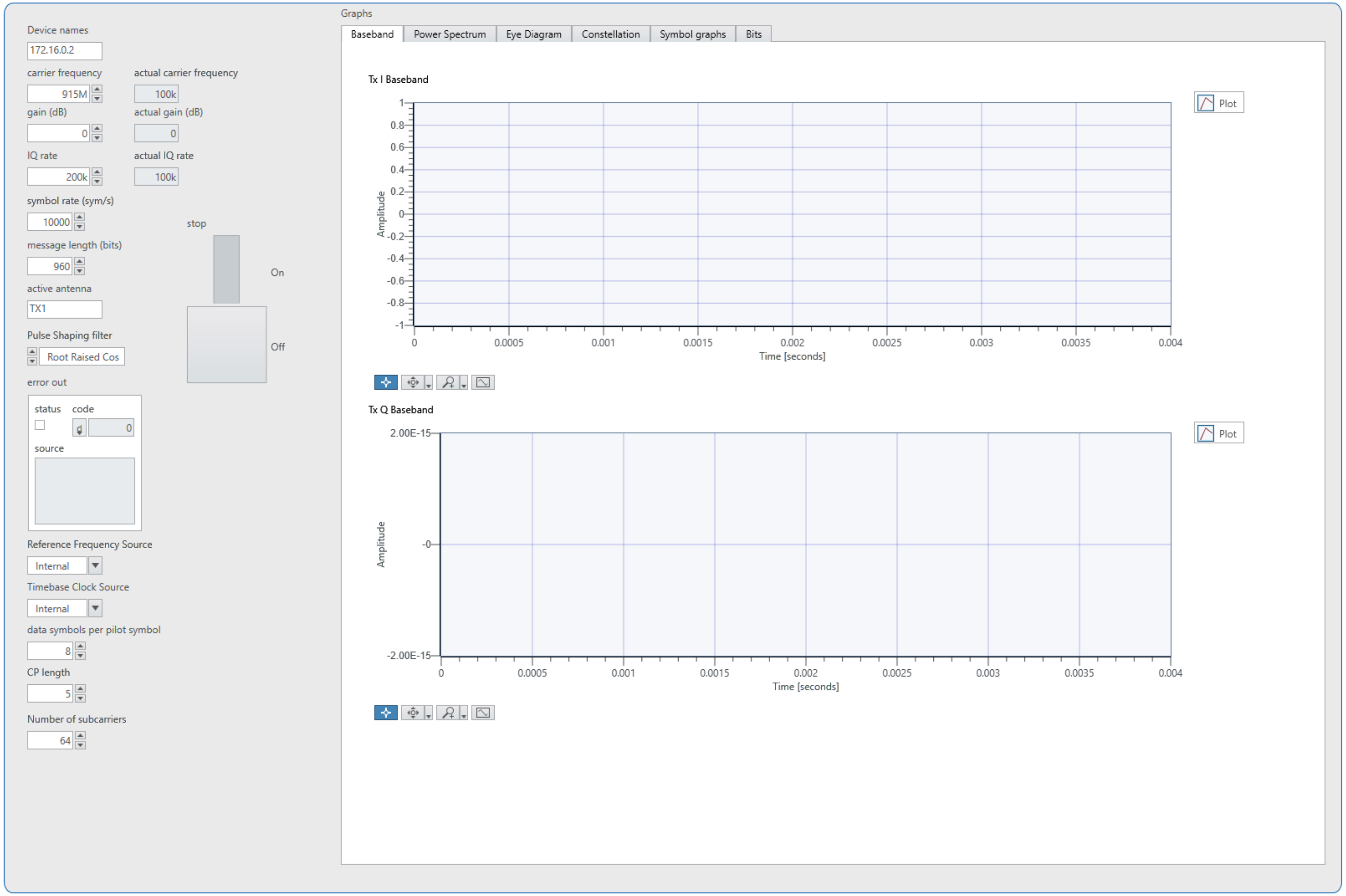
OFDM system in LabVIEW

The diagram figures below have been formatted to fit on an A4 page. To view these diagrams in more detail, please see the files in the electronic appendix H.



```
% mapping input bit stream into symbols
% note - ":" and index swapped around when compared to the MATLAB code
bits = transpose(reshapemx(bits_in, 4, length(bits_in)/4))
symbol = (round(bits(:,1)-0.5) .* (3-(bits(:,2)*(2))) ...
- 1i*(round(bits(:,3)-0.5) .* (3-(bits(:,4)*(2)))) )/sqrt(10);

% serial to parallel
rows = length(symbol)/N
symbols_parallel = transpose(reshapemx(symbol, N, rows))

% IFFT each stream
symbols_IFFT = ifft(symbols_parallel)

% obtain CP for each stream
OFDM_sym_len = length(symbol)/N
CP = symbols_IFFT([1:OFDM_sym_len] , [N+1-CP_length:N])

% add CP to each stream
CP_symbols = [CP symbols_IFFT]

% parallel to serial
stream_length = (length(symbol))+(rows*CP_length)
symbol_stream = reshapemx(transpose(CP_symbols), 1, stream_length)
```

Figure C.1: A diagram showing the blocks in the OFDM transmitter. The diagram is made of three rows. The purple area in the first row contains the set up of the USRP, the red area contains the MathScript node that handles the symbol mapping, cyclic prefixing, and the IFFT of the symbols. The first and second row contains blocks highlighted in blueto handle the insertion of pilots,message framing, upsampling, pulse shaping, and normalising. The grey highlighted "while" loop sends the data to the USRP to be transmitted. The third and final row highlighted in green contains the blocks that handle graph creation.



Device names: 172.16.0.2

carrier frequency: 915M

actual carrier frequency: 100k

gain (dB): 0

actual gain (dB): 0

IQ rate: 200k

actual IQ rate: 100k

symbol rate (sym/s): 10000

message length (bits): 960

active antenna: TX1

Pulse Shaping filter: Root Raised Cos

error out: status ☐ code 0 source

Reference Frequency Source: Internal

Timebase Clock Source: Internal

data symbols per pilot symbol: 8

CP length: 5

Number of subcarriers: 64

Figure C.2: A diagram showing the front panel of the OFDM transmitter. The left hand side contains parameters for the user to enter to configure the USRP. The main section of the panel contains graphs and diagrams.

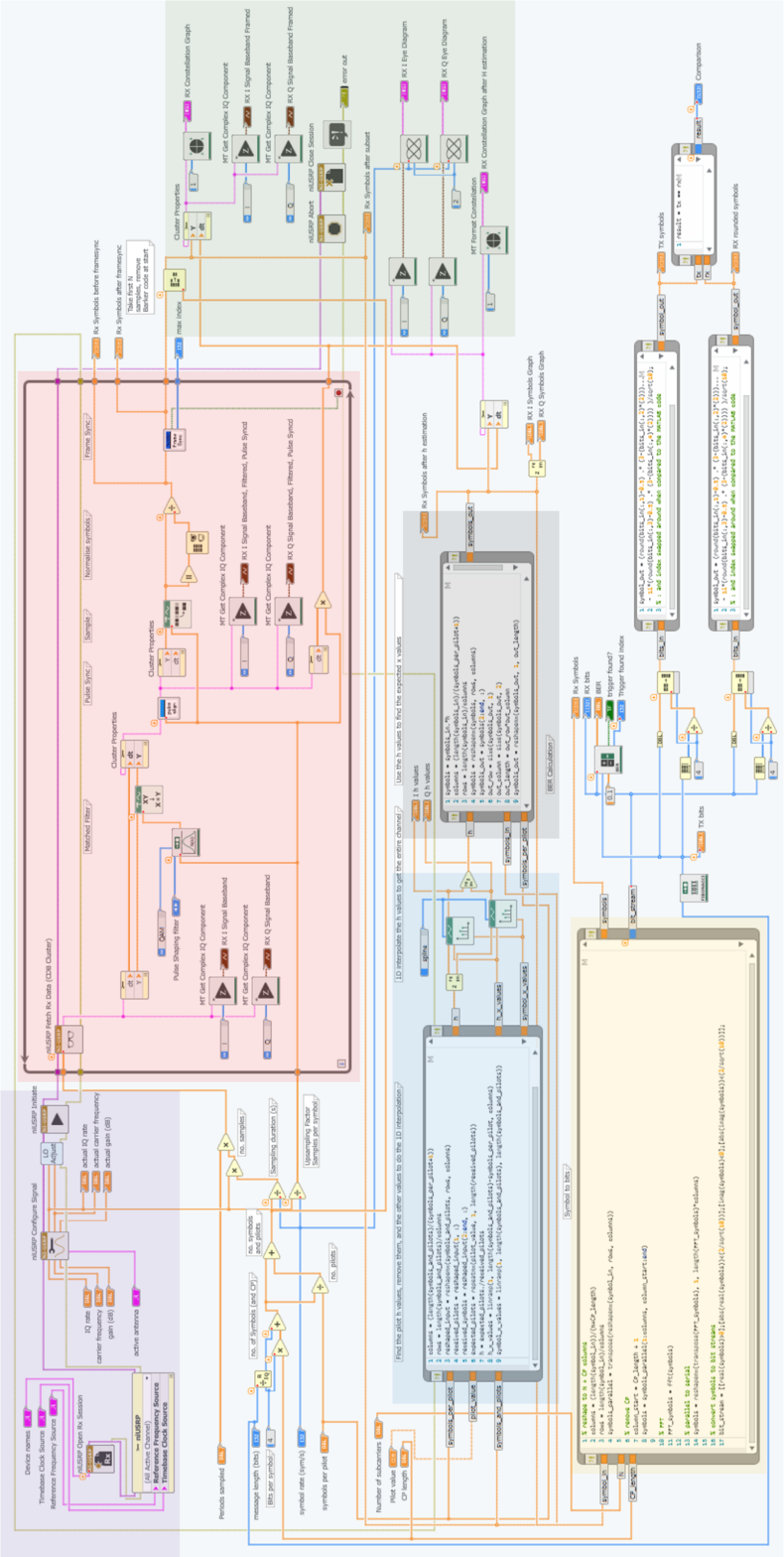
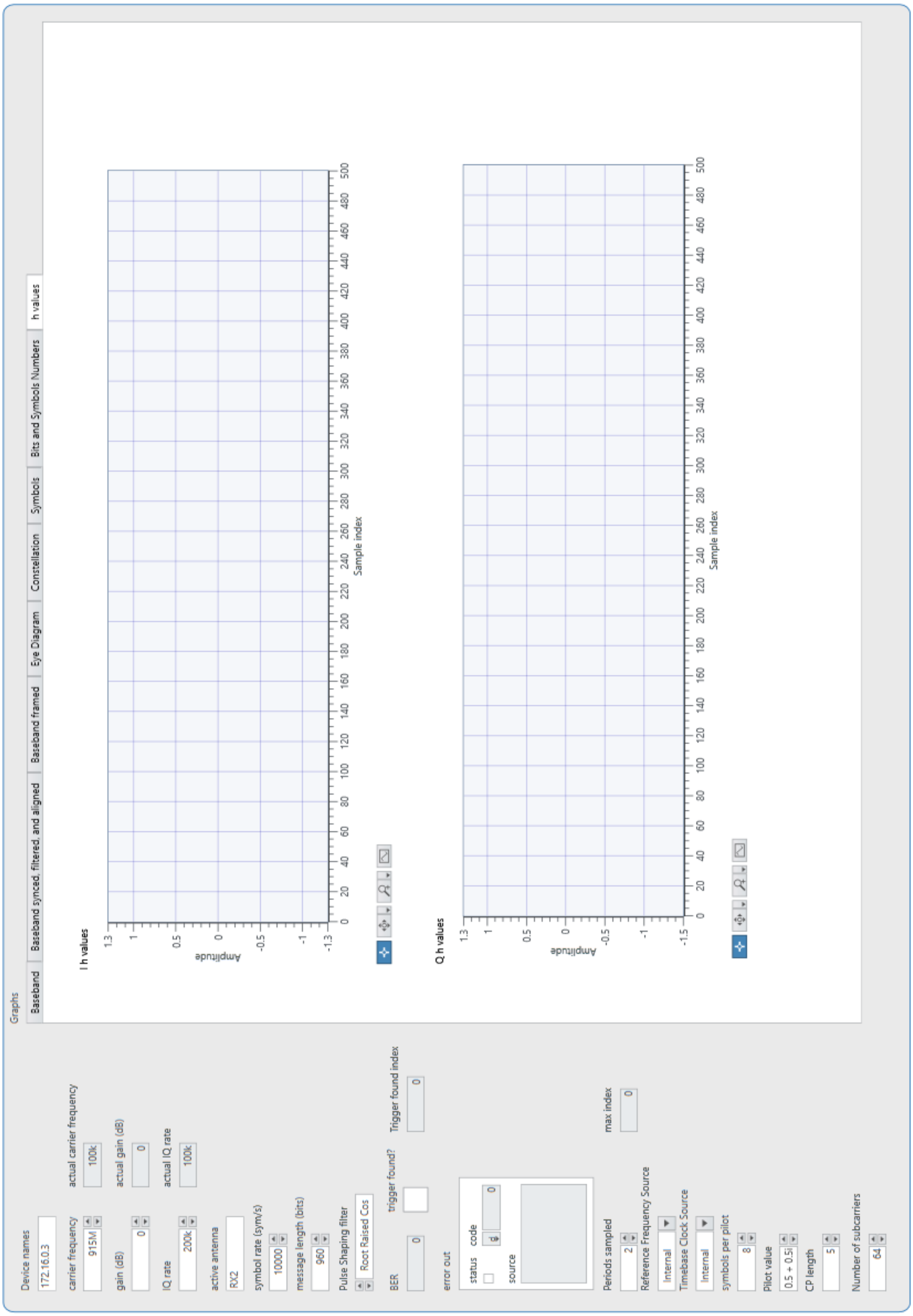


FIGURE C.3: A diagram showing the blocks in the OFDM receiver. The diagram is made of three rows. The purple area in the first row contains the set up of the USRP, the red area contains a “while” loop that matched filters, aligns, samples, normalises, and DBPSK decodes the signal to find the start of the message. The green areas in the first and second rows set up the output graphs on the front panel. The blue area in the second row uses the pilot symbols and interpolation to estimate the channel. The grey area in the second row uses the estimated channel to recover the data. The third row decodes the symbols to bits by removing the cyclic prefix and running an FFT on the symbols. This is compared with the original bit stream to calculate the BER.



Device names 172.16.0.3

carrier frequency 915M

actual carrier frequency 100k

gain (dB) 0

actual gain (dB) 0

IQ rate 200k

actual IQ rate 100k

active antenna RX2

symbol rate (sym/s) 10000

message length (bits) 960

Pulse Shaping filter Root Raised Cos

BER 0

trigger found? ☐

Trigger found index 0

error out

status ☐

code 0

source

Periods sampled 2

max index 0

Reference Frequency Source Internal

Timebase Clock Source Internal

symbols per pilot 8

Pilot value 0.5 + 0.5i

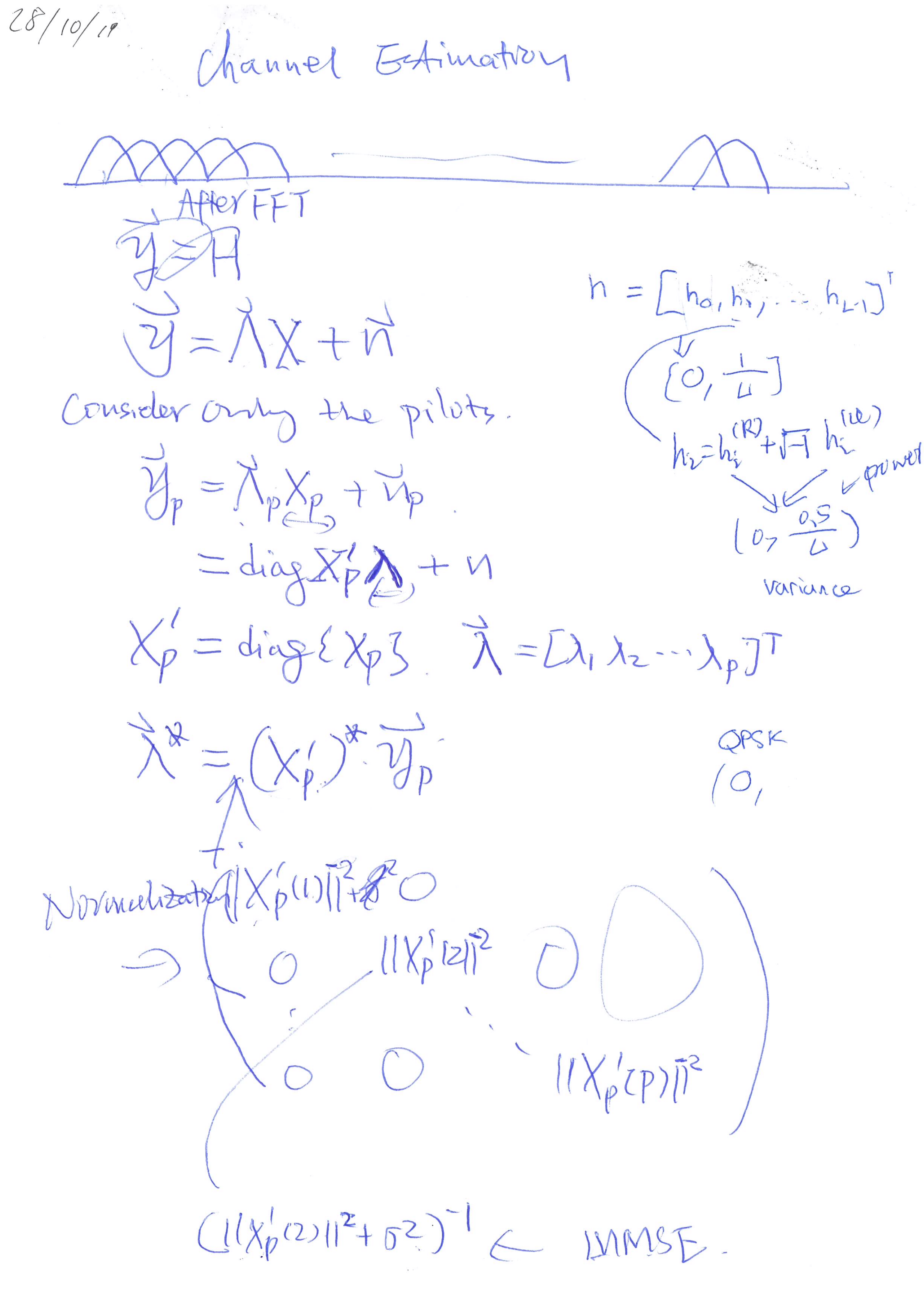
CP length 5

Number of subcarriers 64

Figure C.4: A diagram showing the front panel of the OFDM receiver. The left hand side contains parameters for the user to enter to configure the USRP. The main section of the panel contains graphs and diagrams.

Appendix D

Channel Estimation



28/10/19

Channel Estimation

After FFT

$\vec{y} = H$

$\vec{y} = \vec{\Lambda} X + \vec{n}$

Consider only the pilots.

$\vec{y}_p = \vec{\Lambda}_p X_p + \vec{n}_p$

$= \mathrm{diag}\, X_p' \vec{\Lambda} + n$

$X_p' = \mathrm{diag}\{X_p\}$ $\vec{\lambda} = [\lambda_1\ \lambda_2 \cdots \lambda_p]^T$

$\vec{\lambda}^* = (X_p')^* \cdot \vec{y}_p$

$h = [h_0, h_1, \cdots h_{L-1}]^T$

$(0, \frac{1}{L})$

$h_i = h_i^{(R)} + \sqrt{-1}\, h_i^{(I)}$

power

$(0, \frac{0.5}{L})$

variance

QPSK

$(0,$

Normalization

$$\begin{pmatrix} \|X_p'(1)\|^2+\sigma^2 & & 0 \\ 0 & \|X_p'(2)\|^2 & 0 \\ \vdots & & \ddots \\ 0 & 0 & \|X_p'(P)\|^2 \end{pmatrix}$$

$(\|X_p'(2)\|^2 + \sigma^2)^{-1}$ ← MMSE.

FIGURE D.1: A derivation of time domain channel estimation, provided by Lie-Liang Yang (continues in following page).

$$\vec{h}_t = [h_0, h_1, \ldots, h_{L-1}]^T \quad L=5.$$

$$\vec{h}_f = FFT\cdot(\Psi_L \cdot \vec{h}_t).$$

$\vec{\Psi}_L$: First L columns of identity matrix I_N.

$$\vec{h}_f = \begin{bmatrix} \vec{h}_f(1) \\ h_f(2) \\ h_f(3) \\ \vdots \\ h_f(N) \end{bmatrix} = FFT\cdot(\Psi_L \vec{h}_t) = F\Psi_L\vec{h}_t \qquad Ⓐ$$

Pilots

$$\underbrace{\vec{h}_f(P)} = \underbrace{F_P}\,\Psi_L \underbrace{\vec{h}_t}$$

obtained from FFT matrix by keeping those rows corresponding to the pilots.

$$\underbrace{\vec{h}_t} = \Psi_L^T F_P^H \cdot \vec{h}_f(P).$$

Time-domain channel estimated.

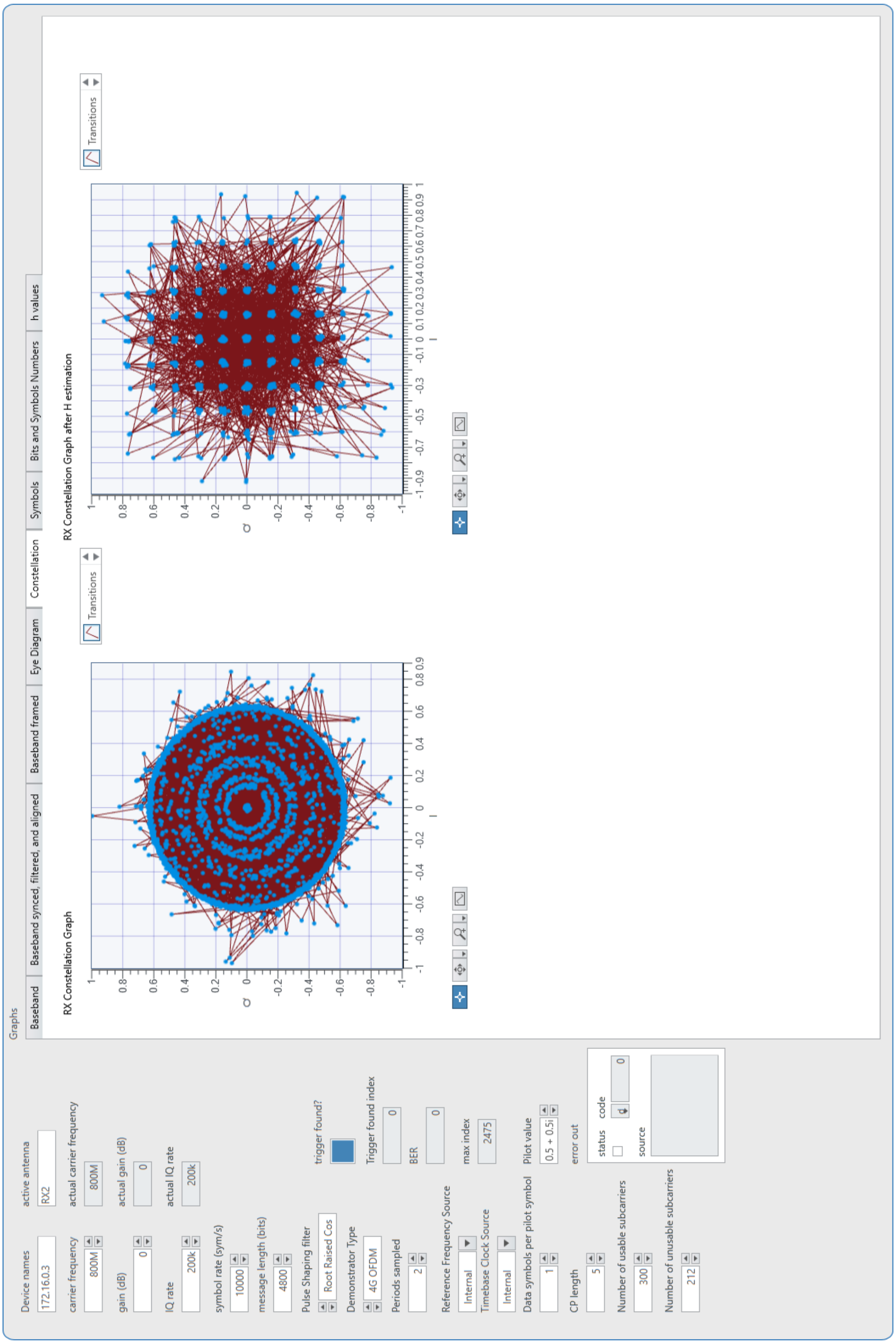
~~Then for the ith subcarriers~~

Use (A) again to obtain all unknown channels.

Appendix E

LabVIEW Demonstrator

The diagram figures below have been formatted to fit on an A4 page. To view these diagrams in more detail, please see the files in the electronic appendix H.



Device names: 172.16.0.3

active antenna: RX2

carrier frequency: 800M

actual carrier frequency: 800M

gain (dB): 0

actual gain (dB): 0

IQ rate: 200k

actual IQ rate: 200k

symbol rate (sym/s): 10000

message length (bits): 4800

Pulse Shaping filter: Root Raised Cos

trigger found?

Demonstrator Type: 4G OFDM

Trigger found index: 0

Periods sampled: 2

BER: 0

Reference Frequency Source: Internal

max index: 2475

Timebase Clock Source: Internal

Data symbols per pilot symbol: 1

Pilot value: 0.5 + 0.5i

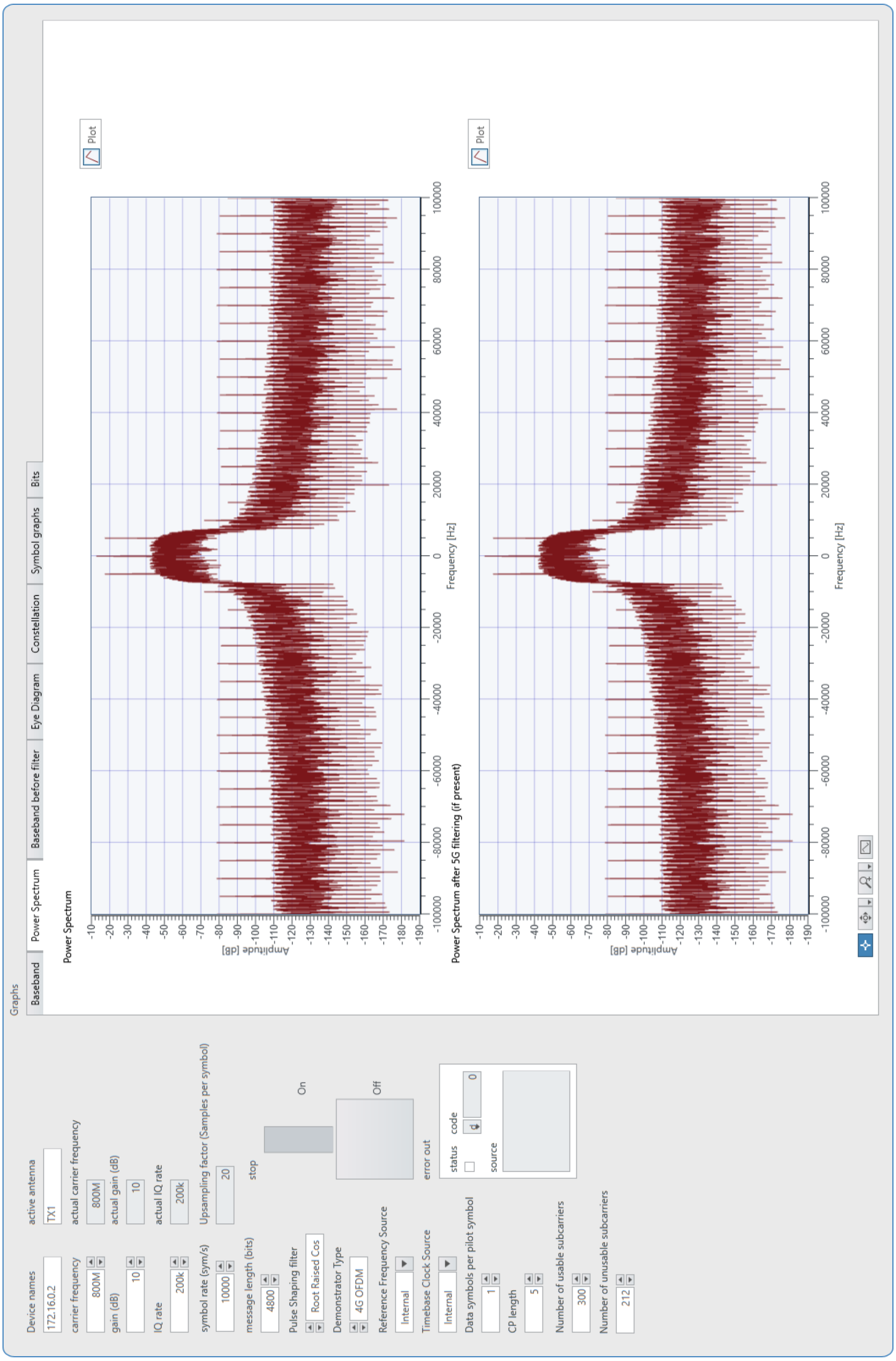
CP length: 5

error out: status ☐ code 0 source

Number of usable subcarriers: 300

Number of unusable subcarriers: 212

Figure E.1: A diagram showing the front panel of the demonstrator transmitter. The left hand side contains parameters for the user to enter to configure the USRP. The main section of the panel contains graphs and diagrams.



Device names: 172.16.0.2
active antenna: TX1
carrier frequency: 800M
actual carrier frequency: 800M
gain (dB): 10
actual gain (dB): 10
IQ rate: 200k
actual IQ rate: 200k
symbol rate (sym/s): 10000
Upsampling factor (Samples per symbol): 20
message length (bits): 4800
Pulse Shaping filter: Root Raised Cos
Demonstrator Type: 4G OFDM
Reference Frequency Source: Internal
Timebase Clock Source: Internal
Data symbols per pilot symbol: 1
CP length: 5
Number of usable subcarriers: 300
Number of unusable subcarriers: 212
error out: status ☐ code 0

Figure E.2: A diagram showing the front panel of the demonstrator receiver. The left hand side contains parameters for the user to enter to configure the USRP. The main section of the panel contains graphs and diagrams.

Appendix F

Additional Results

In MATLAB, we analysed the effect of CFO and designed a mitigation technique for CFO based on pilot correction. The results for the performance of the original mitigation technique is shown in Figure F.1. This model can correct CFO of 500Hz. When the CFO increases however the performance worsens drastically as the BER reaches high error floors. From Figure F.2 and Figure F.3, CFO causes a fixed phase offset, an offset relative to the origin and noise. An increases in the CFO increases these effect causing higher phase offset, a larger offset with respect to the origin and noise with stronger magnitude. The large constellation point in the constellation diagram corresponds to all the pilot symbols which are given the same magnitude.

The symbols after the pilot based correction are shown in Figure F.4. Although the phase offset and the offset relative to the origin is reduced, there remains some offset as well as noise which causes interference and hinders the performance.

In order to get rid of the offset, we chose to use two batches pilot symbols located at different constellation points. The performance of this improved system is shown in Figure F.5. However there is a tradeoff, due to ICI each subcarrier has an influence on the other subcarriers. Hence having two different batches of pilot symbols causes some symbols to tend towards one of the values of the pilot batch and other symbol to tend towards the other batch. As a result, this creates two separate clusters of data symbols at each constellation point increasing the amount of noise at the receiver. This effect is shown in Figure F.6 and Figure F.7. The higher the CFO is the higher the ICI will be and as a result the noise will cause the performance to deteriorate as is shown in Figure F.5.

This mitigation technique has limitations as it does not get rid of the noise induced by the ICI due to the CFO. However, this mitigation technique allows our system to be robust against CFO of up to 1kHz. Using our mitigation technique our system is able to accurately recover data corrupted by moderate CFO.

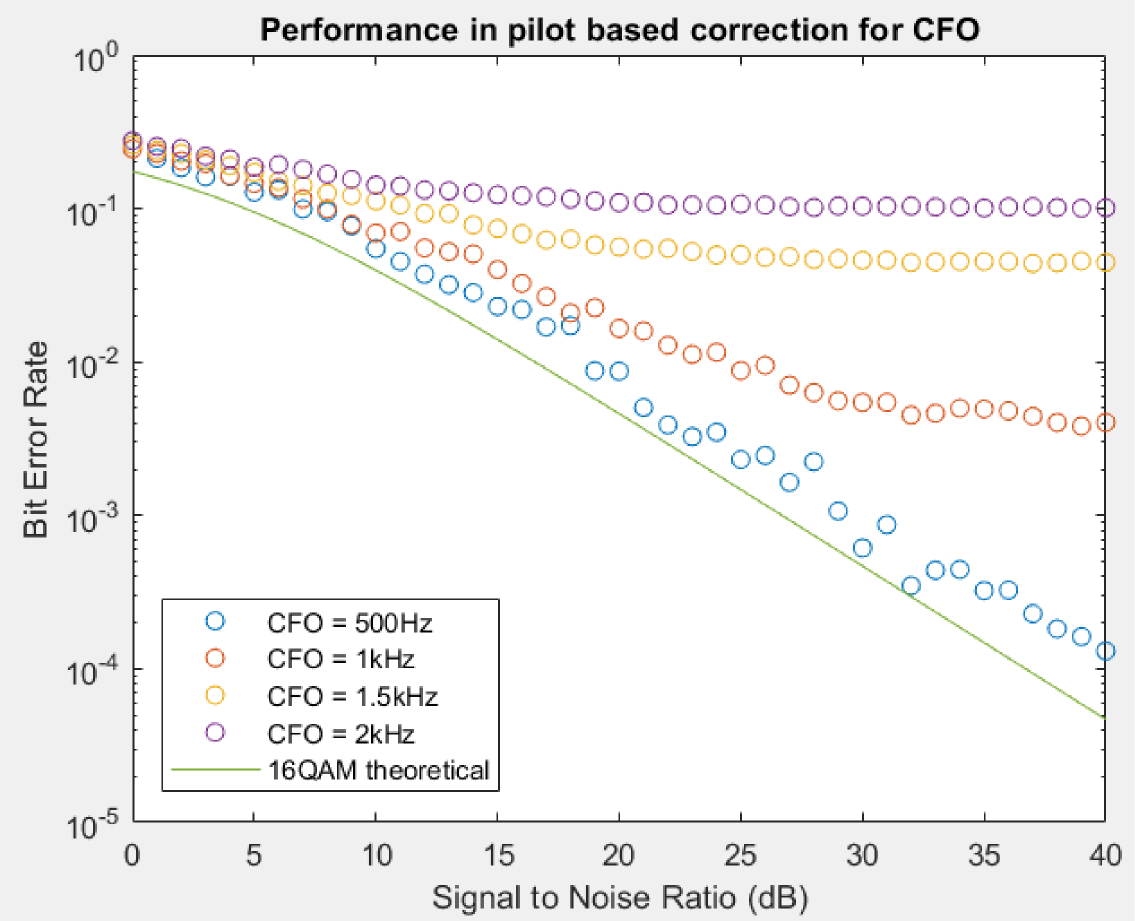


FIGURE F.1: BER in terms of SNR for OFDM system induced with varying CFO

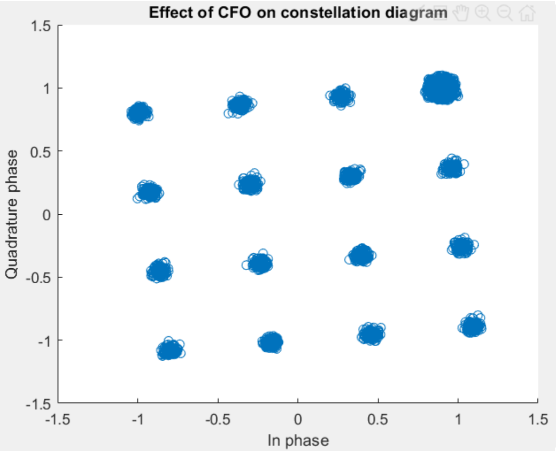


FIGURE F.2: Constellation diagram of 16QAM symbols induced with a CFO of 500Hz.

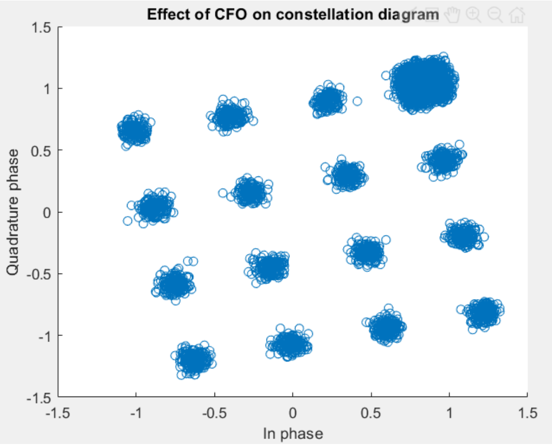


FIGURE F.3: Constellation diagram of 16QAM symbols induced with a CFO of 1000Hz

The reason why the BER in terms of SNR plot in Figure F.1 and Figure F.5 never reach the theoretical 16QAM performance is because the channel estimation method is based on pilot. As mentioned in Chapter 6.5, the error in the estimation of the values due to the noise affecting the pilots causes some interference and slightly reduces the

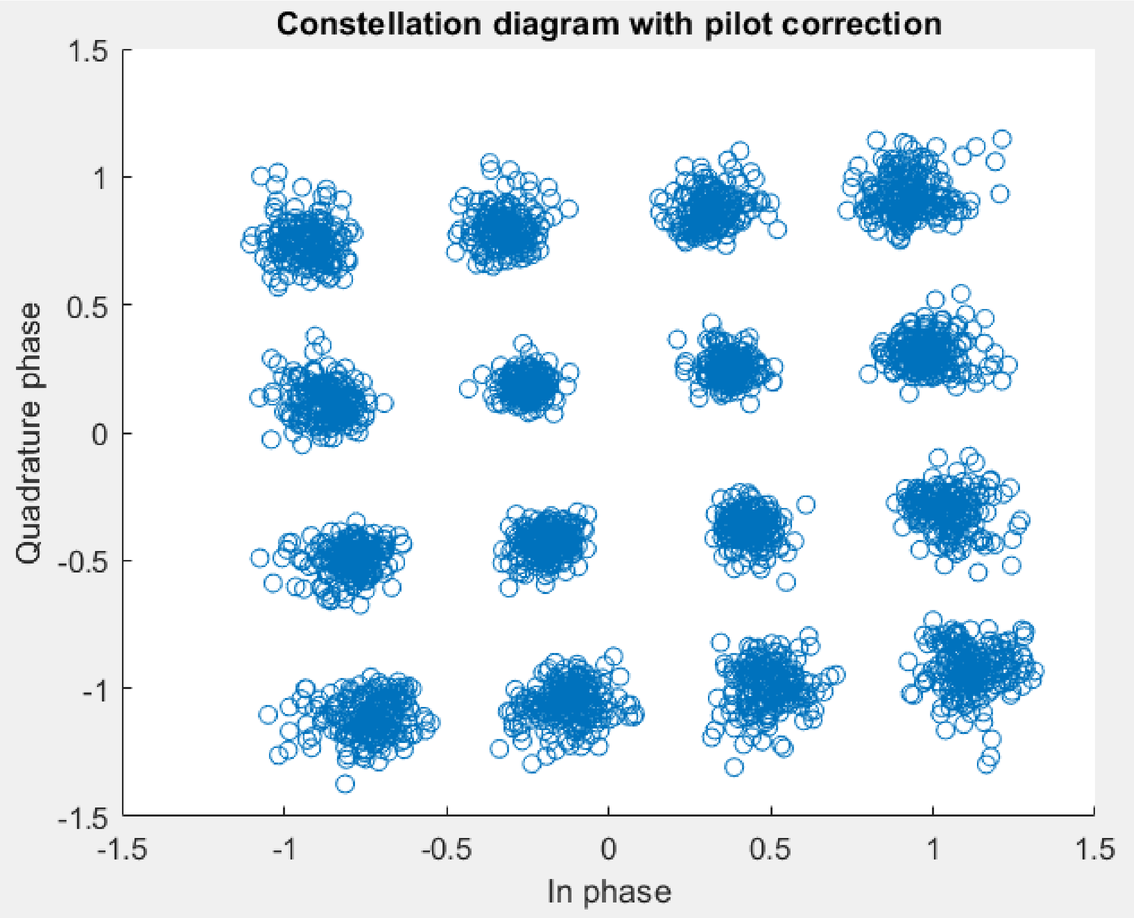


Figure F.4: Corrected constellation diagram with CFO of 1000Hz using pilot based correction

performance of the system.

FIGURE F.5: BER in terms of SNR for OFDM system induced with varying CFO using two batches of pilots with different magnitudes

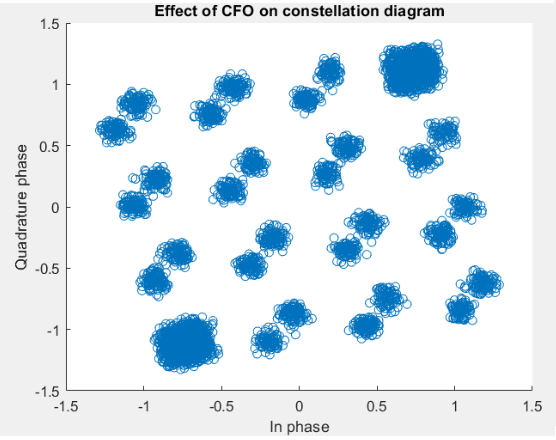


FIGURE F.6: Constellation diagram of 16QAM symbols induced with a CFO of 1000Hz using two batches of pilots with different magnitudes.

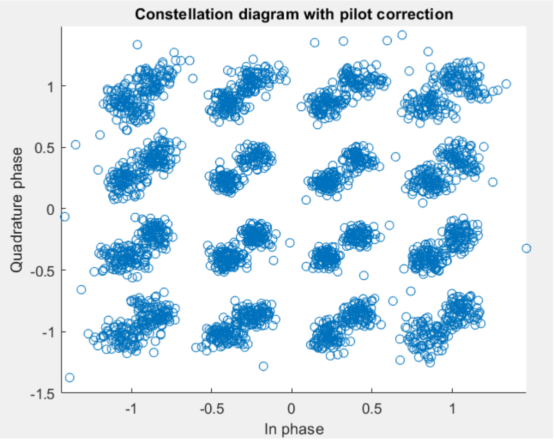


FIGURE F.7: Corrected constellation diagram of 16QAM symbols induced with a CFO of 1000Hz using two batches of pilots with different magnitudes

Appendix G

Filter Response

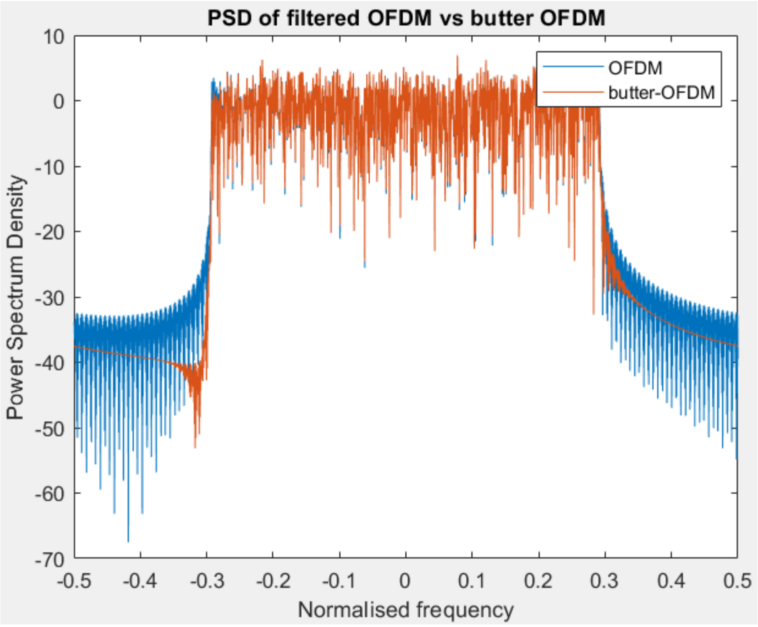


Figure G.1: Power spectral density of OFDM symbol filtered using a Butterworth filter.

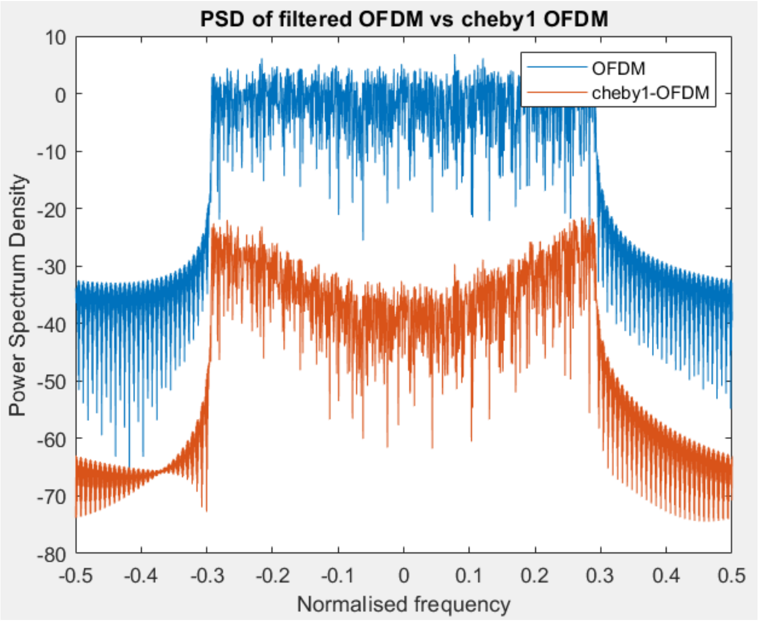


FIGURE G.2: Power spectral density of OFDM symbol filtered using a Chebyshev type 1 filter.

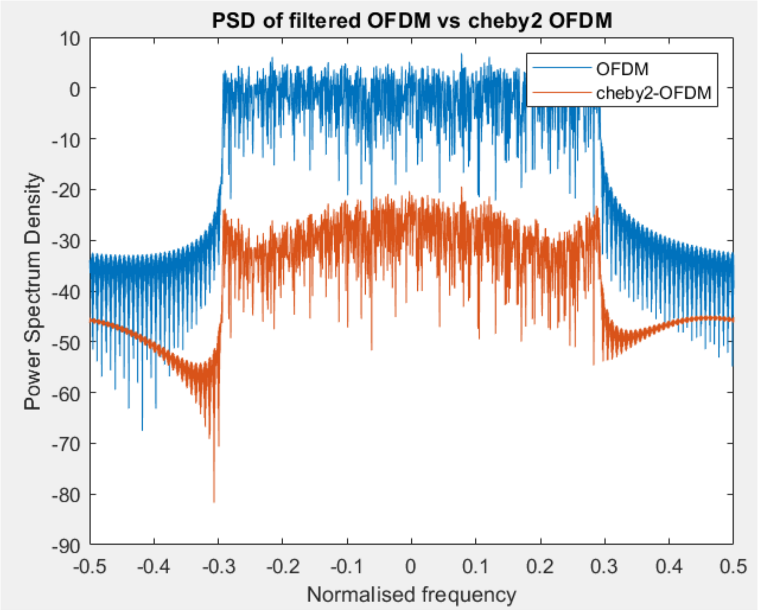


FIGURE G.3: Power spectral density of OFDM symbol filtered using a Chebyshev type 2 filter.

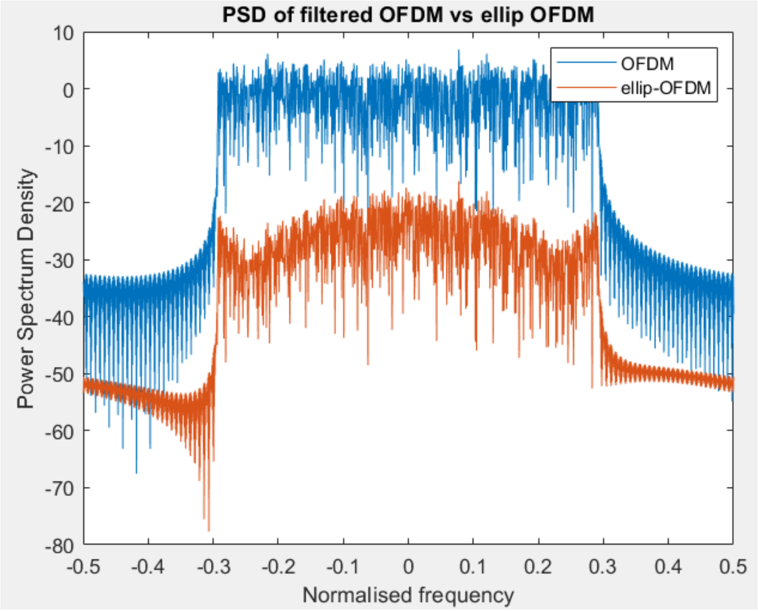


Figure G.4: Power spectral density of OFDM symbol filtered using an elliptic filter.

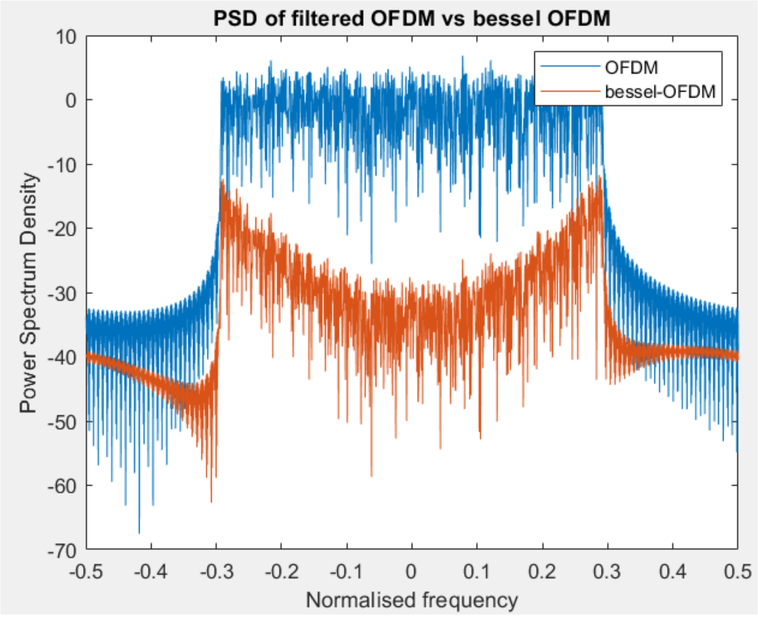


Figure G.5: Power spectral density of OFDM symbol filtered using a Bessel filter.

Appendix H

Electronic Appendix Index

This appendix includes a list of all of the files located in the report's accompanying electronic appendix. The location of each file is displayed, along with a brief description of the file's purpose when required.

- gdp43/ .... Root folder
  - tree.pl .... Script to produce this tree
  - tree.txt
  - Comms_matlab .... Coursework files from previous modules to refresh MATLAB skills
    - Elec1207
      - Dynamic
        - m01_GenerateSignal.m
        - m02_AddCosine.m
        - m03_MultiplyCosine.m
        - m04_AnalogueModulation.m
      - Static
        - func_dequantise.m
        - func_low_pass_filter.m
        - func_manchester_decode.m
        - func_manchester_encode.m
        - func_nrz_decode.m
        - func_nrz_encode.m
        - func_pam.m
        - func_ppm.m
        - func_pulse_coded_demodulation.m
        - func_pulse_coded_modulation.m
        - func_pwm.m
        - func_quantise.m
        - func_random_signal.m
        - func_reconstruction_filter.m
        - func_sample.m
        - main01_signals.m
        - main02_pm.m
        - main03_fm.m
        - main04_am.m
        - main05_dsbsc.m
        - main06_qam.m
        - main07_ssbsc.m
        - main08_sampling.m
        - main09_pam.m
        - main10_pwm.m
        - main11_ppm.m
        - main12_quantisation.m
        - main13_pcm.m
        - main14_nrz.m

- `gdp43/` . . . . Root folder
  - `Comms_matlab` . . . . Coursework files from previous modules to refresh MATLAB skills
    - `Elec1207`
      - `Static`
        - `main15_manchester.m`
        - `main16_ook.m`
        - `main17_bpsk.m`
        - `main18_bfsk.m`
        - `main19_mask.m`
        - `main20_mpsk.m`
        - `main21_mfsk.m`
        - `main22_digital_qam.m`
        - `__MACOSX`
          - `._func_pam.m`
          - `._func_ppm.m`
          - `._func_pwm.m`
          - `._main01_signals.m`
          - `._main05_dsbsc.m`
          - `._main08_sampling.m`
          - `._main09_pam.m`
          - `._main10_pwm.m`
          - `._main11_ppm.m`
          - `._main12_quantisation.m`
          - `._main19_mask.m`
          - `._main22_digital_qam.m`
    - `Elec2220`
      - `AM.m`
      - `BER_bpsk.m`
      - `PLL.m`
      - `qpsk_system_demo.m`
    - `Maunder Coursework`
      - `dequantise.m`
      - `desample.m`
      - `high_pass_filter.m`
      - `low_pass_filter.m`
      - `main.m`
      - `pcm_decode.m`
      - `pcm_encode.m`
      - `quantise.m`
      - `raised_cosine_filter.m`

- `gdp43/` ..... Root folder
  - `Comms_matlab` ..... Coursework files from previous modules to refresh MATLAB skills
    - `Maunder Coursework`
      - `receiver.m`
      - `receiver_BPSK.m`
      - `root_raised_cosine_filter.m`
      - `sample.m`
      - `Thumbs.db`
      - `transmitter.m`
      - `transmitter_BPSK.m`
  - `Management` ..... Location of project management files
    - `gantt_chart.pdf`
    - `gantt_chart_2.pdf`
    - `GDP43_GDP_ELEC6247_gdpproposalform19_meh_lly.rtf`
    - `Hardware loan.docx`
    - `PERT_chart.pptx`
    - `PERT_chart_screenshot.docx`
    - `Project Specification and Plan.docx`
    - `Project Specification and Plan.pdf`
    - `Project_Gantt_Chart.xlsx`
    - `Risk Management.docx`
    - `risk_management.pdf`
    - `skills_audit.docx`
    - `skills_audit.pdf`
  - `matlab` ..... Location of all MATLAB files created in this project
    - `Analog_channel_16QAM.m` ..... 16QAM in time domain
    - `Analog_OFDM_16QAM.m` ..... 16QAM multi carrier modulation
    - `channel_estimation.m` ..... LS channel estimation using one value for pilots
    - `Channel_estimation_random.m` .. LS channel estimation using random values for pilots
    - `channel_estimation_two_pilots.m` . LS channel estimation using two values for pilots
    - `Channel_H.m`
    - `Channel_matrix.m` ..... Time domain channel estimation
    - `Channel_test.m` ..... 16QAM OFDM over Rayleigh fading channel
    - `Channel_test2.m` ..... QPSK OFDM over Rayleigh fading channel
    - `Channel_test3.m` ..... BPSK OFDM over Rayleigh fading channel
    - `Channel_test4.m` ..... 64QAM OFDM over Rayleigh fading channel
    - `clipping.m` ..... Clipped time domain message

- `gdp43/` .... Root folder
  - `matlab` .... Location of all MATLAB files created in this project
    - `CP.m` .... Analysis of small CP length
    - `filtered_channel.m`
    - `filtered_channel_.m` . Performance in Rayleigh fading channel when clipped
    - `filtered_clipping.m` .... Performance in AWGN channel when clipped
    - `Filtered_OFDM.m` .... PSD for 4G OFDM and 5G f-OFDM
    - `filter_mitigation.m` Plot the PSD of an OFDM symbol using Butterworth filter
    - `filter_multiple.m`. Plot the PSD of an OFDM symbol using multiple filters
    - `filter_response.m` .... Plot the theoretical response of multiple filters
    - `frequency_localised_f_ofdm.m` .... Multiple subband f-OFDM Tx
    - `frequency_offset.m` .... Analysis of CFO with no correction
    - `frequency_offset_estimate.m` .... Using pilots to correct CFO
    - `frequency_offset_estimate_random_pilots.m` Using randomly placed pilots to correct CFO
    - `frequency_offset_estimate_two_pilots.m` Using two constellation point for pilots to correct CFO
    - `Frequency_selective_channel.m`
    - `math_test.m`
    - `Matlab_Raychan.m`
    - `MEHcode.m` .... BPSK performance in AWGN
    - `MEH_16QAM_code.m` .... 16QAM performance in AWGN channel
    - `MEH_64QAM_code.m` .... 64QAM performance in AWGN channel
    - `MEH_Analog_OFDM_code.m`
    - `MEH_OFDM_analog_code.m`
    - `MEH_OFDM_channel.m`
    - `MEH_OFDM_code.m`
    - `MEH_OFDM_QPSK.m` .... QPSK OFDM in AWGN channel
    - `MEH_QPSK_code.m` .... QPSK performance in AWGN channel
    - `MMSE.m` .... MMSE based channel estimation
    - `OFDM_rayleigh_flat.m`
    - `results_0.mat` .... File used to store results
    - `testing.m`
    - `time_synchronisation.m` .... Time synchronisation offset correction
  - `Meeting_screenshots` .... Draft figures brought up in supervisor meetings
    - `BER curves screeshots.docx`
    - `channel_estimation_screenshots.docx`
    - `clipped_message_screenshot.docx`
    - `effect_of_CP_screenshot.docx`
    - `email_update_figures.pptx`

- gdp43/ .... Root folder
  - Meeting_screenshots .... Draft figures brought up in supervisor meetings
    - filtered_ofdm_screenshots.docx
    - Screenshots LS channel estimation.docx
    - Screenshots_Rayleigh_perfect_detection.docx
  - Minutes .... Minutes taken from team meetings and supervisor meetings
    - 04_12_19.docx
    - 06_10_19.docx
    - 06_11_19.docx
    - 06_11_19.pptx
    - 07_10_19.docx
    - 08_10_19.docx
    - 09_10_19.docx
    - 13_11_19.docx
    - 13_11_19.pptx
    - 14_10_19.docx
    - 15_10_19.docx
    - 16_10_19.docx
    - 21_10_19.docx
    - 22_10_19.docx
    - 23_10_19.docx
    - 27_11_19.docx
    - 27_11_19.pptx
    - 28_10_19.docx
    - 28_10_19.pptx
    - 29_10_19.docx
    - 30_09_19.docx
  - NI_labs .... All of the LabVIEW files used in the project
    - AMonSubcarrier.gvi
    - BER.xlsx
    - Communication Systems.lvcodedb
    - Communication Systems.lvproject
    - Communication Systems.lvprojectcache
    - Communication Systems_Text_en-US.lvindexcache
    - intro_to_comms_with_ni_usrp.pdf .... Tutorial used to gain LabVIEW experience
    - NI USRP and LabVIEW Comms Getting Started.pdf
    - NI USRP2922 Getting Started.pdf
    - ofdm_results.pptx
    - phase error.gtype
    - screenshots.pptx

- gdp43/ .... Root folder
  - NI_labs .... All of the LabVIEW files used in the project
    - selector.gtype
    - selector_2.gtype
    - solutions_intro_comm_sys_vis_zip.html
    - 16QAM
      - 16QAM.zip
      - 16QAMRx.gvi
      - 16QAMRxPilot.gvi
      - 16QAMRxPilotRM.gvi
      - 16QAMRxPLL.gvi
      - 16QAMTx.gvi
      - 16QAMTxPilot.gvi
      - 16QAMTxRx.gvi
    - 6217lab
      - decode.m
      - DemodulateSubVI.vi
      - Downsample (SubVI).vi
      - DPSK_controls.ctl
      - DPSK_rx.vi
      - DPSK_rx_states.ctl
      - DPSK_tx.vi
      - DPSK_tx_0.vi
      - DPSK_tx_states.ctl
      - PSK_demod (SubVI).vi
    - BasicUSRPLabs
      - AddFrameHeader(Complex).gvi
      - AddFrameHeader(Real).gvi
      - AddLongFrameHeader(Complex).gvi
      - Channel.gvi
      - FrameSync(Complex).gvi
      - FrameSync(Real).gvi
      - LongFrameSync(Complex).gvi
      - PulseAlign(complex).gvi
      - PulseAlign(real).gvi
    - Cluster Constant.gtype
      - Cluster Constant.gtype
    - DBPSK_16QAM .... Used in Chapter 5.2.1 and Appendix B
      - AddDFrameHeader(Complex).gvi
      - DBPSK_16QAMTxPilot.gvi
      - DBPSK_16QAMTxPilotReport.gvi

- `gdp43/` ...... Root folder
  - `NI_labs` ...... All of the LabVIEW files used in the project
    - `DBPSK_16QAM` ...... Used in Chapter 5.2.1 and Appendix B
      - `DBPSK_16QAMTxRx.gvi`
      - `DBSPK_16QAMRxPilot.gvi`
      - `DBSPK_16QAMRxPilotReport.gvi`
      - `DFrameSync(Complex).gvi`
    - `Demonstrator` .... Demonstrator files, used in Chapter 5.2.4 and Appendix E
      - `RxDemonstrator.gvi` ...... Receiver code
      - `TxDemonstrator.gvi` ...... Transmitter code
    - `ExternalFiles`
      - `AC & DC Estimator.gvi`
      - `Basic Multitone.gvi`
      - `Butterworth Filter (DBL).gvi`
      - `Chebyshev Filter (CDB).gvi`
      - `Chebyshev Filter (DBL).gvi`
      - `FFT Power Spectrum and PSD for 1 Chan2.gvi`
      - `FFT Power Spectrum for 1 Chan (CDB)2.gvi`
      - `Impulse Pattern.gvi`
      - `LO Adjust.gvi`
      - `Mean DBL.gvi`
      - `Median Filter2.gvi`
      - `Normalize Vector.gvi`
      - `Quick Scale 1D.gvi`
      - `Ramp Pattern by Samples2.gvi`
      - `Sine Waveform.gvi`
      - `Std Deviation and Variance.gvi`
    - `fOFDM`
      - `fOFDM_DBPSK_16QAMTxPilot.gvi`
      - `fOFDM_DBPSK_16QAMTxPilotFailedGuard.gvi`
      - `fOFDM_DBSPK_16QAMRxPilot.gvi`
      - `fOFDM_DBSPK_16QAMRxPilotFailedGuard.gvi`
    - `Lab10_EyeDiagram`
      - `2D DBL to 1D Cluster.gvi`
    - `Lab11_Equalization`
      - `11BPSKRxTemplate.gvi`
      - `11BPSKRxTemplate_Old_phase_sync.gvi`
      - `11BPSKTxTemplate.gvi`
      - `EqualizerTemplate.gvi`
    - `Lab12_QPSK`
      - `MapDataTemplate.gvi`

- `gdp43/` .... Root folder
  - `NI_labs` .... All of the LabVIEW files used in the project
    - `Lab12_QPSK`
      - `QPSKEqualizerTemplate.gvi`
      - `QPSKRxTemplate.gvi`
      - `QPSKRxTemplateNoEqualiser.gvi`
      - `QPSKTxRx.gvi`
      - `QPSKTxTemplate.gvi`
      - `QPSKTxTemplateNoEqualiser.gvi`
    - `Lab1_Intro`
      - `readme.txt`
    - `Lab2_AM`
      - `Lab2RxTemplate.gvi`
      - `Lab2TxTemplate - Copy.gvi`
      - `Lab2TxTemplate.gvi`
    - `Lab3_FDM`
      - `Lab3RxTemplate.gvi`
      - `Lab3TxTemplate.gvi`
    - `Lab4_ImageRejection`
      - `ChebyshevHilbert.gvi`
    - `Lab5_DSBSC`
      - `Lab5RxTemplate.gvi`
      - `Lab5TxTemplate.gvi`
    - `Lab6_FM`
      - `Lab6RxTemplate.gvi`
      - `Lab6TxTemplate.gvi`
    - `Lab7_ASK`
      - `ASKRxTemplate.gvi`
      - `ASKTxTemplate.gvi`
    - `Lab8_FSK`
      - `FSKRxTemplate.gvi`
      - `FSKTxTemplate.gvi`
    - `Lab9_PSK`
      - `BPSKRxTemplate.gvi`
      - `BPSKTxRx.gvi`
      - `BPSKTxTemplate.gvi`
      - `DBPSKRxTemplate.gvi`
      - `DBPSKTxRx.gvi`
      - `DBPSKTxRx2.gvi`
      - `DBPSKTxTemplate.gvi`

- `gdp43/` .... Root folder
  - `NI_labs` .... All of the LabVIEW files used in the project
    - `OFDM` .... Used in Chapter 5.2.2 and Appendix C
      - `DFrameSyncOFDM(Complex).gvi`
      - `OFDMRxMathscript.gvi`
      - `OFDMTxMathscript.gvi`
      - `OFDMTxRx.gvi`
      - `OFDMTxRxMathscript.gvi`
      - `OFDM_DBPSK_16QAMTxPilot.gvi`
      - `OFDM_DBPSK_16QAMTxPilotFrame.gvi`
      - `OFDM_DBPSK_16QAMTxPilotReport.gvi`
      - `OFDM_DBSPK_16QAMRxPilot.gvi`
      - `OFDM_DBSPK_16QAMRxPilotFrame.gvi`
      - `OFDM_DBSPK_16QAMRxPilotReport.gvi`
    - `PhaseSync`
      - `Freq Off Corr2009.vi`
      - `InsertPilots.gvi`
      - `mod Remove Coarse Frequency Offset.gvi`
      - `mod_Apply_Frequency Offset.gvi`
      - `mod_Continuous_BB-QAM generation.gvi`
      - `MT_Demodulate QAM.gvi`
      - `QAM_Rx.gvi`
      - `QAM_Tx.gvi`
      - `Rx.gvi`
      - `RxChannelEstimation.gvi`
      - `Tx.gvi`
      - `TxChannelEstimation.gvi`
    - `QPSK`
      - `.DS_Store`
      - `Add Noise.gvi`
      - `Carrier Frequency Offset.gvi`
      - `Fading.gvi`
      - `QPSK Demod.gvi`
      - `QPSK Eb.gvi`
      - `QPSK Eq.gvi`
      - `QPSK FIR.gvi`
      - `QPSK Mod.gvi`
      - `QPSK Pilots.gvi`
      - `QPSK Rx.gvi`
      - `QPSK Simulate.gvi`

- `gdp43/` .... Root folder
  - `NI_labs` .... All of the LabVIEW files used in the project
    - `QPSK`
      - `QPSK Sync.gvi`
      - `QPSK Tx.gvi`
      - `QPSK.lvcodedb`
      - `QPSK.lvproject`
      - `QPSK.lvprojectcache`
      - `QPSK.lvsuo`
      - `Random Delay.gvi`
    - `QPSK_new`
      - `Add Noise.gvi`
      - `Carrier Frequency Offset.gvi`
      - `Fading.gvi`
      - `QPSK Demod.gvi`
      - `QPSK Eb.gvi`
      - `QPSK Eq.gvi`
      - `QPSK FIR.gvi`
      - `QPSK Mod.gvi`
      - `QPSK Pilots.gvi`
      - `QPSK Rx.gvi`
      - `QPSK Simulate.gvi`
      - `QPSK Sync.gvi`
      - `QPSK Tx.gvi`
      - `QPSK.lvcodedb`
      - `QPSK.lvproject`
      - `QPSK.lvsuo`
      - `Random Delay.gvi`
  - `Poster`
    - `Guidelines.url`
    - `Poster.pptx`
  - `Report` .... All files used to create the project report
    - `count.html`
    - `Definitions.tex`
    - `ECS.bib`
    - `ecsgdp.cls`
    - `GDP.pdf`
    - `GDP.tex`
    - `Mark scheme.url`
    - `texcount lines and git log.txt`
    - `texcount.pl`

- `gdp43/` .... Root folder
  - `Report` .... All files used to create the project report
    - `Appendices`
      - `Appendix16qamlabview.tex`
      - `Appendixbackground.tex`
      - `Appendixchannelestimation.tex`
      - `Appendixcriticalpath.tex`
      - `Appendixcustomeremail.tex`
      - `Appendixdemonstratorlabview.tex`
      - `AppendixElectronic.tex`
      - `Appendixfilterresponse.tex`
      - `Appendixganttchart.tex`
      - `Appendixgitlog.tex`
      - `Appendixminutes.tex`
      - `Appendixofdmlabview.tex`
      - `Appendixriskmanagement.tex`
      - `Appendixskillsaudit.tex`
    - `Chapters`
      - `Approach.tex`
      - `Background.tex`
      - `Conclusions.tex`
      - `Introduction.tex`
      - `Management.tex`
      - `Objectives.tex`
      - `Resources.tex`
      - `Results.tex`
    - `Figures`
      - `06_10_19-2.pdf`
      - `06_10_19.pdf`
      - `06_11_19-2.pdf`
      - `06_11_19.pdf`
      - `07_10_19-2.pdf`
      - `07_10_19.pdf`
      - `08_10_19.pdf`
      - `09_10_19.pdf`
      - `13_11_19-2.pdf`
      - `13_11_19.pdf`
      - `14_10_19-2.pdf`
      - `14_10_19.pdf`
      - `15_10_19.pdf`

- gdp43/ .... Root folder
  - Report .... All files used to create the project report
    - Figures
      - 16qamrxdiagram.png
      - 16qamrxpanel.png
      - 16qamtxdiagram.png
      - 16qamtxpanel.png
      - 16_10_19.pdf
      - 21_10_19-2.pdf
      - 21_10_19.pdf
      - 22_10_19.pdf
      - 23_10_19.pdf
      - 27_11_19-2.pdf
      - 27_11_19.pdf
      - 28_10_19-2.pdf
      - 28_10_19.pdf
      - 29_10_19-2.pdf
      - 29_10_19.pdf
      - 30_09_19.pdf
      - 5gfilter.PNG
      - 5G_f_ofdm.png
      - 5G_vs_4G.png
      - ber_vs_cfo.png
      - blocktype.png
      - cfo_good_bad.png
      - channel_estimation-2.pdf
      - channel_estimation.pdf
      - chapter_authors.docx
      - chapter_authors.PNG
      - clipped_message.png
      - clipped_performance1.png
      - clipped_performance5.png
      - clipped_performance6.png
      - clipped_performance7.png
      - clipped_performance8.png
      - clipped_performance9.png
      - clipping_PAPR.png
      - comb-type.png
      - cp_matlab.png
      - critical_path.png
      - cyclic_prefix.JPG

- gdp43/ .... Root folder
  - Report .... All files used to create the project report
    - Figures
      - demonstratorrxpanel.png
      - demonstratortxpanel.png
      - filter_analog.png
      - frequency_offset.png
      - frequency_offset_constellation.png
      - f_ofdm_receive.png
      - f_ofdm_transmit.png
      - gantt_chart.pdf
      - gantt_chart_2.pdf
      - multicarrier_freq.png
      - multicarrier_rx.png
      - multicarrier_time.PNG
      - multicarrier_tx.png
      - multipath.png
      - objectives_complete.docx
      - objectives_complete.PNG
      - ofdmrxconstellation.PNG
      - ofdmrxconstellationhestimate.PNG
      - ofdmrxconstellationhestimatesymbol.PNG
      - ofdmrxdiagram.png
      - ofdmrxpanel.png
      - ofdmtxconstellation.PNG
      - ofdmtxdiagram.png
      - ofdmtxpanel.png
      - ofdm_build_ber.jpg
      - ofdm_freq.png
      - ofdm_rx.PNG
      - ofdm_tx.png
      - orthogonal.png
      - pdr1-2.png
      - pdr1-5.png
      - phase_offset.png
      - Presentation1.pptx
      - risk_management.pdf
      - sinc_attenuation.png
      - sinc_attenuation_db.png
      - sinc_shape.png
      - stretch_objectives_complete.PNG

- gdp43/ .... Root folder
  - Report .... All files used to create the project report
    - Figures
      - Thumbs.db
      - time_sync_case1.png
      - time_sync_case2.png
      - time_sync_offset.png
      - usrpfront.PNG
      - usrp_diagram.PNG
  - Seminars .... Presentations stored here
    - FinalPresentation
      - final_presentation.pptx
      - final_presentation_notes.pptx
    - Seminar1
      - first_seminar.pptx
      - first_seminar.zip
      - first_seminar_notes.pptx
    - Seminar2
      - second_seminar.pptx
      - second_seminar.zip
      - second_seminar_notes.pptx
  - Tracey_content
    - 4G 5G demonstrator on NI USRP.docx
    - ELEC6200_briefing270919.pdf
    - Intro_Prj_Management.pptx
  - useful_content
    - 10.11648.j.jeee.20140204.11.pdf
    - Channel_estimation.url
    - HomeAutomationGDP.pdf
    - LieLiang_notes_channel_estimation.pdf
    - lie_notes.pdf
    - Matlab_in_labVIEW_Communications.url
    - Telecommunication_beakdown.pdf
    - Wei.pdf
    - NI USRP DQPSK Transceiver LabVIEW files
      - decode.m
      - DemodulateSubVI.vi
      - Downsample (SubVI).vi
      - DPSK_controls.ctl
      - DPSK_rx.vi
      - DPSK_rx_states.ctl

- gdp43/ .... Root folder
  - useful_content
    - NI USRP DQPSK Transceiver LabVIEW files
      - DPSK_tx.vi
      - DPSK_tx_0.vi
      - DPSK_tx_states.ctl
      - PSK_demod (SubVI).vi
      - USRP_Lab_DQPSK.pdf
    - OQPSKLab_excercise
      - Lab_Notes (Student).pdf
      - Lab_Notes (Supervisor).pdf
      - Supervisor report.pdf
      - O-QPSK LabVIEW VIs
        - Add Noise.gvi
        - Bits-to-chips.gvi
        - Carrier Frequency Offset.gvi
        - Demodulation.gvi
        - Eye+Constellation.gvi
        - Fading.gvi
        - Modulation.gvi
        - O-QPSK Rx.gvi
        - O-QPSK Simulate.gvi
        - O-QPSK Sync.gvi
        - O-QPSK Tx.gvi
        - O-QPSK.gvi
        - O-QPSK.lvcodedb
        - O-QPSK.lvproject
        - O-QPSK.lvprojectcache
        - O-QPSK.lvsuo
        - Orginal and Received SHR.gvi
        - Original chip detection.gvi
        - Original SHR mod.gvi
        - PPDU location.gvi
        - PPDU.gvi
        - Random Delay.gvi
        - Received complex value to bits.gvi
        - Received PHY.gvi
        - Sim demod.gvi

Appendix I

Git Log

This log shows the record of the commits to the project's source code repository.

Listing I.1: The git commit history for this project.

```
4a368ab Ricki 2019-12-06 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
e7b808c Ricki 2019-12-06 First draft of presentation left
8424915 Paul 2019-12-06 minor changes report
512cd95 Ricki 2019-12-06 Updating poster and making report build again
6766647 Ricki 2019-12-05 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
932e6aa Ricki 2019-12-05 Few report and poster tweaks
64fab0f Paul 2019-12-05 minor mods in background
2f47cee Ricki 2019-12-05 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
799424b Ricki 2019-12-05 More poster, updated report
01d35b2 Paul 2019-12-05 progress on final presentation
f25f8b9 Paul 2019-12-05 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
7ff2ae1 Paul 2019-12-05 poster progress
fb9c695 Ricki 2019-12-05 Big changes to report to fit word count
be828e9 Ricki 2019-12-05 More final touches
1099d62 Paul 2019-12-04 appendix update and small addition to report
5984ac8 Ricki 2019-12-04 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
12d3a69 Ricki 2019-12-04 Adding other
d2930b3 Paul 2019-12-04 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
2e20cb5 Paul 2019-12-04 finished CFO
4238d46 Ricki 2019-12-04 More changes to report
864254f Paul 2019-12-04 remove temp file
bcdffb4 Paul 2019-12-04 progress
59fbc63 Paul 2019-12-04 progress in report
30115de Ricki 2019-12-04 Adding appendix
dde9673 Ricki 2019-12-04 Fixed conflicts
3f5eed5 Ricki 2019-12-04 More report additions
8f1ca84 Paul 2019-12-04 merging
9fd62dc Paul 2019-12-04 add reference to equations
9d25382 Ricki 2019-12-04 Updating bibtex
769c93e Ricki 2019-12-04 update!
```

```
da7207f Ricki 2019-12-04 Merge branch ’master’ of https://git.soton.ac.uk/
    gdp43/gdp43
ac42a23 Paul 2019-12-04 changing subfigures to minipages
9e81e41 Ricki 2019-12-04 Merge branch ’master’ of https://git.soton.ac.uk/
    gdp43/gdp43
99da5df Ricki 2019-12-04 Adding small updates
441be6d Paul 2019-12-03 Merge branch ’master’ of https://git.soton.ac.uk/gdp43
    /gdp43
91c256d Paul 2019-12-03 progress in the report
6aa40d4 Ricki 2019-12-03 Merge branch ’master’ of https://git.soton.ac.uk/
    gdp43/gdp43
2c9fc4e Ricki 2019-12-03 More report progress, this time on the management
675be59 Paul 2019-12-03 Merge branch ’master’ of https://git.soton.ac.uk/gdp43
    /gdp43
f296b57 Paul 2019-12-03 progress in report
0218d8c Ricki 2019-12-03 More report progress
3294d0b Ricki 2019-12-03 Merging
9239694 Ricki 2019-12-03 More report progress
ac73e59 Paul 2019-12-02 progress
33d255c Paul 2019-12-02 progress in report
7daa40b Ricki 2019-12-02 Sorted out merges
7fab661 Ricki 2019-12-02 Updating demonstrator
87f0037 Ricki 2019-12-02 updating gantt chart
03462f4 Ricki 2019-12-02 Adding more report stuff
59c8b18 Paul 2019-12-02 report progress
06f91c5 Paul 2019-12-02 uploading
2800862 Paul 2019-12-02 update report and multiple subband f-ofdm
0bec5e9 Ricki 2019-11-29 Merge branch ’master’ of https://git.soton.ac.uk/
    gdp43/gdp43
45f723c Ricki 2019-11-29 Lots of progress made in the report
88add97 Paul 2019-11-29 Merge branch ’master’ of https://git.soton.ac.uk/gdp43
    /gdp43
6fd3f2e Paul 2019-11-29 time sync start, finsihed filtering
99b536f Ricki 2019-11-29 Merge branch ’master’ of https://git.soton.ac.uk/
    gdp43/gdp43
c98631f Ricki 2019-11-29 Pushing so I can pull
6ecda57 Paul 2019-11-29 Merge branch ’master’ of https://git.soton.ac.uk/gdp43
    /gdp43
5a67a68 Paul 2019-11-29 added lie-liangs’s notes on channel estimation
ff1ba69 Ricki 2019-11-29 Sorted out the report issue finally
1c159d3 Ricki 2019-11-28 Committing everything so I can go back and fix the
    report
65aaf30 Ricki 2019-11-28 Removed another temp file
b1a5795 Ricki 2019-11-28 committing report, before trying to fix
ebf6ed6 Ricki 2019-11-28 Updated gantt chart
778a128 Ricki 2019-11-28 More poster
370508b Ricki 2019-11-28 More report progress
20f94d3 Ricki 2019-11-28 Adding final presentation
96aab4f Ricki 2019-11-28 Adding new minutes
4799445 Ricki 2019-11-28 Adding minutes figures for the appendix
d6d07c9 Ricki 2019-11-27 Sorting out commands
2491766 Ricki 2019-11-27 Fixed errors with the math equations
6857350 Ricki 2019-11-27 Merge branch ’master’ of https://git.soton.ac.uk/
    gdp43/gdp43
af216b5 Ricki 2019-11-27 Updating files, trying to get frames working, and
    filter working
cda024f Paul 2019-11-26 Working on report added figures to background
154d137 Ricki 2019-11-26 Updating the references
73ba455 Ricki 2019-11-25 Completed OFDM background research
```

```
bde381e Ricki 2019-11-25 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
ba0b5d4 Ricki 2019-11-25 More progress
7b9cfa0 Paul 2019-11-25 matlab and report progress
9402961 Ricki 2019-11-25 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
58fb484 Ricki 2019-11-25 Adding a lot of report progress
6f7d9b3 Paul 2019-11-25 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
b3a0f78 Paul 2019-11-25 improvement of filtered and frequency offset
2ea0f3b Ricki 2019-11-25 Adding word count perl script
ae9f6e4 Ricki 2019-11-24 Doing some clean up of the directory
73b8fa8 Ricki 2019-11-24 Set up the fofdm files, added more images and report content
b0896ca Ricki 2019-11-23 Added more to report
3944fec Ricki 2019-11-23 Got OFDM wirelessly working
bf00e65 Ricki 2019-11-20 Created the OFDM files
ce391f2 Ricki 2019-11-20 Fixed the BER calculator, changed the threshold to 0.1, it now works
8cc9d4e Ricki 2019-11-20 Fixed the array shaping so that 16QAM works over wireless channel, good BER
daff209 Ricki 2019-11-20 Made report structure easier
ea75be0 Ricki 2019-11-20 Finally got 16QAM constellation working to a good level
5ba82fe Ricki 2019-11-18 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
c1fdc2a Ricki 2019-11-18 First draft of the dbpsk and 16qam system
dd776d6 Paul 2019-11-18 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
e589255 Paul 2019-11-18 start of frequency offset
26a1e42 Ricki 2019-11-18 Got DBSPK working on the USRP
1674e91 Ricki 2019-11-18 Completed second seminar
34d9cc6 Ricki 2019-11-17 Added dbpsktxrx
4a9112a Ricki 2019-11-14 Updated seminar
85822c8 Ricki 2019-11-13 Second Seminar complete
8225bce Paul 2019-11-13 clipped message screenshot
4a2054d Paul 2019-11-13 screenshot of channel estimation
0605a2a Paul 2019-11-13 CP screenshot
fc25a6b Paul 2019-11-13 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
614c982 Paul 2019-11-13 End of filtered OFDM with progress on PAPR
ae3c338 Ricki 2019-11-13 Big progress
8b5c16a Ricki 2019-11-11 Progress trying to get frequency offset fixed, added more repors
42a7795 Paul 2019-11-11 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
7afe017 Paul 2019-11-11 empty filtered matlab
4fedc96 Paul 2019-11-11 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
070bc06 Paul 2019-11-11 deleted cluster constant to be able to commit matlab files
b87b1e1 Paul 2019-11-11 power spectral density of simple ofdm
85cdfa8 Ricki 2019-11-08 Trying to fix freq offset
a3fb188 Ricki 2019-11-07 more labview
cb4a3b1 Ricki 2019-11-07 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
9eda6ff Ricki 2019-11-07 Labview
d67354a Ricki 2019-11-06 More report
a3e4466 Ricki 2019-11-06 trying to fix the phase error
```

```
b3912a5 Ricki 2019-11-06 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
6521e15 Ricki 2019-11-06 more work on report
ea4c3f7 Ricki 2019-11-06 updated the ppt for the meeting
038b595 Paul 2019-11-06 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
3d118fb Paul 2019-11-06 Small amount of text added
a2a2da9 Ricki 2019-11-06 More intro
ac61334 Paul 2019-11-06 Formatting equation in approach
9d4fae3 Ricki 2019-11-05 Adding poster dimensions
a48793a Ricki 2019-11-05 Adding poster folder
5c9c1a8 Ricki 2019-11-05 Done acknowledgements
3c44b70 Ricki 2019-11-05 Moved a lot of files around, big tidy up
274069a Ricki 2019-11-05 Fixed the abstract
2afed9a Ricki 2019-11-05 Finished making gitignore
cca8071 Ricki 2019-11-05 Deleting more temp files, not needed in repo
98a172e Ricki 2019-11-05 Sorted out these unnecessary files that don’t need to be gitted
9bfec9b Paul 2019-11-05 Added more text in approach: CP, chan est, matlab basic and ofdm
713192b Paul 2019-11-05 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
1d564c4 Paul 2019-11-05 More report and CP stuff
6db8b2d Ricki 2019-11-05 Sorted out the structure of the report, lots of formatting
bbd4983 Ricki 2019-11-05 Updating tex
82c9a4c Ricki 2019-11-05 Updating ppt images for the meeting tomorrow
f0f3b51 Ricki 2019-11-05 Completed OFDM in LabVIEW
3b130c6 Ricki 2019-11-05 Completed OFDM, next step is to tidy everything up
4d225b4 Ricki 2019-11-04 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
0e5e96b Ricki 2019-11-04 Started first 64 channel OFDM system, need to complete and fix issues
8fdca6d Paul 2019-11-04 Adding a symbolic math file and lly’s channel detection method
0f2f815 Ricki 2019-11-04 Adding updated 16QAM
f8fc679 Ricki 2019-11-03 Started the Objectives chapter
b8e5b93 Ricki 2019-11-03 Cleaned up the OFDM layout
7ab2aa3 Ricki 2019-11-03 Added CP to OFDM
e8f75e8 Ricki 2019-11-02 Trying more out
3dcb7c3 Ricki 2019-11-02 Tried fixing phase sync issues
2317253 Ricki 2019-10-30 More 16QAm progress
e8f82ca Ricki 2019-10-30 Trying to do 16QAM on USRP now instead of ideal simulation
f056b5b Ricki 2019-10-30 Completed 16QAM without USRP
a7e60cd Ricki 2019-10-30 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
11d96ca Ricki 2019-10-29 Started the 16QAM stuff
ab0fb3f Paul 2019-10-29 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
26715f2 Paul 2019-10-29 MMSE introduced
cbfb83f Ricki 2019-10-29 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
1ab48cd Ricki 2019-10-29 Doing the examples without the USRP, completed BSPK and QPSK
d9f7062 Paul 2019-10-29 Normalised code
ac9aed7 Paul 2019-10-29 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
f5ede04 Paul 2019-10-29 Normalising codes to get more accurate results
```

```
b1dd735 Ricki 2019-10-28 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
d46d13c Ricki 2019-10-28 Adding updated minutes
3064078 Paul 2019-10-28 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
e64a773 Paul 2019-10-28 small paragraph in report about approach on matlab
177e629 Ricki 2019-10-28 Adding extra image to ppt
4f670c0 Ricki 2019-10-28 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
d1508e8 Ricki 2019-10-28 LabVIEW stuff, trying to get QPSK working
4effb8a Ricki 2019-10-28 LabVIEW stuff, trying to get QPSK working
072ab52 Ricki 2019-10-28 Updating gantt chart
bcba77b Ricki 2019-10-28 Updating minutes
ce04020 Paul 2019-10-28 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
b7e82d3 Paul 2019-10-28 get rid of asv file
30ea76d Paul 2019-10-28 Channel estimation and minor changes to fading channels
e54267b Ricki 2019-10-27 More progress on equalisers and qpsk
b9ae88f Ricki 2019-10-25 trying to get equaliser working
1cca0ae Ricki 2019-10-25 Adding more set up for the report
7ec0c7c Ricki 2019-10-25 Updating report structure
baf8cfc Ricki 2019-10-23 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
02a6f62 Ricki 2019-10-23 Moving onto equalisation to enable qpsk
c794ab4 Paul 2019-10-23 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
b2ea16e Paul 2019-10-23 Fading channels with PSK not working + addition of 64 QAM
233fd14 Ricki 2019-10-23 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
53c8998 Ricki 2019-10-23 Adding minutes and completed ASK labview
a272f7c Ricki 2019-10-22 Statement of originality
5824602 Ricki 2019-10-22 DSB and ASK
2a7a690 Paul 2019-10-22 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
44cabee Paul 2019-10-22 Working channel_test for rayleigh fading channel
defe4d3 Ricki 2019-10-22 Report starting
7557d22 Ricki 2019-10-22 Updating slides and Gantt chart
91c99a8 Paul 2019-10-22 matlab reorganisation 2
5368e7d Paul 2019-10-22 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
f70dcf4 Paul 2019-10-22 reorganising matlab code
2f192d9 Ricki 2019-10-21 AM completed fully, trying to get FDM to work
a8e595a Ricki 2019-10-21 Updating minutes with supervisor meeting
ea7ea36 Ricki 2019-10-21 Adding rest
8155df3 Ricki 2019-10-21 Saving project so that I can revert back
f31fce8 Ricki 2019-10-21 Adding files, so I can revert back
280470e Ricki 2019-10-21 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
05b285b Ricki 2019-10-21 Renaming minutes
25a6e12 Paul 2019-10-21 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
ed78c30 Ricki 2019-10-21 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
bf5d9ff Ricki 2019-10-21 Adding minutes and the labview progress
939754d Paul 2019-10-21 ber curves screenshots
b72e60f Paul 2019-10-20 Merge branch ’master’ of https://git.soton.ac.uk/gdp43/gdp43
```

```
09953c1 Paul 2019-10-20 Frequency selective channel code
6a00f5c Ricki 2019-10-18 Fixing slide total
8551020 Paul 2019-10-18 slides update
04fd52e Paul 2019-10-17 Remove temp files
bafdf0e Paul 2019-10-17 no progress
97cb880 Ricki 2019-10-16 Adding labview files from today and the minutes and the seminar
0b61e6b Ricki 2019-10-15 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
1a078cf Ricki 2019-10-15 Adding Lab work and minutes
e99c7a3 Paul 2019-10-15 DFT codes for OFDM
aac5b94 Ricki 2019-10-15 Adding minutes
50ca106 Ricki 2019-10-15 Adding rest of NI labs
89c6078 Ricki 2019-10-14 Completing minutes
4b87be9 Ricki 2019-10-14 Updating minutes, supervisor meeting
1f4165f Ricki 2019-10-14 Adding minutes
e113e4c Paul 2019-10-14 New analog OFDM 16 qam modulated
d32aaa3 Paul 2019-10-10 Working analog 16QAM transceiver
0348253 Ricki 2019-10-09 Adding minutes and Gantt chart
0549a54 Ricki 2019-10-09 Adding USRP starter guides
c821174 Paul 2019-10-09 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
cee646e Paul 2019-10-09 In progross OFDM
1b57ecf Ricki 2019-10-09 updating minutes
74eb2fa Paul 2019-10-09 Updating Analog OFDM
48700dd Ricki 2019-10-09 Adding new minutes and start of modified OFDM code
8063fa0 Ricki 2019-10-08 updated minutes, almost done quantising
225419c Ricki 2019-10-08 Adding RM files
9874a4e Ricki 2019-10-08 Adding a few spacing lines
ad3f942 Paul 2019-10-08 First attempt at an OFDM modulation (no DAC)
d350030 Ricki 2019-10-08 Adding today's minutes and the 16QAM code
c3a318e Paul 2019-10-08 Adding matlab code QPSK
51bb563 Paul 2019-10-08 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
eb9c9c8 Ricki 2019-10-08 Not sure what changes have happened here, committing anyway
5ba909f Paul 2019-10-08 Matlab code for QPSK
00be5de Paul 2019-10-07 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
5f26a9e Paul 2019-10-07 PERT charts
f4f00c7 Ricki 2019-10-07 Adding MEH code for us to try out
ad5fbdd Ricki 2019-10-07 Updated minutes
3679ddf Ricki 2019-10-07 Added more on spec and gantt chart, updated minutes
ccd331c Ricki 2019-10-07 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
5d9479e Ricki 2019-10-07 Adding tutorial labs for the USRP
668960b Ricki 2019-10-07 Updating spec
575cc7d Paul 2019-10-07 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
1d7dd59 Paul 2019-10-07 Matlab files and PERT chart
cd9ce3b Ricki 2019-10-07 Updated minutes
faff48e Ricki 2019-10-07 More to Gantt chart
b96b81d Ricki 2019-10-07 Adding more to report
6c56f40 Ricki 2019-10-07 Adding report files
63f3182 Paul 2019-10-07 Risk assessment matrix included
5fbfcbc Paul 2019-10-07 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
0af462f Ricki 2019-10-07 Deleting old gantt chart
3ad2a5e Ricki 2019-10-07 Updating minutes and gantt chart
```

```
40afb5f Paul 2019-10-07 Merge branch 'master' of https://git.soton.ac.uk/gdp43/gdp43
bbe50c8 Paul 2019-10-07 Changes to Risk assessment and Project brief
7fb56ce Ricki 2019-10-07 Adding hardware loan information document
4a58cf5 Ricki 2019-10-06 Adding more documents and minutes, attempt two
6748156 Ricki 2019-10-06 Adding more documents and minutes
8b7f67b Ricki 2019-10-06 Adding link for getting matlab in labview commuications
ef274ed Ricki 2019-09-30 Adding other presentations
3876efa Ricki 2019-09-30 Removing temp file
31d0505 Paul 2019-09-30 Uploaded first minutes
5a75568 Ricki 2019-09-30 Adding scanned notes from kick-off meeting
7a4f0ce Ricki 2019-09-30 Initial commit
```

Appendix J

Meeting Minutes

Minutes: 30/09/2019

Kick-off meeting

Met our two supervisors.

Two halves to the project to be worked on in parallel:

- Learn about OFDM, 4G, 5G using the provided slides
- Simulation on MATLAB:
    - Start off on an easy system (eg BPSK)
    - Move onto OFDM
    - Then 4G
    - Then 5G
- Practical application using the NI USRP:
    - Use NI tutorials
    - Learn LabView communications
    - OFDM
    - 4G
    - 5G

Post kick-off

- Set up the git repo on both laptops
- Set up Meistertask project for setting tasks and to-do lists
- Ricki nominated as project manager

Tasks

- Need to read the content and understand the theory:
    - Comms
    - Project management
- Paul to email supervisors about ethics, health & safety, and GDPR

Next meeting

A1	Thursday 3rd 14:00 over Skype
A2	Discuss ethics, H&S, and GDPR
A3	Discuss project and plan using APM methodology
A4	Define objectives and stretch objectives
A5	Create a Project Specification Document (including Gantt chart or similar)
A6	Make a risk assessment

Minutes: 06/10/2019

Review last meeting’s tasks

A1	Thursday 3rd 14:00 over Skype	Complete
A2	Discuss ethics, H&S, and GDPR	Ethics, H&S, and GDPR do not need to be considered, confirmed by MEH
A3	Discuss project and plan using APM methodology	Combined into single task B1
A4	Define objectives and stretch objectives	
A5	Create a Project Specification Document (including Gantt chart or similar)	
A6	Make a risk assessment	Incomplete

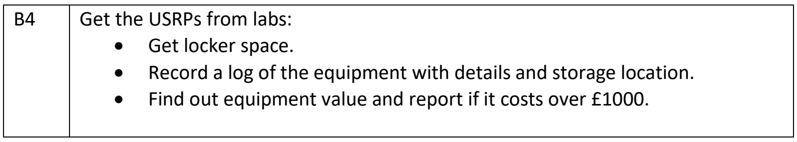
Progress

Made list of objectives:

- Build:
  - Set up the hardware and software. Use the tutorials on NI website to get a simple BPSK communications link working.
  - Implement OFDM structure.
  - Implement 4G/5G.
  - Improve uplink by implementing SC-FDMA.
  - Improve downlink by implementing OFDMA.
- Analyse/Test on performance:
  - Cyclic prefix design
  - Channel estimation
    - Create model for channel (H)
    - Vary channel estimation error
  - Carrier frequency offset
  - Time synchronisation offset (need to ask for more detail)
  - Filtering (need to ask for more detail)
  - Inter-user synchronisation in uplink
  - PAPR:
    - Increase number of carriers
    - Detect arising issues
- Design mitigation techniques for:
  - Carrier frequency offset
  - Time synchronisation offset (need to ask for more detail)
  - Filtering (need to ask for more detail)

Tasks

B1	Complete the draft project brief and decide what objectives are stretch objectives (including Gantt chart or similar) using APM
A6	Complete a risk assessment
B2	Get some simple comms code working on MATLAB, look at first and second year code on module notes pages
B3	Install LabVIEW communications



B4	Get the USRPs from labs: • Get locker space. • Record a log of the equipment with details and storage location. • Find out equipment value and report if it costs over £1000.

Minutes: 07/10/2019

Review last meeting's tasks

B1	Complete the draft project brief and decide what objectives are stretch objectives (including Gantt chart or similar) using APM	Complete
A6	Complete a risk assessment	Complete
B2	Get some simple comms code working on MATLAB, look at first and second year code on module notes pages	Continued onto C1
B3	Install LabVIEW communications	Not required, using lab PCs
B4	Get the USRPs from labs: • Get locker space. • Record a log of the equipment with details and storage location. • Find out equipment value and report if it costs over £1000.	Complete

Progress

- Report LaTeX template set up.
- Risk assessment done.
- Meeting with supervisors:
    - Lie has a third-year project student, who is going to do some MATLAB simulations on the same OFDMA/4G stuff.
    - If we don't have the time to do the simulations, then we could ask this student to see their work.
    - They are planning on creating a new module to do with transceiver design, and our work will help contribute towards that.
    - For channel estimation we will start off with a basic one.
    - Will need to take PAPR into account in the report, "the biggest challenge", lots of research is happening here to try and tackle this, especially with 5G as thee are so many subcarriers. The more subcarriers, the higher the PAPR.
    - Look into index modulation, it's a technique they are looking into to try and tackle the above thing, as it brings about higher energy efficiency.
    - MATLAB simulations can be used to investigate PAPR, probably not possible to investigate using the USRP as we may have limited access to the tools. They think the only thing we can do in the USRP is to introduce clipping to lose the peak.
    - Inter-user synchronisation in uplink moved to the stretch goals (lowest priority in the stretch goals), they are more interested in the downlink scenarios.
- Completed second draft of spec with stretch goals.
- Completed Gantt chart.
- Submitted project spec on hand in.

Tasks

C1	Basic MATLAB completed (QPSK or similar)
C2	OFDM completed on MATLAB
C3	USRP set up, basic tutorial completed

Minutes: 08/10/2019

Review last meeting's tasks

C1	Basic MATLAB completed (QPSK or similar)	Compete
C2	OFDM completed on MATLAB	Incomplete
C3	USRP set up, basic tutorial completed	Incomplete

Progress

- Understood MEH's BPSK MATLAB code.
- Adapted this code to get a 4-ary QPSK scheme working.
- Adapted this code to get a 16QAM scheme working.
- Got digital part of OFDM working.
- Now implementing the analog part of BPSK, in preparation of getting it working for OFDM. This is incomplete and will be carried on tomorrow.

Tasks

C2	OFDM completed on MATLAB
C3	USRP set up, basic tutorial completed

Minutes: 09/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status
C2	OFDM completed on MATLAB	RT+PD	Incomplete
C3	USRP set up, basic tutorial completed	RT	Complete

Progress

- Issues with configuring the USRP, have spoken to Dave Batt about this. Ricki to manage.
- Sorted USRP issues, it is now being detected by PC.
- Completed Intro to USRP lab.
- Getting close to completing OFDM with analog parts.

Tasks

Name	Task	Assigned
D1	Complete a basic BPSK design on USRP from tutorial	RT
D2	Try USRP with antenna instead of coaxial cable	RT
C2	OFDM completed on MATLAB	RT+PD

Minutes: 14/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status
D1	Complete a basic BPSK design on USRP from tutorial	RT	Incomplete
D2	Try USRP with antenna instead of coaxial cable	RT	Incomplete
C2	OFDM completed on MATLAB	RT+PD	Complete

Progress

- More progress on USRP needed.
- OFDM on MATLAB is completed in time domain but need to complete in frequency domain using FFT and IFFT functions.
- Meeting with supervisors:
    - Question: Is the time domain OFDM equivalent to the FFT method?
        - FFT is an implementation of a multicarrier system. OFDM is done using FFT, that makes it OFDM.
    - Question: H matrix, does this represent the multipath interference from the channel? What should we use for H?
        - Frequency selective fading comes from delay spread (the time duration of all the scattered signals to arrive), delay spread is in the time domain, 1/delay spread is the channel coherence bandwidth, if the channel bandwidth is smaller than the coherence bandwidth, it is frequency non-selective fading, or in other words, flat fading.
        - L in his notes is the number of paths that the receiver can identify. So, the H matrix is made up of multiple paths where L is the notation of the paths. It's to do with delay-spread/resolution of the signal transmitted. We should start with one value in the H matrix. (need to check these notes)
        - Some of the channels might not be faded independently, they might be correlated (affected similarly).
        - Start from the matrices in his notes, middle of page 1, H-bar matrix is circular.
        - Start with some random values for H or look in his textbook or find some functions in MATLAB, or make them Gaussian, with the power being 1.
        - Assume that the received signal power is 1, this is what he's talking about when he wants to normalise
    - Question: Do we model the system in terms of the maths y = Hx + n, or model in terms of the analog and digital signals?
        - When we sample, the observation is in the time domain, the FFT takes it to the frequency domain
        - Lie-Liang suggested we keep it in matrix form in MATLAB
    - Question: Explain certain slides from Lie-Liang's OFDM lecture
    - Question: In 4G as it uses SC-FDMA in the uplink and OFDM in the downlink
        - We should focus on the downlink scenario, OFDM symbols are in the frequency domain, SC-FDMA symbols are in the time domain
    - Question: In performance, we should plot SNR with BER

    - Look at Ber2 function on MATLAB
  - Send the 3YP student a scanned copy of these notes
    - Pp2g17, also send this link https://secure.ecs.soton.ac.uk/notes/elec3204/lly/ELEC3204-MC-OFDM-principles18.pdf
  - We should email our supervisors any progress we make on LABVIEW
  - We can also send them our presentation for comments before we submit on handin.
  - We need to have many points when doing the MATLAB simulations, 10,000 bits per SNR value is a good number to get a smooth BER/SNR curve.
  - MEH recommends splitting our bit sequence into frames, eg 1000 bits a frame. In MATLAB we need to simulate what we're doing in USRP with the frames. When testing the code keep the bit total small, and then to get the graph we need to increase the number of bits.
  - Follow Lie-Liang's notes for the ideal case for the simulation.
  - What happens if the CP length is shorter than L, we will get some inter symbol interference. L is the number of paths the receiver gets from multipath interference. We need to investigate this later on in the term for the theory behind this. For the mean time we should use the ideal case.
  - As we're focusing more on the modulation, QPSK is fine.
  - Look at the SNR, normalised power, received signal power.
  - Once the OFDM is set up, change CP size, change L size. Then after this we can move onto the LTE(4G).
  - USRP progress is paramount.
- For the channel matrix H, we should pick a random value for the transmitter side, only have one value so L=1. On the receiver side, start off with y = Hx + v, and just demodulate y to investigate the BER. Then move onto channel estimation of H and removing the Gaussian noise and finding the inverse of H so that we can get x instead of y.

Tasks

Name	Task	Assigned
D1	Complete a basic BPSK design on USRP from tutorial	RT
E1	Complete a QPSK design on USRP	RT
E2	Get MATLAB code onto a LabVIEW design for USRP	RT
D2	Try USRP with antenna instead of coaxial cable	RT
E3	Improve OFDM MATLAB code to use FFT	PD

Minutes: 15/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status
D1	Complete a basic BPSK design on USRP from tutorial	RT	
E1	Complete a QPSK design on USRP	RT	
E2	Get MATLAB code onto a LabVIEW design for USRP	RT	
D2	Try USRP with antenna instead of coaxial cable	RT	
E3	Improve OFDM MATLAB code to use FFT	PD	

Progress

- More progress on USRP needed.
-

Tasks

Name	Task	Assigned
D1	Complete a basic BPSK design on USRP from tutorial	RT
E1	Complete a QPSK design on USRP	RT
E2	Get MATLAB code onto a LabVIEW design for USRP	RT
D2	Try USRP with antenna instead of coaxial cable	RT
E3	Improve OFDM MATLAB code to use FFT	PD

Minutes: 16/10/2019

Review last meeting’s tasks

Name	Task	Assigned	Status
D1	Complete a basic BPSK design on USRP from tutorial	RT	Incomplete
E1	Complete a QPSK design on USRP	RT	Incomplete
E2	Get MATLAB code onto a LabVIEW design for USRP	RT	Postponed
D2	Try USRP with antenna instead of coaxial cable	RT	Incomplete
E3	Improve OFDM MATLAB code to use FFT	PD	Complete

Progress

- More progress on USRP done, completed AM, moving onto FDM
- Working on seminar slides, draft completed
- FFT working on OFDM MATLAB code
- Now moving onto channel estimation in MATLAB, plotting BER under various conditions

Tasks

Name	Task	Assigned
F1	Send seminar slides to supervisors for review	PD
F2	Finish FDM in USRP	RT
D1	Complete a basic BPSK design on USRP from tutorial	RT
E1	Complete a QPSK design on USRP	RT
D2	Try USRP with antenna instead of coaxial cable	RT

Minutes: 21/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status
F1	Send seminar slides to supervisors for review	PD	Complete
F2	Finish FDM in USRP	RT	Incomplete
D1	Complete a basic BPSK design on USRP from tutorial	RT	Incomplete
E1	Complete a QPSK design on USRP	RT	Incomplete
D2	Try USRP with antenna instead of coaxial cable	RT	Incomplete

Progress

- Working on FDM, having trouble with debugging
- Submitted seminar slides
- Supervisor meeting:
  - USRP:
    - AM working
    - Is current approach correct (from email)?
    - FFT graph frequency peaks can be orders of magnitude out or just incorrect
    - FFT graph doesn't go beyond 100kHz, carrier frequency can't be seen
    - Carrier frequency can't go below 380 MHz, sampling frequency/IQ rate can't go above 50 MS/s, how can we produce anything that works?
      - The USRP handles the up sampling, filtering, and maybe the root cosine filtering so that we don't have to. We don't have to create the carrier ourselves, it should be defined in the USRP config
      - We should treat the LabVIEW part as the digital part, and the USRP handles all the analog stuff
  - MATLAB:
    - How to normalise the results when dividing by the square of magnitude
      - Our results were better than the theory, they advised we look at this
    - LLY said that our BER diagram in the seminar slides was correct.
    - LLY said that the x axis for the BER graphs should be E_b/N_0 instead of SNR as different modulation schemes have different numbers of bits per symbol, and therefore the energy spent on each bit varies.
    - LLY said that we should change to 64 subcarriers on the channel estimation code and change the path (L value) to 5 and then send the pilot symbols throughout.
    - We need to investigate how the number of paths affects the correlation between the sub carrier channel estimations, and how the number of pilot symbols helps us to get a better estimation.
    - As long as the cyclic prefix is greater than the number of paths L, then we should be okay in the perfect channel example.
- After reading the USRP block diagram, found out that the multiplying by the carrier is done within the USRP and not within LabVIEW. We just need to supply the USRP with the samples that need modulating.

- We removed the carrier part from the TX USRP and it worked, we don't need to bother with this

Tasks

Name	Task	Assigned
F2	Finish FDM in USRP	RT
D1	Complete a basic BPSK design on USRP from tutorial	RT
E1	Complete a QPSK design on USRP	RT
D2	Try USRP with antenna instead of coaxial cable	RT

Minutes: 22/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status
F2	Finish FDM in USRP	RT	Complete
D1	Complete a basic BPSK design on USRP from tutorial	RT	Incomplete
E1	Complete a QPSK design on USRP	RT	Postponed
D2	Try USRP with antenna instead of coaxial cable	RT	Postponed

Progress

LabVIEW:

- Met with MEH in the lab, fixed FFT being a factor of 10 out
- Had issues with BPFs, but leaving this for now
- Leaving FDM and moving on to DSBSC
- Issue with DSBSC is that the received signal has a frequency twice that of the transmitted signal.
- We've also noticed that the received signal from the USRP is modulated to an "intermediate" frequency of 100kHz, instead of being the baseband signal that we gave to the USRP at the transmitter end. This explains why we need to use band pass filters centered around 100kHz.
- Going to move onto ASK and see if I can make any progress with that, as it uses AM which we've established already.

MATLAB

- Adding noise constant

Tasks

Name	Task	Assigned

Minutes: 22/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status

Progress

LabVIEW:

- Completed ASK, BER is around 0.5 which isn't great
- Moving onto BPSK
- Now working on QPSK but need to do the equalising lab first, so that we can negate the effects of the channel
- Having trouble on the equalising part, will have to continue tomorrow

MATLAB

Tasks

Name	Task	Assigned

Minutes: 28/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status

Progress + Supervisor meeting

LabVIEW:

- BPSK completed last time but BER is not 0 even without the channel block that creates the multipath propagation
- Having issues implementing a working equaliser that compensates for phase misalignment and channel interference
- QPSK is far off from completion, which is stopping us from doing QAM

MATLAB:

- Channel estimation on the equaliser
- Channel fading

Supervisor meeting:

MATLAB:

- Channel estimation, consider only the pilot symbols, make sure that the matrices are normalised (see handwritten notes)
- See the second page of the handwritten notes about using the FFT in matrix form and finding out the unknowns after knowing the known terms from the pilots. From this we can calculate h(t), and then we can go back to the start equation and find out the values of the other symbols that aren't pilots.
- Time domain channel estimated from looking at it from the frequency domain.
- First we have the pilot, then we know the data, we use the known data to estimate the channel, from this channel we can estimate the missing data in the time domain. As long as we use more pilots than the multipath length L, we can find the value of h(t), and then from this we can find out the FFT and estimate the entire channel.
- We cannot remove the channel estimation error. If the inaccuracy if from the SNR, then a higher TX power can reduce this. To get a better channel estimator, include the random noise in the matrices.
- Get LLY to send us the paper on the theory
- LLY wants Paul to finish the channel estimation issues this week, next week to work on the frequency offset.

- OFDM system is basically 4G already, 5G adding of the filter is currently unknown but we'll have to figure out how to put in MATLAB. Adding of the filter adds some error, as the cut off frequencies may stop it from being completely orthogonal. This results in a slight loss of performance. We may need to do some investigations on this (LLY will look into this also).

LABVIEW:

- Why is there low amplitude at the beginning of RX for BPSK?
  - Adding frame header (Barker code), possible to extend past 13 bits?
  - After sending 1000 bit 1s, BER is 0.022, 22 bits incorrect from the start of the sequence
  - LLY thinks that this is an error in the synchroniser, and that we should use more bits for the header (they used 1000 bits in other modules)
  - Look into whether the pulse align VI is getting the right sample time
- Equaliser not fixing multipath issues, or phase synchronisation
  - Should we do it ourselves in a mathscript?
  - Try it out using Paul's MATLAB code
  - LLY says that we may not have to worry about equalisers in the time domain, as we can work in the frequency domain and use a CP to remove the need for this
- LabVIEW running slow with complex receivers (up to 10 second delay on QPSK), what should we do further down the line when our receivers will have to deal with up to 64 subcarriers?
- Do you have access to the instructor resources?
- The variations in the QPSK constellation diagram may be introduced by the cosine filter. Check to see if the filter is digitised, and check to see what the convolution is doing
- Email MEH about this
- Work on OFDM/QPSK without the channel estimation or equaliser, just try and get the modulation and symbol mapping done, worry about the channel multipath problems later as we can try and estimate this using Paul's MATLAB scripts perhaps?

Tasks

Name	Task	Assigned

Minutes: 29/10/2019

Review last meeting's tasks

Name	Task	Assigned	Status

Progress

LabVIEW:

- BPSK needs fixing:
    - Have a longer header length so that you can avoid that transient start on the receiving end
    - Try it without the USRP with no channel and everything in one gvi file
    - Don't bother with the equaliser, just get it working ideally first
- Then move onto QPSK once BPSK is done
- Look into the root raised cosine filter, why is it causing such variation in the symbols?
    - Send all ones, check the constellation points
    - Could create your own filter characteristics to apply convolution to
    - One point to note that is on the receiving end after the signal goes through the second shaping filter, the resulting constellation diagram is much better
- Work on dividing your message up into frames as well, currently its all one frame of 1000 bits

Found out that the convolution of the filter and the upsampled signal puts the extra elements at the start and at the end, the ones at the start are the ones that is making our sequence unsynced.

The framesync is not aligning the sequence correctly, why? It turns out that the BER calculator kind of finds the start of the sequence and makes up for the misalignment. When we work on cyclic prefixing we'll need to edit the frameheader and framesync functions so that they use a cyclic prefix instead of a Baker code.

Framesync bug found, the threshold detector had a threshold of 0 and a min width of 20. This meant that the cross correlation sequence had to get 20 values greater than zero for it to find the start of the frame. This was never met. We set the width to the default of 1 and set the threshold to 20. This fixed the issue and was proved by looking at the BER Trigger Found Index, which was now 1. The 1000 + 26 input bits are now 1000 + 8 output bits, where the first 8 (from convolution) and the 26 Baker bits are removed, with just the 8 bits at the end, which are removed anyway by taking the first 1,000 bits.

MATLAB:

Tasks

Name	Task	Assigned

Minutes: 06/11/2019

Review last meeting's tasks

Name	Task	Assigned	Status

Progress

LabVIEW:

- Currently only transmitting one frame repeatedly, do you want the frame size and number of frames to be customisable?
  -
- 16QAM completed in LabVIEW.
- 16QAM issues when tried on USRP:
  - Phase synchronisation issues, tried using PLL to estimate phase and also the method in the tutorial. The phase is sometimes pi radians out of sync. Tested on a different set of USRPs, same issue applies.
  - Difficulty extracting the imaginary part of the waveform as it seems to be a copy of the real part.
  - Go through the book and see if you can better estimate this
- Tried contacting NI about the software being really slow, we need a Serial Number or the Service ID of your Volume License Agreement to be able to access their support.
  - Number found: M61X22964, ticket submitted.
- Progress, I don't think I'm making enough progress here.
  - Supervisors are not worried, keep going on the phase error issue.
- Implemented OFDM in LabVIEW without use of USRP.

MATLAB:

- Skeleton code made for the different types of channel estimation, including LLY's method discussed last week. They don't seem to be very accurate, the maths LLY showed didn't match up and parts had to be normalised to get good values.
- Emails sent to MEH about it.
- Does the CP length effect the ICI (inter carrier interference) in addition to the ISI?
  - ICI is from frequency offset, the CP is only for ISI.
- How to model frequency offset in MATLAB? As we're not doing any carrier stuff.
  - LLY hasn't prepared this yet. Will come to later. There are two ways in his multicarrier notes that we a look at. One case is all subcarriers have the same offset, the other is one of the subcarriers is offset, so the main carrier offset and the subcarrier offset. Apparently the main carrier frequency offset is easy to remove (this is talked about in the tutorials, when they do 915 and 915.1MHz).
- What do you mean by time synchronisation and what types of simulation can I do? Either ambiguity in the clock, or in the sampling?

- What aspects of PAPR should I analyse, and how to demonstrate?
    - Could we run several simulations with a different number of subcarriers?
    - What LLY wants to see is for a given range, what is the effect of PAPR on the performance? The approach is you do the IFFT then add the CP then check the amplitude of the time signals. We should vary the linear range to be greater than N, then N-1, N-2, N-3. This range is the cut off for the amplitude, then see how this affects the BER.
    - Filtered OFDM will take some time. We should assume an ideal filter for this, or use the MATLAB filter functions.
- If there is time at the end, we could simulate the multi user case (OFDMA).

Misc:

- Should we add a background research chapter to our report?
    - Yes, Tracey expects this chapter

Tasks

Name	Task	Assigned

Minutes: 13/11/2019

Progress

LabVIEW:

- Still struggling to fix the frequency offset. Have tried multiple different methods including tutorial's phase synchronisation, Rob Maunder's equaliser, PLL, and some blocks in LabVIEW that try to fix frequency offsets.
  Have done some research and have found different methods but they all seem maths heavy. Is this the right approach?
- Tried using the MIMO cable to synchronise the clocks to overcome this issue for the meantime, frequency offset seems to be corrected and am now using pilot symbols to fix the constant phase error.
- Assuming I continue working with the MIMO cable to synchronise clocks, I can achieve the first two categories of technical goals.
- Given the time constraints and the remaining outstanding objectives, may be worth swapping some of the objectives and stretch objectives as I'm not keeping to the time plan. Eg analyse effect of carrier frequency offset on performance?
    - Meeting
        - Transmit the whole frame at the start that consists of pilots, and then do the channel estimation from there
        - Could try using differential PSK at the start of the data sequence, decode this, and then this removes the all of the difficulties, and then you're locked on
            - Always doing differential demodulation, and then cross correlating this, and once we're locked on we can then proceed with normal 16QAM as it will find the start of the frame and we can assume the first symbol will be the pilot symbol that we can then fix the frequency offset
  - Fix the frequency offset issue first, and then work on the rest
  - No lab report required, MEH will take care of this
  - Filtered OFDM can be done in LabVIEW by using the filter blocks and supplying it the coefficients that Paul can supply, as the MATLAB filter toolboxes won't be supported in LabVIEW

MATLAB:

- Working on filtered OFDM, simulated with AWGN channel.
- Studying the effects of clipping on PAPR on F-OFDM and OFDM.
- Studying the effects of PAPR on the performance.
- Meeting
    - Using the sinc function to generate coefficients for the FIR filter. Toolbox is used to create the filter, coefficients to feed into the toolbox filter were made by Paul.
    - Draw graphs after the IFFT and get the figures and use this in your explanation in the seminar when describing how clipping will affect the PAPR and the BER. We can use this in our powerpoint.
        - Error rate vs clipping for a given SNR will be a good graph.

    - MEH mentions for us to justify why we are clipping from 0.5 to 1 in the investigation, MEH says we need to include this justification in our report. It could be that MATLAB is normalising it, worth looking into.
  - Things that are left to do on the MATLAB is the frequency offset and the time synchronisation offset, which Lie-Liang has provided some hand derived notes for. In simulation we are only dealing with the baseband which makes things easier in LLY's view.
    - LLY has recommended to look on IEEExplore to find lots of sources on this. Something about adding some randomness to the simulations to increase the amount of ICI, we can get some good graphs here the greater the randomness is.
    - Need to estimate the effect of the offset, then apply the correction before the FFT.
  - Part 3 project students struggled with IFFT on MATLAB, Paul used dftmtx to create the matrix and then divide by the square of the matrix size.

Tasks

Name	Task	Assigned

Minutes: 27/11/2019

Progress

LabVIEW:

- Fixed the frequency and phase offsets through channel estimation
- What frame structure do you want?
    - Didn't give an answer
- RX is struggling to detect a single TX frame, can detect repeated TX frames. Using a threshold detector at the RX to find the start of the TX frame
    - Didn't get an answer
- What should final demonstrator have? Eg choice of either 4G or 5G by enabling/disabling the filter? This has been done
- What bandwidth to use? The theory doesn't match up to our results, using a symbol rate of 10,000
- Told by NI to use NXG in the future
- Filter only allows *some* of the subcarriers to pass through, according to LLY. Is this a better approach for the f-OFDM?
- Could send three different things over the thing, eg divide 256 into three portions and then filter each of the three on the receiver and demodulate each of the three.
    - Eg 2MHz divide by 256 to get bandwidth for each subcarrier. Assume 64, 128, 64 subcarriers to divide the bandwidth into. We assume that all the subcarriers have the same bandwidth.
    - The length of the FFT recovers the right stuff somehow
- BER below 0.0001, preferably 0
    - Current BER ranging from 0.0039 to 0, seems to be random
    - Upped TX gain doesn't seem to help
        - This suggests that there is interference, or an error floor. Where is this source of interference coming from? Eg:
            - Channel estimation error
            - Other sources of interference

MATLAB:

- Pilot-based correction completed
- Approval of filtering approach (sent in email)
    - LLY agreed to approach, sinc is the way to go however it is ideal, one thing to try is the Butterworth filter or some other ones to see the real-life method.
- Expectations for time synchronisation
    - Shift the values along the t values in MATLAB, which is simple enough.

Project:

- Review report structure
    - Split of theory between Background, Approach, and Results?
    - Divide the results into two sections:
        - MATLAB
        - USRP

        - Ideal
        - With CP
        - Etc
    - Then in the analysis, reflect the results back to the background theory
- When will we receive the marks?
- Report currently on 8,000 words
    - Background and Approach almost done
    - Results and Management need work
    - Ask about word count (5k limit per person breaks down with team of two)
        - LLY said that we can have more, he said that he would argue about it if it is contested
    - Do you want a git commit log in the appendix?
    - Rest of the LabVIEW test results should go in the appendix

Poster:

- How much detail? We've seen a range from last year's examples.
    - Have a small background
    - Emphasis on the challenges of implementation
    - Show results of both MATLAB and LabVIEW
    - Focus on the OFDM results
    - LLY wants the most important things in the poster
    - Add the photo of the USRP

Minutes: 04/12/2019

Progress

MATLAB:

- Analyse effect of filtering on performance, how much data?
    - LLY is happy for you to add the current MATLAB work to the report.

Report:

- A letter of support or other document written by the external partner can be included in the appendix. This should comment on the project output and alignment with their expectations. This document should be referenced in the main report, but should be included as a document in the appendix
    - MEH will sort this out.
- When will we receive the marks?
- Report currently on 12,500 words
    - Ask about word count (5k limit per person breaks down with team of two)
        - LLY said that we can have more, he said that he would argue about it if it is contested
        - MEH isn't bothered either, we need to check with Tracey
- MEH can send you an existing report if you don't have it, for project management ideas.
- Send MEH the email chain of the NI support

Poster:

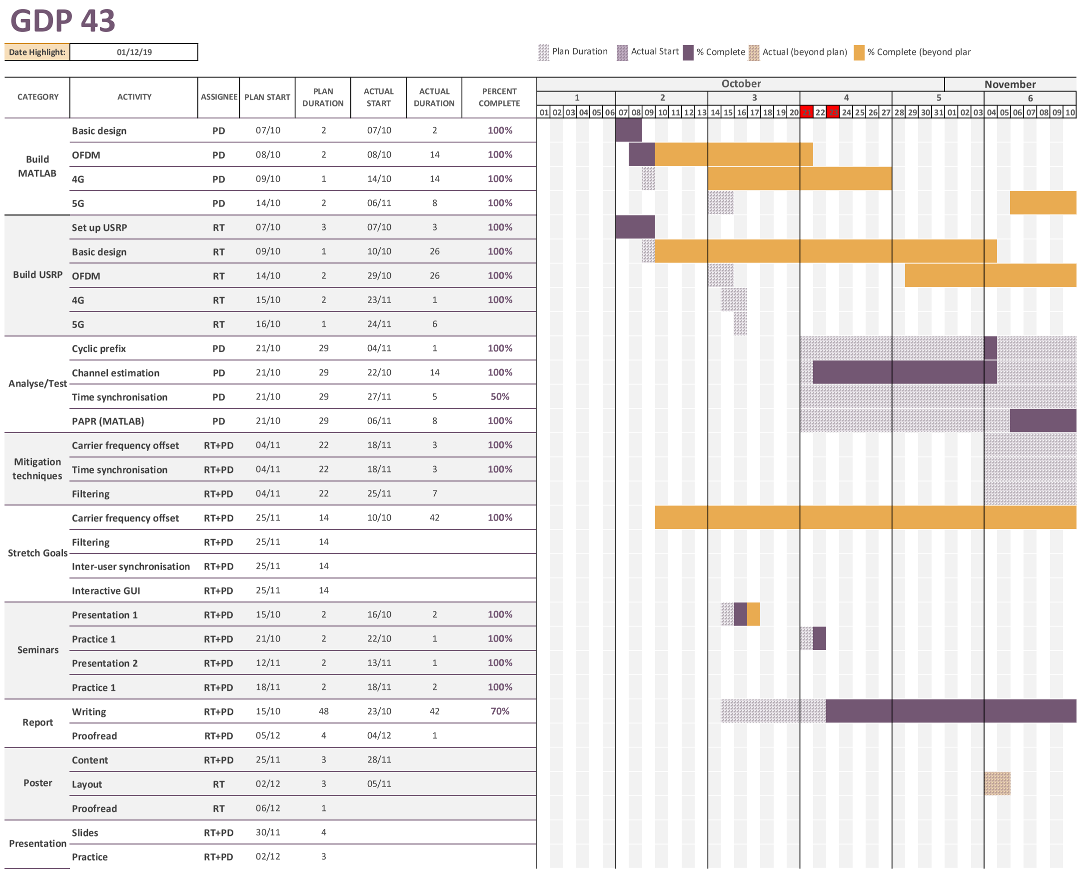
- Started already, planning on finishing tomorrow

Presentation:

- Going to complete tomorrow

Appendix K

Gantt Chart



GDP 43

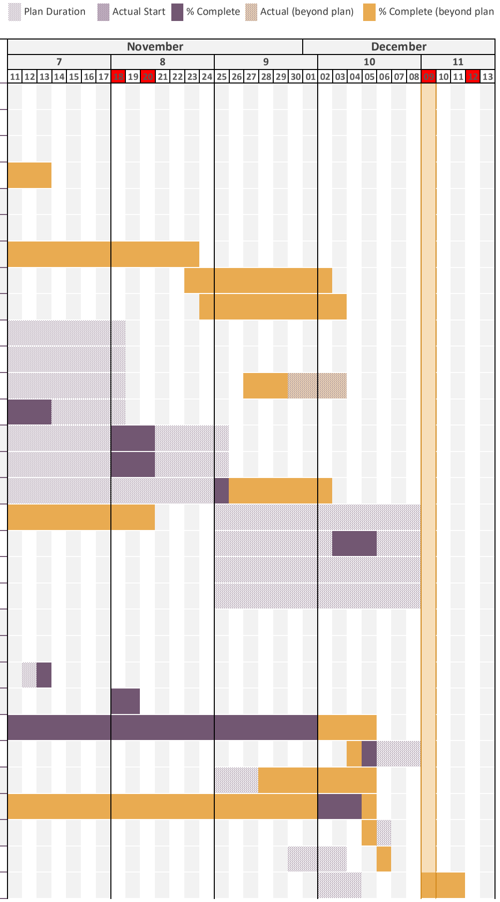
Date Highlight:	01/12/19

CATEGORY	ACTIVITY	ASSIGNEE	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Build MATLAB	Basic design	PD	07/10	2	07/10	2	100%
	OFDM	PD	08/10	2	08/10	14	100%
	4G	PD	09/10	1	14/10	14	100%
	5G	PD	14/10	2	06/11	8	100%
Build USRP	Set up USRP	RT	07/10	3	07/10	3	100%
	Basic design	RT	09/10	1	10/10	26	100%
	OFDM	RT	14/10	2	29/10	26	100%
	4G	RT	15/10	2	23/11	1	100%
	5G	RT	16/10	1	24/11	6	
Analyse/Test	Cyclic prefix	PD	21/10	29	04/11	1	100%
	Channel estimation	PD	21/10	29	22/10	14	100%
	Time synchronisation	PD	21/10	29	27/11	5	50%
	PAPR (MATLAB)	PD	21/10	29	06/11	8	100%
Mitigation techniques	Carrier frequency offset	RT+PD	04/11	22	18/11	3	100%
	Time synchronisation	RT+PD	04/11	22	18/11	3	100%
	Filtering	RT+PD	04/11	22	25/11	7	
Stretch Goals	Carrier frequency offset	RT+PD	25/11	14	10/10	42	100%
	Filtering	RT+PD	25/11	14			
	Inter-user synchronisation	RT+PD	25/11	14			
	Interactive GUI	RT+PD	25/11	14			
Seminars	Presentation 1	RT+PD	15/10	2	16/10	2	100%
	Practice 1	RT+PD	21/10	2	22/10	1	100%
	Presentation 2	RT+PD	12/11	2	13/11	1	100%
	Practice 1	RT+PD	18/11	2	18/11	2	100%
Report	Writing	RT+PD	15/10	48	23/10	42	70%
	Proofread	RT+PD	05/12	4	04/12	1	
Poster	Content	RT+PD	25/11	3	28/11		
	Layout	RT	02/12	3	05/11		
	Proofread	RT	06/12	1			
Presentation	Slides	RT+PD	30/11	4			
	Practice	RT+PD	02/12	3			

GDP 43

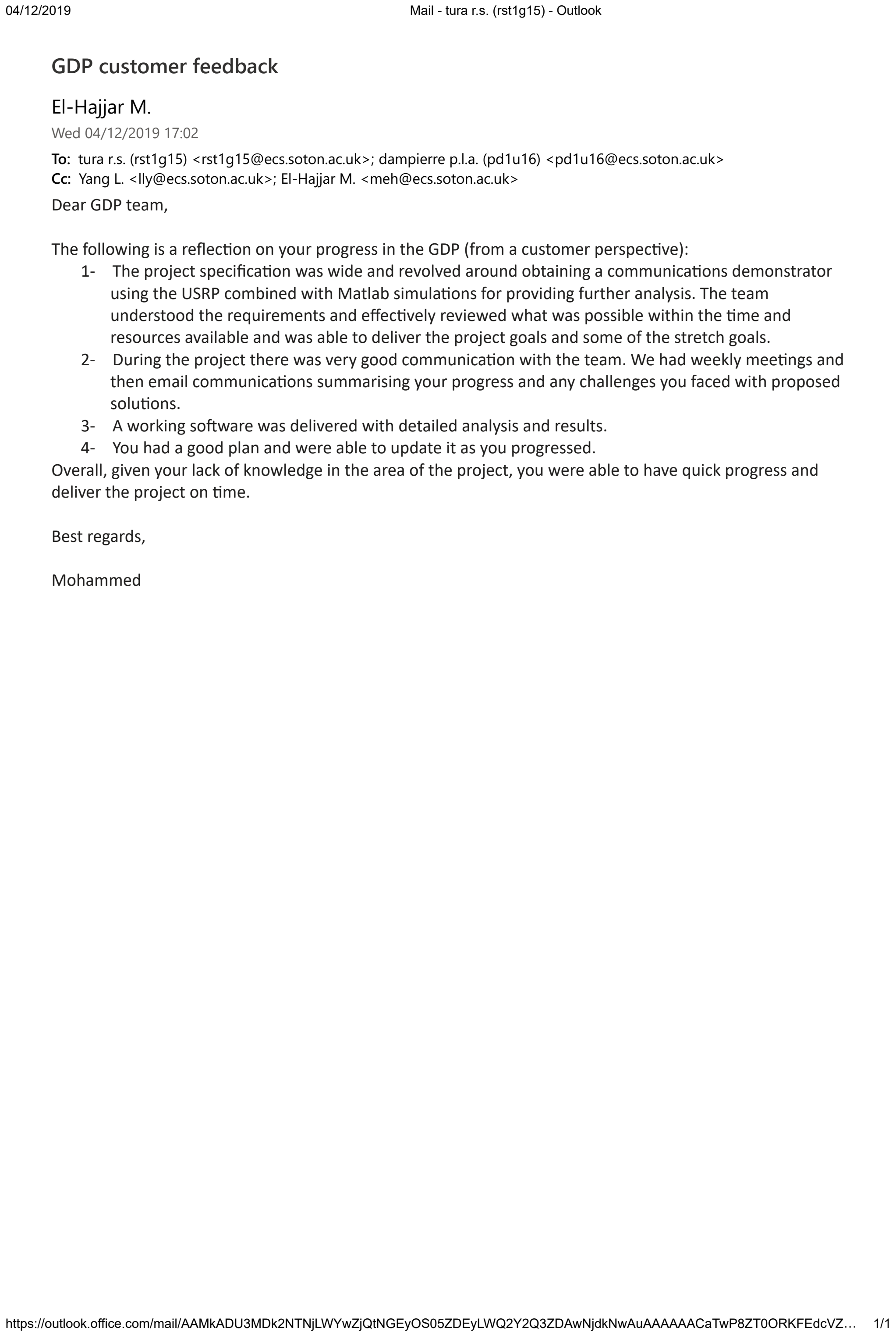
Date Highlight: 09/12/19

CATEGORY	ACTIVITY	ASSIGNEE	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Build MATLAB	Basic design	PD	07/10	2	07/10	2	100%
	OFDM	PD	08/10	2	08/10	14	100%
	4G	PD	09/10	1	14/10	14	100%
	5G	PD	14/10	2	06/11	8	100%
Build USRP	Set up USRP	RT	07/10	3	07/10	3	100%
	Basic design	RT	09/10	1	10/10	26	100%
	OFDM	RT	14/10	2	29/10	26	100%
	4G	RT	15/10	2	23/11	10	100%
	5G	RT	16/10	1	24/11	10	100%
Analyse/Test	Cyclic prefix	PD	21/10	29	04/11	1	100%
	Channel estimation	PD	21/10	29	22/10	14	100%
	Time synchronisation	PD	21/10	29	27/11	7	50%
	PAPR (MATLAB)	PD	21/10	29	06/11	8	100%
Mitigation techniques	Carrier frequency offset	RT+PD	04/11	22	18/11	3	100%
	Time synchronisation	RT+PD	04/11	22	18/11	3	100%
	Filtering	RT+PD	04/11	22	25/11	8	100%
Stretch Goals	Carrier frequency offset	RT+PD	25/11	14	10/10	42	100%
	Filtering	RT+PD	25/11	14	03/12	3	100%
	Inter-user synchronisation	RT+PD	25/11	14			
	Interactive GUI	RT+PD	25/11	14			
Seminars	Presentation 1	RT+PD	15/10	2	16/10	2	100%
	Practice 1	RT+PD	21/10	2	22/10	1	100%
	Presentation 2	RT+PD	12/11	2	13/11	1	100%
	Practice 1	RT+PD	18/11	2	18/11	2	100%
Report	Writing	RT+PD	15/10	48	23/10	44	100%
	Proofread	RT+PD	05/12	4	04/12	2	100%
Poster	Content	RT+PD	25/11	3	28/11	8	100%
	Layout	RT	02/12	3	05/11	31	100%
	Proofread	RT	06/12	1	05/12	1	100%
Presentation	Slides	RT+PD	30/11	4	06/12	1	100%
	Practice	RT+PD	02/12	3	09/12	3	100%



Appendix L

External Partner Support



04/12/2019 Mail - tura r.s. (rst1g15) - Outlook

GDP customer feedback

El-Hajjar M.

Wed 04/12/2019 17:02

To: tura r.s. (rst1g15) <rst1g15@ecs.soton.ac.uk>; dampierre p.l.a. (pd1u16) <pd1u16@ecs.soton.ac.uk>
Cc: Yang L. <lly@ecs.soton.ac.uk>; El-Hajjar M. <meh@ecs.soton.ac.uk>

Dear GDP team,

The following is a reflection on your progress in the GDP (from a customer perspective):

1- The project specification was wide and revolved around obtaining a communications demonstrator using the USRP combined with Matlab simulations for providing further analysis. The team understood the requirements and effectively reviewed what was possible within the time and resources available and was able to deliver the project goals and some of the stretch goals.
2- During the project there was very good communication with the team. We had weekly meetings and then email communications summarising your progress and any challenges you faced with proposed solutions.
3- A working software was delivered with detailed analysis and results.
4- You had a good plan and were able to update it as you progressed.

Overall, given your lack of knowledge in the area of the project, you were able to have quick progress and deliver the project on time.

Best regards,

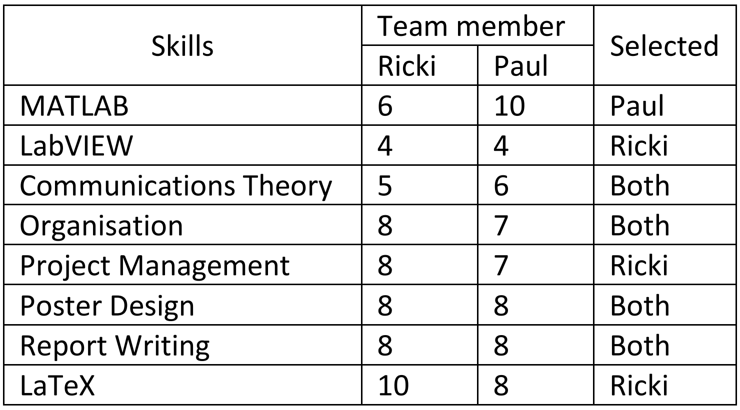
Mohammed

https://outlook.office.com/mail/AAMkADU3MDk2NTNjLWYwZjQtNGEyOS05ZDEyLWQ2Y2Q3ZDAwNjdkNwAuAAAAAACaTwP8ZT0ORKFEdcVZ… 1/1

FIGURE L.1: An email from the project supervisor and acting customer for this project supporting the project's progress.

Appendix M

Skills Audit



Skills	Team member		Selected
	Ricki	Paul	
MATLAB	6	10	Paul
LabVIEW	4	4	Ricki
Communications Theory	5	6	Both
Organisation	8	7	Both
Project Management	8	7	Ricki
Poster Design	8	8	Both
Report Writing	8	8	Both
LaTeX	10	8	Ricki

Figure M.1: A skills audit carried out to help assign project tasks.

Appendix N

Critical Path Analysis

Figure N.1 is a PERT chart that describes the flow of the project. The project's tasks are identified and then arranged based on how they depend on each other. Each task has an early start, early finish, late start, and late finish timings which allow for flexible planning when organising work and maintaining progress. From the PERT chart, the critical path is as follows:

- Initial work
- Build
- Analysis and Test
- Final Presentation

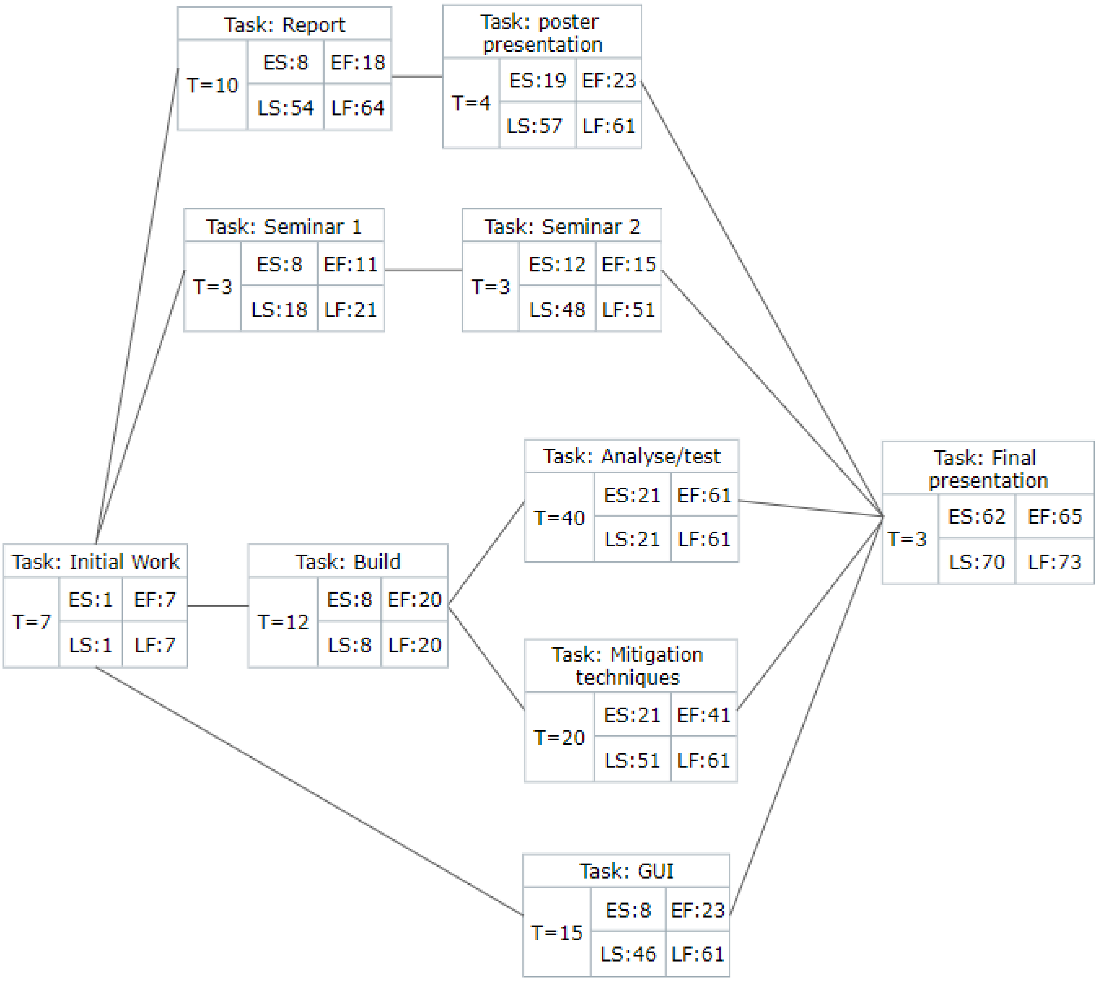


Figure N.1: A PERT chart for the project.

Appendix O

Risk Management

Risk Management

Risks

Technical

RT1: Software crashing – medium risk (software crashing is frequent but the impact is minor as all the progress is saved externally)
RT2: NI USRP crashing – medium risk (reliable hardware is less likely to fail but the impact on the project would be major)
RT3: Losing files – medium risk (losing files is improbable as the group is using the Southampton git to version control and save our files but the severity is catastrophic)
RT4: Overambitious Goals – medium risk (overambitious goals would compromise the success of the project but strong time management would allow us to crash tasks in order to finish project successfully)

Personnel

RP1: Illness – high risk (probability of a team member falling ill is frequent and the severity of the risk is major as the team only has 2 members)
RP2: Unavailability of team members – low risk (due to diligent management it is improbable that any team members would be unavailable for a period of time that would jeopardise the success of the project)

External

RE1: Unavailability of our supervisors – low risk (our supervisors have assured us that they will be available for the duration of the project)

Risk Assessment	**Severity**				
Probability	Insignificant	Minor	Moderate	Major	Critical
Rare	🟩	🟩	🟩	🟨 RT2, RT3	🟧
Unlikely	🟩	🟩 RP2, RE1	🟨	🟨	🟧
Possible	🟩	🟨	🟨 RT4	🟧 RP1	🟧
Likely	🟨 RT1	🟨	🟧	🟧	🟥
Almost Certain	🟨	🟨	🟧	🟥	🟥

🟩 low risk
🟨 medium risk
🟧 high risk
🟥 critical risk

Management

Contingency into the schedule

Effective Technology Transfer/Reporting so that team members can put in some effort into tasks that prove more challenging than originally planned.