

# Lab Manual: Communications Principles

Using the EMONA Communications Explorer board  
for ADS MAX



## Introduction & Sample Chapter





## Documented capabilities of the Emona Communications board

Lab 1: Introduction to the EMONA Communications Explorer Board

Lab 2: Modeling equations

Lab 3: FFT and Spectra

Lab 4: Amplitude Modulation

Lab 5: Amplitude Demodulation

Lab 6: DSBSC Modulation and Demodulation

Lab 7: SSB Modulation and Demodulation

Lab 8: FM Modulation

Lab 9: FM Demodulation

Lab 10: FSK

Lab 11: BPSK

Lab 12: QPSK

Lab 13: Introduction to DSSS

Lab 14: SNR and BER measurements

Lab 15: Principles of OFDM

Lab 16: Sampling, PAM and Nyquist

Lab 17: Carrier regeneration with Costas Loop

Lab 18: ASK Modulation and Demodulation

Lab 19: Principles of Superheterodyne

Lab20: Channel characterization

Lab21: Introducing SDR principles with AM, PM and FM

Lab22: Introducing M-level QAM, PSK, MSK modulation in SDR

**>>> SAMPLE CHAPTER Lab23: Introducing OFDM in SDR**

## Introduction

This Communications Principles Lab Manual covers a broad range of introductory digital and analog telecommunications topics through a series of hands-on laboratory experiments. Each experiment is written to support the theoretical concepts introduced in the class work of a first course in modern telecommunications.

In order to make the student's learning experience more memorable, the student is able to view a variety of signals on the ADS MAX oscilloscope including their own voice undergoing the modulation or coding being investigated.

Each lab experiment presents an interesting, hands-on learning experience for the student. In each experiment the student is challenged to build, measure and consider: there are no “instant” or “cookbook-style” experiments. The EMONA Communications Explorer Board is actually a true engineering modeling system where students see that the block diagrams so common in their textbooks represent real functioning systems.

## Prerequisites

Experiments in this volume have been prepared for students with only a basic knowledge of mathematics and a limited background in physics and electricity.

Students with a higher level of competence in mathematics will also gain a deeper understanding of telecommunications theory by using this system. Due to the engineering “modeling” nature of the board, they will be able to investigate more complex issues, carry out additional measurements and then contrast their findings to their theoretical understanding and mathematical analysis.

This lab manual was designed for students who have completed the following courses and have a working knowledge of the following hardware, software, and tools.

## Background: Teaching methodology behind the “block diagram approach”

The Emona Communications Explorer board draws on a well-established experimental methodology that brings to life the “universal language” of telecommunications, the BLOCK DIAGRAM. Originally developed in the 1970’s by Tim Hooper, a senior lecturer in telecommunications at The University of New South Wales, Australia, and further developed by Emona Instruments, this modeling approach is used by thousands of students around the world, **to implement practically any form of modulation or coding.**

### Block Diagrams

Block diagrams are used to explain the principle of the operation of electronic systems (like a radio transmitter for example) without worrying about how the circuit works. Each block represents a part of the circuit that performs a separate task and is named according to what it does. Examples of common blocks in communications equipment include the *adder*, *multiplier*, *oscillator*, and so on.

The board is a collection of blocks (called modules) that are patched together to implement dozens of telecommunications experiments. Experiments make use of the board together with the ADS MAX providing the instrumentation.

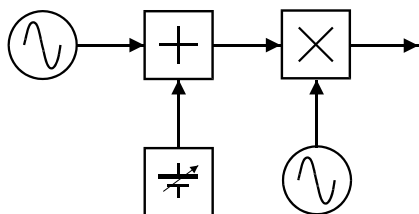


Figure 1: Example block diagram

This approach to implementing telecommunications experiments through realizing BLOCK DIAGRAMS has the following benefits in the educational environment:

- Students gain practical experience with true mathematical modeling hardware, designed specifically for implementing telecommunications theory.
- Students actually build each experiment stage-by-stage, in an engineering manner, by following the BLOCK DIAGRAM.

- Students are free to try “what-if” scenarios to validate their understanding of the theory being investigated, by viewing real, real-time electrical signals.
- The board is designed to allow students to make mistakes, hence students will learn from their hands-on experiences as they investigate their findings.

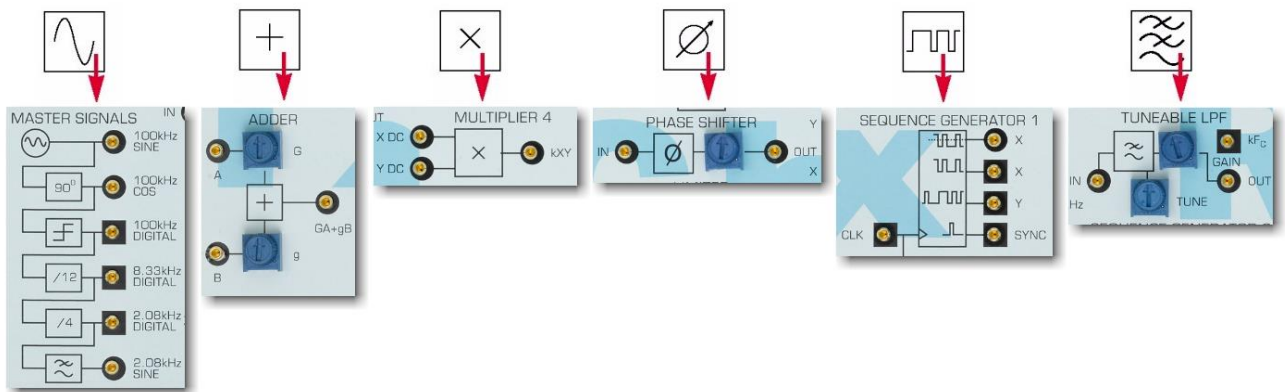


Figure 2: Example individual circuit blocks

### One-to-One Relationship

The figure above illustrates the one-to-one relationship between each block of the BLOCK DIAGRAM and the independent functional circuit blocks of the board.

The functional blocks of the board are used and re-used in experiments, just as blocks of the block diagram reappear in many different implementations, and just as LabVIEW blocks are interconnected to form program flows.

# Lab 1: Introduction to the EMONA Communications Explorer board

## Learning Objectives

After completing this lab, you should have the ability to complete the following actions.

1. Use the ADS MAX Oscilloscope and Function Generator
2. Describe the basic functionality of individual circuit modules on the board.
3. Patch together these modules to model block diagrams and build systems.

# Lab 2: Modeling equations

## Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Contrast the addition of electrical signals in relation to the math of addition
2. Describe the effect of phase shifts on signals
3. Understand the relationship between math theory and its implementation with real electrical circuits

# Lab 3: FFT and spectra

## Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Understand the spectrum of an impulse train.
2. Understand the spectrum of a filtered impulse train.
3. Understand the relationship between the duty cycle of a periodic pulse train and its spectrum.
4. Understand the finite spectrum of a sinc pulse train.
5. Understand the spectrum of variable-length pseudorandom sequence and how such sequences can be used for analog noise generation.
6. Understand the effects of clipping and half-wave rectification on a signal's spectrum.

## Lab 4: Amplitude Modulation

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real AM signal
2. Examine a real AM signal with scope and compare it to its original message
3. Use multiple message sources in your AM examination
4. Describe the term “depth of modulation”

## Lab5: Amplitude Demodulation

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real AM signal
2. Examine a real AM signal with scope and compare it to its original message
3. Use multiple message sources in your AM examination
4. Demodulate an AM signal using two different methods
5. Describe the effects and meaning of over- and under-modulation of the carrier
6. Compare original and demodulated signals
7. Explain the term “product modulation” as well as the math.

## Lab 6: DSBSC modulation & demodulation

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real DSBSC signal
2. Examine a real DSBSC signal with scope and compare it to its original message
3. Use multiple message sources in your DSBSC examination
4. Describe the term “depth of modulation”
5. Describe the effects and meaning of over and under modulation of the carrier
6. Compare original and demodulated signals
7. Describe distortion in the recovered signal

8. Identify the effect of phase and frequency errors on the demodulation process
9. Explain the term “product modulation”

## Lab 7: SSB modulation & demodulation

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real SSB signal
2. Examine a real SSB signal with a scope
3. Discuss the differences between SSB and DSBSC
4. Demodulate an SSB signal

## Lab 8: FM Modulation

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real FM signal using multiple messages
2. Examine a real FM signal with scope and compare it to its original message
3. Calculate the power in the FM signal
4. Describe the bandwidth of an FM signal
5. Calculate the frequency deviation of the FM modulator

## Lab 9: FM Demodulation

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Describe a zero-crossing detection method
2. Discuss frequency to voltage translation
3. Recover a variety of FM modulated messages
4. Describe the FM spectrum of FM modulated speech

## Lab 10: Frequency Shift Keying (FSK)

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real FSK signal
2. Describe the concepts of mark and space in the signal
3. Recover the data from an FSK signal using envelope detection
4. Explain the use of a comparator with bandlimited data signals in FSK

## Lab 11: Binary Phase Shift Keying (BPSK)

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real BPSK signal
2. Describe a BPSK signal in time and frequency domain
3. Explain the use of product demodulation in BPSK
4. Explain the need for data recovery in BPSK demodulation

## Lab 12: Quadrature Phase Shift Keying (QPSK)

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Examine the operation of a Serial to Parallel converter and v/v
2. Generate real BPSK and QPSK signals
3. Describe a QPSK signal in time and frequency domain
4. Explain the use of product detector demodulation in BPSK and QPSK
5. View QPSK as constellation, including phase delays

## Lab 13: Introduction to DSSS (Spread Spectrum)

In this lab you will create a DSSS signal with a simple message, explore its characteristics in the frequency domain, understand how DSSS is recovered with a unique key and why it is resistant to jamming and interference.

## Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real DSSS signal using a simple message
2. Describe the spectrum of a DSSS signal
3. Discuss the recovery of a DSSS signal: what works, what doesn't
4. Discuss the resistance of DSSS to jamming signals

## Lab 14: SNR & BER measurements

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Create an eye diagram
2. Identify the optimum sampling point in a noisy signal
3. Calculate Signal to Noise measurements
4. Calculate Bit Error Rates (BER) for digital signals
5. Plot BER vs. SNR diagrams for a digital signal
6. Create a noisy baseband channel between transmitter and receiver

## Lab 15: Principles of OFDM

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Build an OFDM signal with 3 subcarriers
2. Recover the data using an Integrate & Dump process
3. Understand the meaning of orthogonality of subcarriers
4. Recognise the data carrying capacity of multiple channels
5. Describe the limitations due to PAPR
6. Introduce the concept of IDFT

## Lab 16: Sampling & Reconstruction

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Understand natural sampling and sample-and-hold approaches and what these approaches look like when applied to time domain signals.
2. Understand the frequency-domain representation of a sampled signal.
3. Understand the role of a reconstruction filter when recovering a sampled signal.
4. Understand the cause of aliasing in a sampled system and its relationship to the Nyquist Sample Rate.

## Lab 17: Carrier regeneration with the Costas Loop

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Build a Costas loop
2. Regenerate a carrier signal from carrier-less incoming signal
3. Understand the effect of the control voltage on the VCO
4. Appreciate the necessity of tuning the loop VCO
5. Recover from both analog and digital signals
6. Understand the basics of loop analysis

## Lab 18: ASK modulation & demodulation

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Generate a real ASK signal at both baseband and bandpass
2. Describe the concept of amplitude modulation with digital data
3. Recover the data from an ASK signal using envelope detection
4. Explain the use of a comparator with bandlimited data signals in ASK
5. Recognize the frequency spectrum of ASK signals

## Lab 19: Principles of Superheterodyne

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Describe the superheterodyne process and its benefit
2. Discuss the purpose of the IF stage
3. Describe the tuning capability of the local oscillator
4. Discuss the necessity of synchronization of carriers

## Lab 20: Channel characterization

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Evaluate channel characteristics
2. Consider amplitude, phase and frequency effects
3. Familiarity with a Bode Analyzer
4. Understand the benefits of channel equalization

## Lab 21: Introducing SDR principles with AM PM FM

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Implement modulation with complex modulation signals
2. Contrast continuous math with complex IQ notation
3. Familiarity with a Quadrature Modulator
4. Understand the difference between AM, PM and FM from in complex domain
5. Describe modulation with phasor diagrams.

## Lab 22: Introducing M-level QAM / PSK in SDR

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Examine the operation of M-level modulation scheme
2. Implement various M-level modulation schemes via I & Q
3. Describe M-level modulation in time and frequency domain
4. Explore Constant Envelope modulation schemes
5. Extend your investigation to other IQ based schemes.

## Lab 23: Introducing OFDM in SDR

### Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Build an OFDM signal with 8 complex subcarriers
2. Implement complex OFDM symbols at passband
3. Utilize the principle of IFFT
4. Recognize the noise resistance of multiple frequency channels
5. Understand the necessity of Channel Equalization
6. Utilize Test Vectors to characterize a channel

# Lab Manual: Communications Principles

Using the EMONA Communications Explorer board  
for ADS MAX



## Lab 23: Introducing OFDM in SDR



*List of Updates*

<b>Date</b>	<b>Details</b>
20/7/2025	Introduced to ADS MAX implementation

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# Lab 23: Introducing OFDM in SDR

## Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Build an OFDM signal with 8 complex subcarriers
2. Implement complex OFDM symbols at passband
3. Utilize the principle of IFFT
4. Recognize the noise resistance of multiple frequency channels
5. Understand the necessity of Channel Equalization
6. Utilize Test Vectors to characterize a channel

## Prerequisites

You should have completed Lab 1, Lab 2 and Lab 15 and be familiar with the equipment, its use and the handling precautions for the equipment.

## Required Tools and Technology

Platform: ADS MAX

Instruments used in this lab:

- Oscilloscope-Time
  - Oscilloscope-FFT
  - Function Generator
- 

Hardware: Emona Communications Board

Components used in this lab:

- Six BNC to 2mm banana-plug leads
  - Assorted 2mm banana-plug patch leads
  - Set of headphones or earbuds
- 

Software: DIGILENT WaveForms

V3.23.72 or later

Files used in this lab:

**L23-setup-datastream\*.dwf3work**

**L23-setup-TestPattern\*.dwf3work**

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## Expected Deliverables

In this lab, you will collect the following deliverables:

- ✓ Calculations
- ✓ Data from measurements
- ✓ Observations
- ✓

Your instructor may expect you complete a lab report. Refer to your instructor for specific requirements or templates.

## Section 1: Mapping data bits to OFDM symbols

### 1.1 Theory and Background

OFDM, Orthogonal Frequency Division Multiplexing, sounds very intimidating at first, but once we break down this label we will see that it is already quite familiar. “Frequency Division Multiplexing” is now a familiar concept from previous experiments. It is the multiplexing, or distributing, of a data stream amongst multiple frequencies.

A single main data stream is split into many lower rate data streams (multiplexing). Each one of these streams is then individually modulated onto a separate sub-carrier (modulation) and finally recombined into a single composite OFDM signal to be transmitted.

“Orthogonal” means “independent of each other” and refers to the frequencies involved in each sub carrier. These frequencies need to be independent to each other and this is achieved by choosing their respective frequencies carefully. We will find that each frequency, or “sub-carrier” will be orthogonal to the others if they are all harmonically related to each other. Simply put, each of the frequencies used should be integer multiples of each other eg 1kHz, 2kHz, 3kHz, ... or perhaps 5kHz, 10,kHz, 15kHz,

What is special about this relationship is that the nulls in the frequency spectrum of each modulated subcarrier will occur at the same frequency, which allows each subcarrier’s main node to be independent of its adjacent subcarriers, again, in the frequency domain.

Although the carriers overlap in the frequency domain, they can be perfectly separated in the receiver because they are orthogonal. The orthogonality property means that the null points of the spectra align.

This is exhibited in Figure 1 below

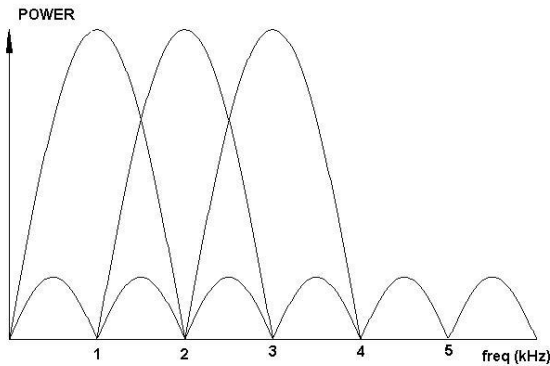


Figure 1: Orthogonal subcarriers in frequency domain

For simplicity in this example the number of carriers  $N$  is chosen to be three.

The sub-carriers to be used are as follows:

- a) 1 kHz subcarrier to be BPSK modulated by the 1 kbps data signal 1
- b) 2 kHz subcarrier to be BPSK modulated by the 1 kbps data signal 2
- c) 3 kHz subcarrier to be BPSK modulated by the 1 kbps data signal 3

Each of the 3  $m(t)$  signals is an independent data stream which is used to modulate each of the respective sub-carriers. By using three bipolar data outputs we can multiply each of them with a sub-carrier to form 3 independent BPSK signals. One can think of each data bit as being the coefficient of that particular sub-carrier frequency component at that instant in time.

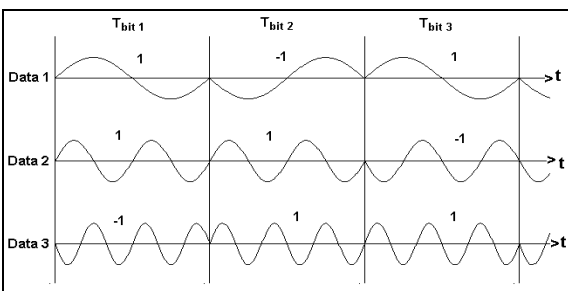


Figure 2: Subcarriers in time domain

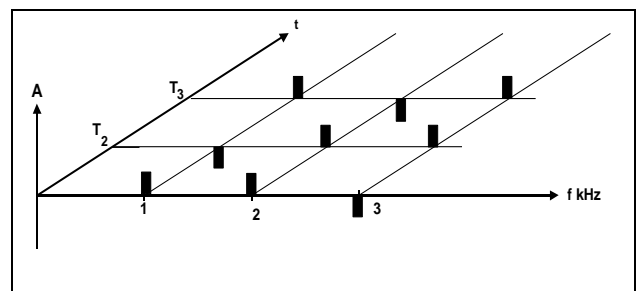


Figure 3: Subcarriers in frequency domain

To implement the IDFT in analog form, these three BPSK signals are then added together. In this way the parallel bits together form a set of coefficients of all the sub-carriers at each instant in time. Think of this as an “additive synthesis”.

Let us explore this process further. Imagine that we have our 3 bit streams represented as follows:

Data 1: 1, -1, 1, -1, 1..... Data 2: 1,1,-1,-1,-1..... Data 3: -1,1,1,-1,1.....

Data1 is the relative phase of the 1 kHz sub-carrier as a BPSK signal. Data2 and Data3 are of the 2 kHz and 3 kHz signals respectively.

For the duration of the first bit period, we will have a non-inverted 1 kHz carrier, a non-inverted 2 kHz carrier, and an inverted 3 kHz carrier relative to the other two.

For the duration of the second bit period, we will have an inverted 1 kHz carrier, a non-inverted 2 kHz carrier, and a non-inverted 3 kHz carrier.

These signals are all added together to form the output of our IDFT function and the basis for our OFDM signal. This is illustrated below in Figure 4.

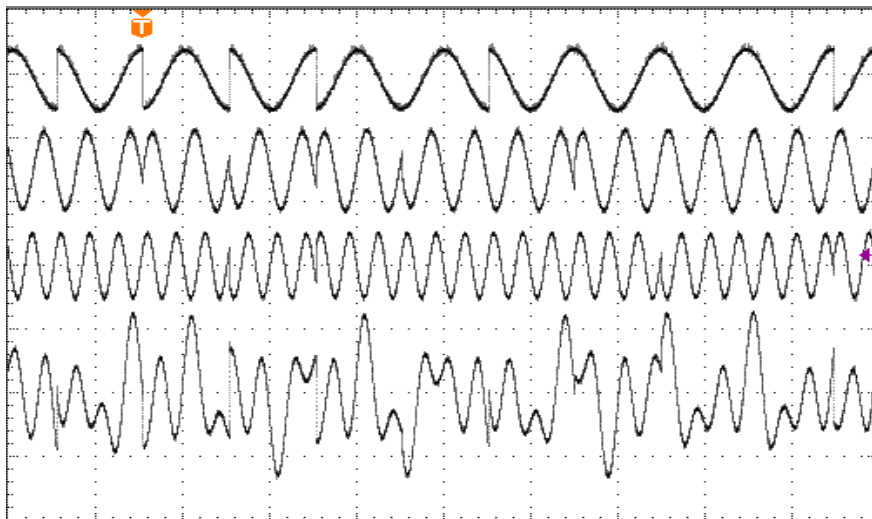


Figure 4: Individual subcarriers; and summed together

## 1.2 Introducing complex modulation

In a previous Lab 12, we introduced the mapping of multiple digital bits onto dual orthogonal carrier waveforms known as Quadrature Modulation QPSK.

If we wish to map more than 1 bit at a time ie 2 bits, this will encode to 4 possible states. These must be mapped to a quadrature pair of signals to enable 4 states to be encoded per “symbol”.

By decimating a bit data stream into bit pairs, these pairs can be mapped via QAM modulation to a 4 point complex QAM baseband waveform. This 2 bit mapping can be

carried out for multiple subcarrier frequencies and then these multiple QAM waveforms can be added together to create a multiple frequency waveform (like FDM) with distinct (orthogonal) bit pair data being carried at each frequency. We call this Orthogonal Frequency Division Multiplexing, OFDM and this modulation signal is constructed at baseband. Again, think of this as an “additive synthesis” of a continuous-time analog signal.

As you may intuit, the relevant parameters are:

- how many bits per sub-carrier frequency
- how many distinct sub-carrier frequencies per accumulated waveform
- how many samples per waveform cycle is this waveform is to be constructed digitally.

In this experiment we will use the following parameters:

- 2 bits per sub-carrier, mapped as QAM ie: 0:1 >> -1:+1 V (for simplicity)
- 8 sub-carriers (plus DC) set 1kHz apart (for convenience)
- 16 bits, or 8 complex points per OFDM “symbol”
- 64 samples per OFDM symbol of duration 1ms (to meet Nyquist sampling criteria)

It is easy to visualise this mapping process as follows:  
Imagine a bit stream:

10 11 00 10 10 00 01 ....

Mapped to complex pairs as per QAM mapping as follows:

<b>b0, b1</b>	<b>i , q</b>
0, 0	{+1, +1}
0, 1	{-1, +1}
1, 0	{+1, -1}
1, 1	{-1, -1}

This results in complex point stream  
{+1, -1} {-1, -1} {+1, +1} {+1, -1} {+1, -1} {+1, +1} {-1, +1} ...

And each of these points would be sequentially applied to 8 subcarriers:

f1, f2, ...f7, f8

This covers 8 complex points, which results in 8 cos/sin signal pairs being added together for a time duration of 1 ms...that is one 1kHz cycle. This period is known as an OFDM symbol time.

We have chosen to sample this symbol at 64kSps resulting in 64 points per 1 ms period.

This summation of complex weighted sinusoidal signal pairs looks like this:

$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} (A_k + jB_k) \left[ \cos\left(\frac{2\pi kn}{N}\right) + j\sin\left(\frac{2\pi kn}{N}\right) \right]$$

Figure 5: Equation for IFFT

Where  $N = 64$  and  $x[n]$  is a complex stream with  $n = 64$ . Both domains have 64 points.

In summary what is happening is a mapping of numerous complex frequency components back to a complex continuous time domain signal. We are reconstructing a signal from the addition of multiple singular frequencies.

This process can be accomplished with an IFFT transform.

64 discrete complex coefficients in: 64 complex time domain samples out.

Since we are only interested in 8 + 8 subcarriers (positive and negative), 48 (64-16) components of the IFFT remain unused and left as zero. We are only utilizing the lower 8 subcarriers so that they are oversampled to capture them with higher resolution.

Remember, when we mention “complex” values or signals this simply indicates that two values or signals are being handled at once.

Also note, that the resultant complex time domain signal will include both positive AND negative frequency components. Read up about “negative” frequency components and ensure you understand them. In short, they are sinusoids whose time domain response is the reverse of positive frequencies and enable us to represent frequencies below 0 Hz mathematically. This all makes sense once you modulate these signals up to passband eg 100kHz. You will then have sidebands above 100kHz as expected...and also below 100kHz due to the “negative” frequency components.

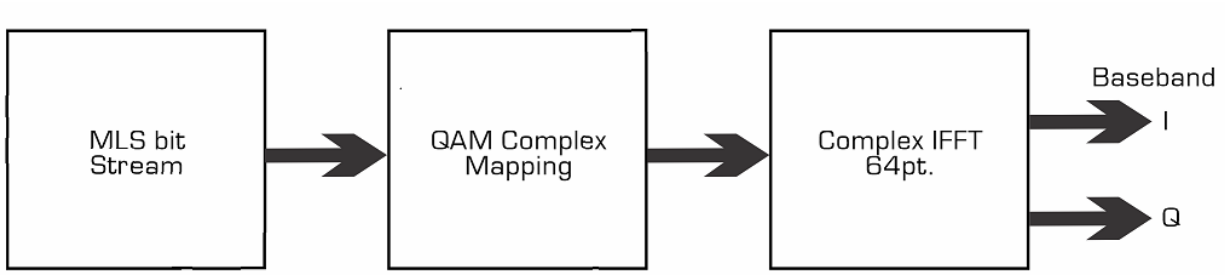


Figure 6: Bit mapping to symbol block diagram

An excellent online source material about this is:

*Lyons, R., Quadrature Signals: Complex, But Not Complicated*

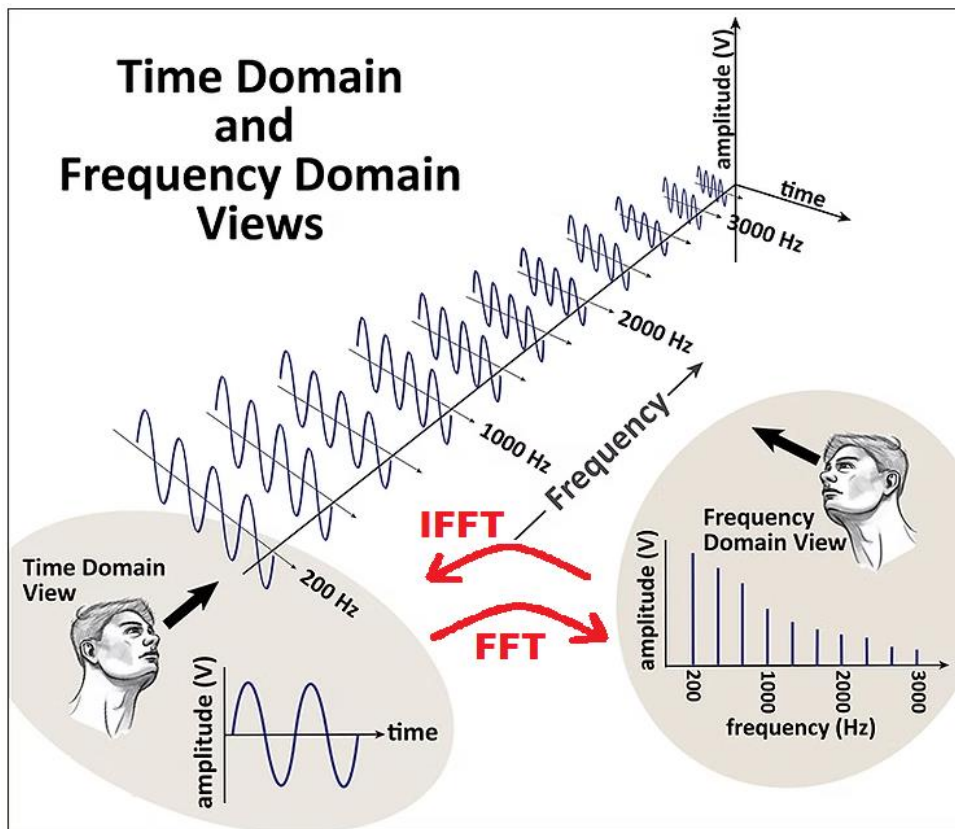


Figure 7: The dual perspectives of time and frequency domains

From <https://www.hamradioschool.com/post/time-frequency-domain-signal-views>

## 1.2 Implement: Creating the OFDM I/Q modulation signals

In this experiment we are working within the limitation of the analog i/o available on the ADS MAX unit. We will output the predefined I/Q signals from the FUNCTION GENERATOR outputs FG1 and FG2. These are passed to the IQ modulator and multiplied up to the passband at 100kHz on the DXIQ Communications Explorer board.

Following that the single OFDM passband signal will be passed through a “channel” and then demodulated back down to baseband .

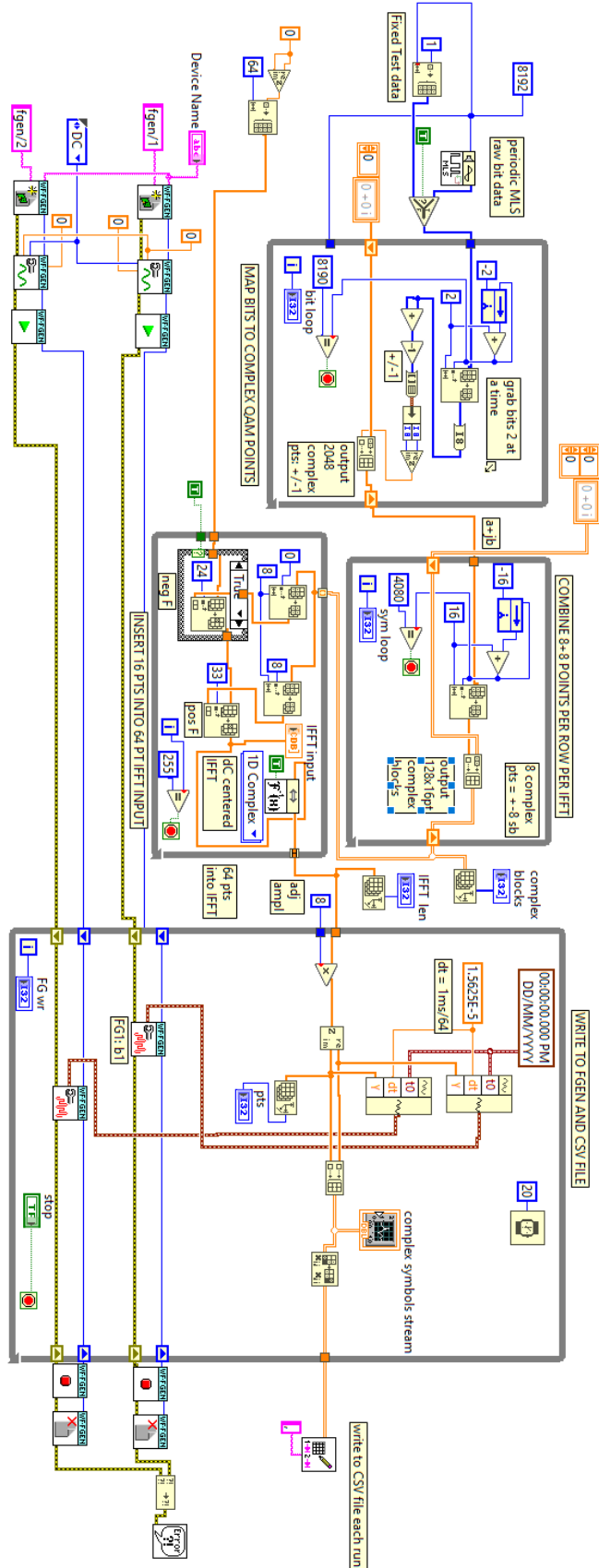
Using the 4 channel Scope instrument, we can view all these signals in both the time and frequency domains.

The predefined IQ signals have been created in LabVIEW from a 8192 bit MLS data stream, mapped to a complex QAM pair and then passed through a complex IFFT block...as discussed above. This results in 256 sequential unique symbols.

The resulting sampled complex output streams are saved in and output from the ADS MAX Function Generator using its Custom waveform IMPORT mode.

This is a powerful feature which enables us to load various signals for relevant parts of the experiment and has been used several times throughout this Lab Manual.

Figure 8: LabVIEW code to generate the pre-defined OFDM IQ baseband signals



## Powering up the ADS MAX + EMONA Communications Explorer Board

1. Ensure that the ADS MAX Application Board power button at the top left corner of the unit is OFF (not illuminated).
2. Carefully plug the Emona Communications board (ECB) into the ADS MAX ensuring that it is fully engaged both front and back.
3. Ensure that you have connected the ADS MAX to the PC using the USB cable and that the PC is turned on.
4. Turn on the Application Board *Power* button by pressing it once and confirm that it is illuminated. The LEDs on the ECB should also be illuminated. If they are not, then switch the unit off immediately and check for connection or insertion errors.
5. Open the WAVEFORMS software on your PC.  
Open the supplied workspace file for this experiment:  
**L23-setup-datastream\*.dwf3work**

The instrument panel will open into a convenient configuration relating to this experiment. You can modify and save the workspace configuration to suit yourself

6. RUN each of the tabbed instruments when needed and when switching between tabs. Refer to the WAVEFORMS User documentation for details about each instrument.

### Scope Configuration

Channel Voltage range	2V/div
Horizontal Timebase	1ms/div
Trigger	Type: Analog edge, Source: Channel 1 input, Rising
Probe Attenuation	1x

### 1.3 Implement: Build the IQ modulator with OFDM IQ signals

In this particular experiment we will start with the predefined I/Q signal pair and pass this a Quadrature Modulator to move the signal up to the passband at 100kHz.

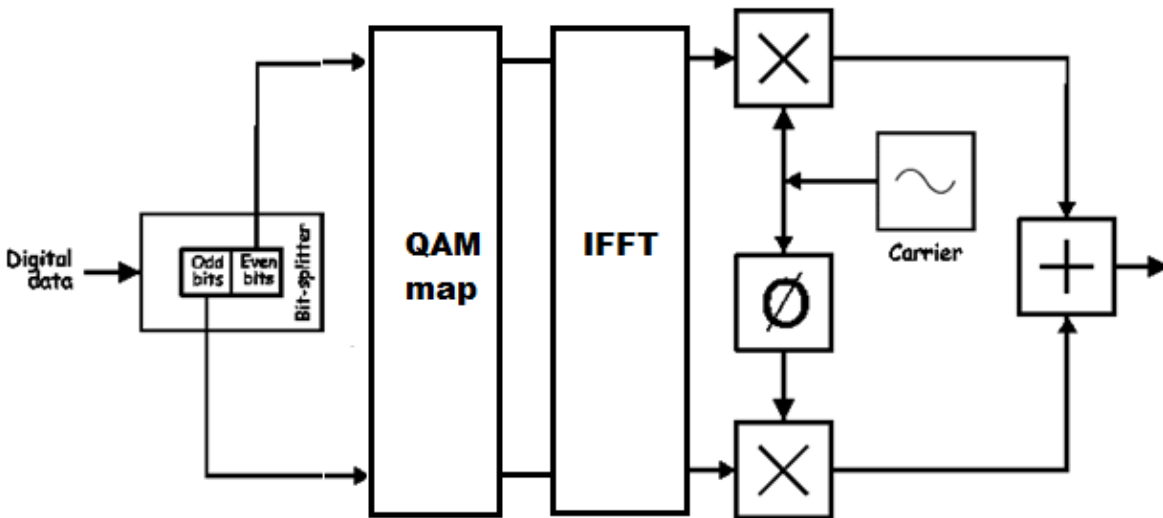


Figure 9: System block diagram for modulation

1. Build the Quadrature Modulator with input connections from the dual FUNCTION GENERATORS. Load the workspace. .RUN ALL the WAVEGEN and connect the scope channels to both I/Q input signals as well as the passband signal at the output of the Modulator.

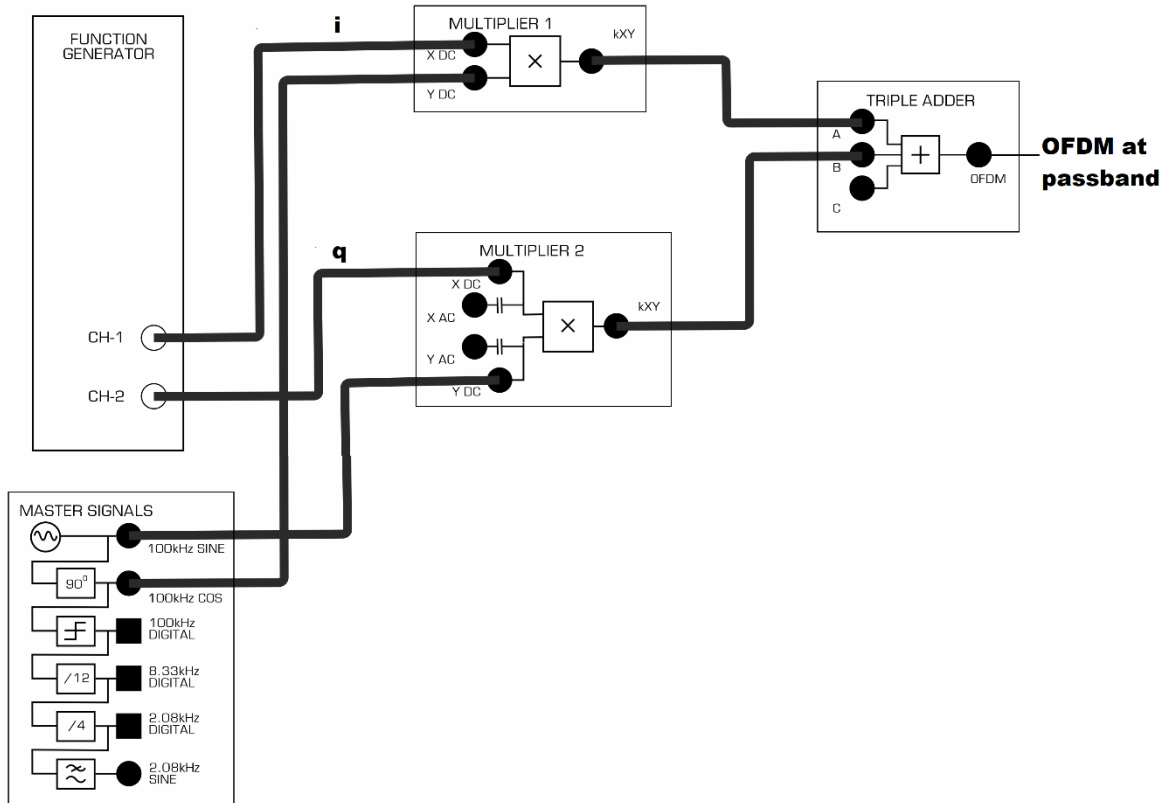


Figure 10: Modulation patching diagram

2. View all 3 signals in both the time and frequency domains.

3-1 What can you observe about the spectrum of each signal ? Discuss negative frequencies ?

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3. View the I/Q signals with a Timebase setting of 500us/div. Can you notice a periodic discontinuity every 1 ms on both signals? The signal between these discontinuities is known as an OFDM “symbol”.

3-2 Why are there discontinuities ? What is the sampling rate ? How many samples per OFDM symbol ?

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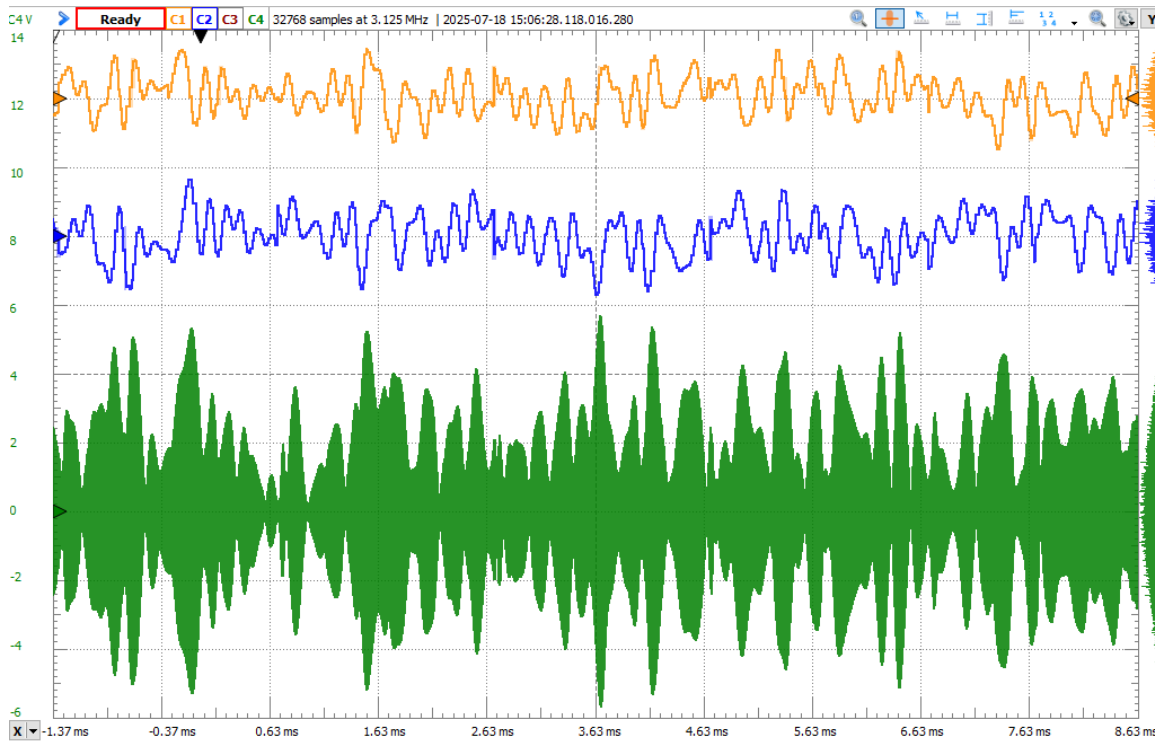


Figure 11: Example baseband I/Q signals and passband for OFDM

Notice that although a constant-envelope modulation scheme such as QAM is used for every carrier, the OFDM signal does not have constant envelope. Since the OFDM signal is the sum of many carriers, it has very high Peak to Average Power Ratio (PAPR). If the maximum amplitude on one carrier is  $V$ , the maximum possible amplitude of the OFDM signal is  $N \times V$ , for  $N$  sidebands. This maximum will be achieved when all the carriers are aligned, which, in general, when  $N$  is large occurs very rarely.

$$PAPR = \frac{|x(t)|^2}{P_{avg}}$$

- The high PAPR is the major practical disadvantage of OFDM. The high PAPR requires OFDM transmitters to use power amplifiers that are a linear over a very wide range. Since the maximum amplitude of the transmitted signal occurs rarely, only a small range of the power amplifier must be used most of the time. This is very inefficient. Although any non-linearities present in the transmitter chain will increase the BER, some amplitude clipping (which is a nonlinear operation) is used in practical systems. Since it happens very rarely, it can be tolerated.

Keep this issue in mind throughout the rest of the experiment.

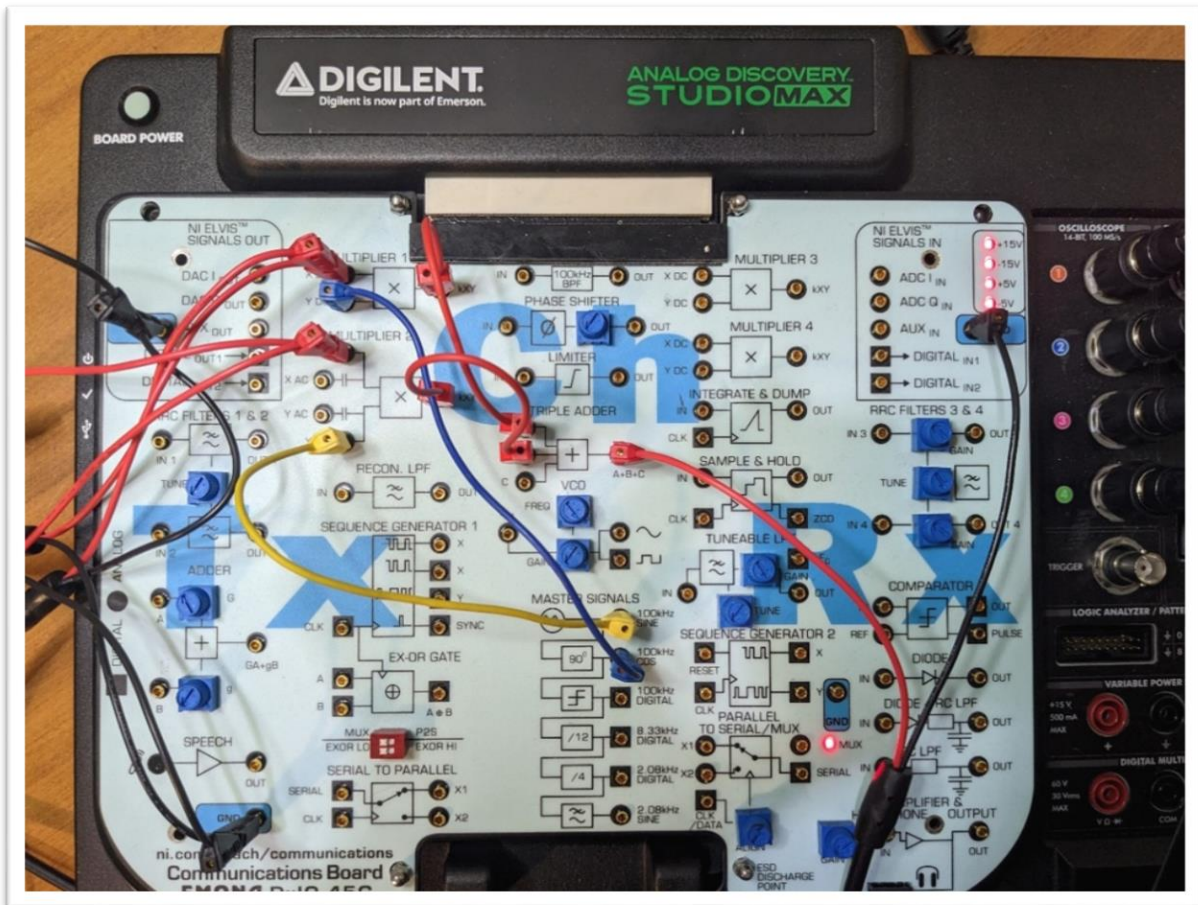


Figure 12: Patching for OFDM modulation to passband only

## 1.4 Implement: Introducing a passband channel

Now we will observe the passage of the signal through a bandlimited channel and observe the impact of phase delays, bandlimiting and clipping.

1. Pass the OFDM signal through the 100kHz BPF block. Observe both the input and output in the time and frequency domains.

4-1 What can you observe about the amplitude and spectrum of each signal ? Explain your findings.

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2. Reduce the amplitude of the OFDM and pass it signal through the LIMITER block. Aim to reduce the severity of the limiting. Observe both the input and output in the time and frequency domains.

4-2 What can you observe about the amplitude and spectrum of each signal ? Explain your findings.

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3. Introduce an ADDER and add the VCO signal to the OFDM . Observe both the input and output in the time and frequency domains whilst moving the frequency of the VCO signal back and forth across the spectrum. You can think of the VCO signal as a single frequency jamming signal.

4-3 What impact do you think the jamming signal will have on the OFDM signal at the receiver ?.

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## 1.5 Implement: Demodulation down to baseband

Now we will multiply the signal back down to baseband using dual MULTIPLIER blocks and baseband filters. Each MULTIPLIER uses a quadrature carrier from the transmitter. We use the same carriers so as to have synchronized carriers and to simplify the experiment by not needing to regenerate and lock the local oscillators. We think of these as “stolen” from the transmitter.

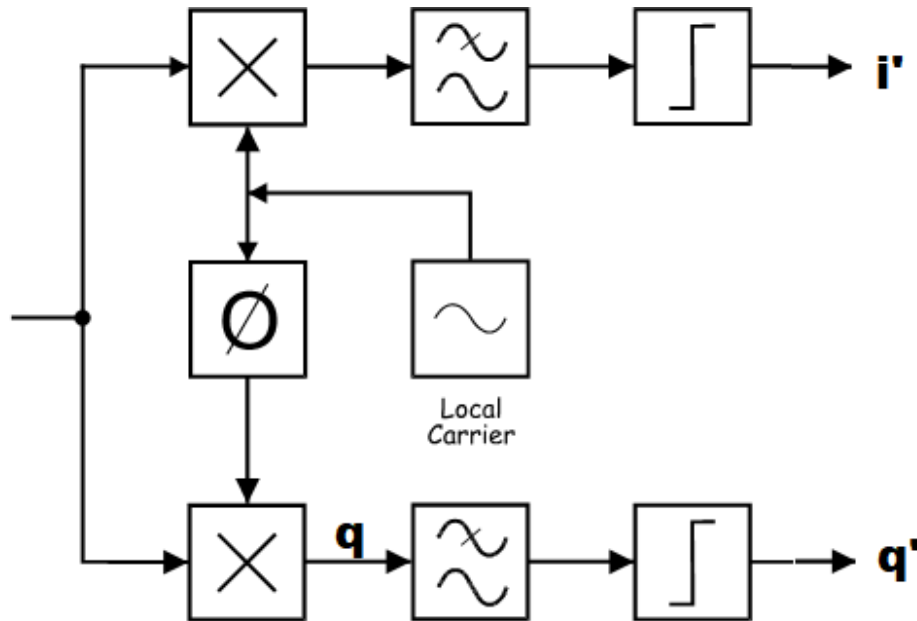


Figure 13: Block diagram for demodulation to complex baseband signals

Although we are using the same quadrature carriers from the transmitter, this does not mean that the phase relationship between the OFDM signal and the demodulating carriers is optimum for recovery. There are numerous sources of phase delay in the path from the transmitter.

We can compensate for these by adding our own manually tuned phase delay using the PHASE SHIFTER block. Its purpose is to set the total phase delay to zero relative to the original phase to the transmitter Multipliers.

1. Add on the Quadrature Demodulator to your existing experiment setup. set the RRC FILTER Gains to midway and the TUNE to maximum.

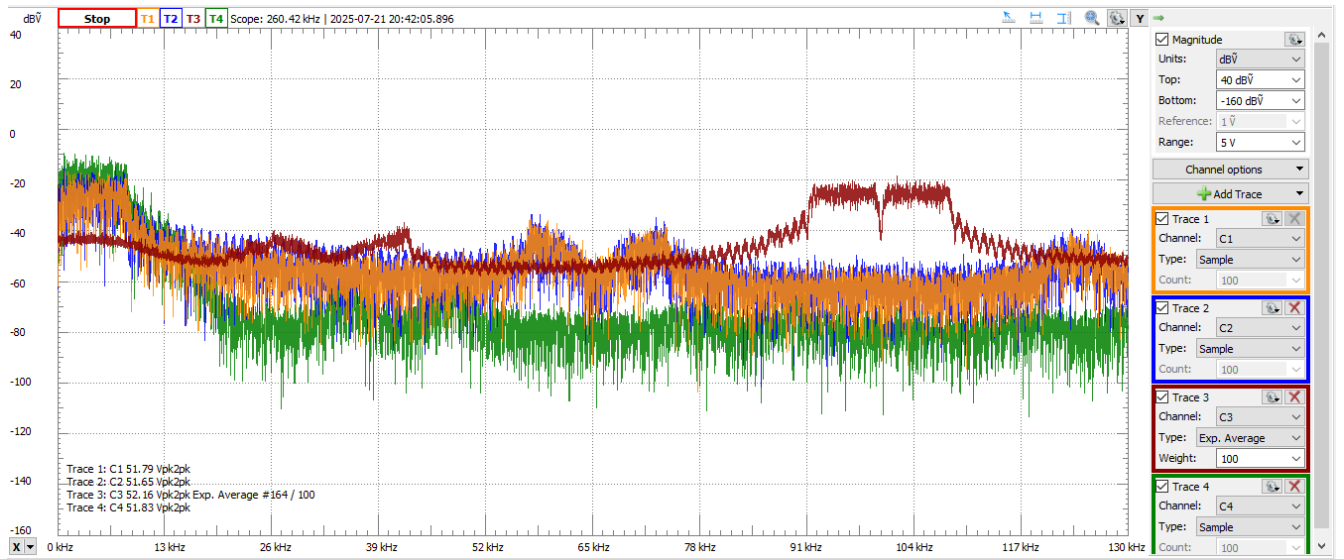


Figure 14: OFDM spectrum at baseband & passband

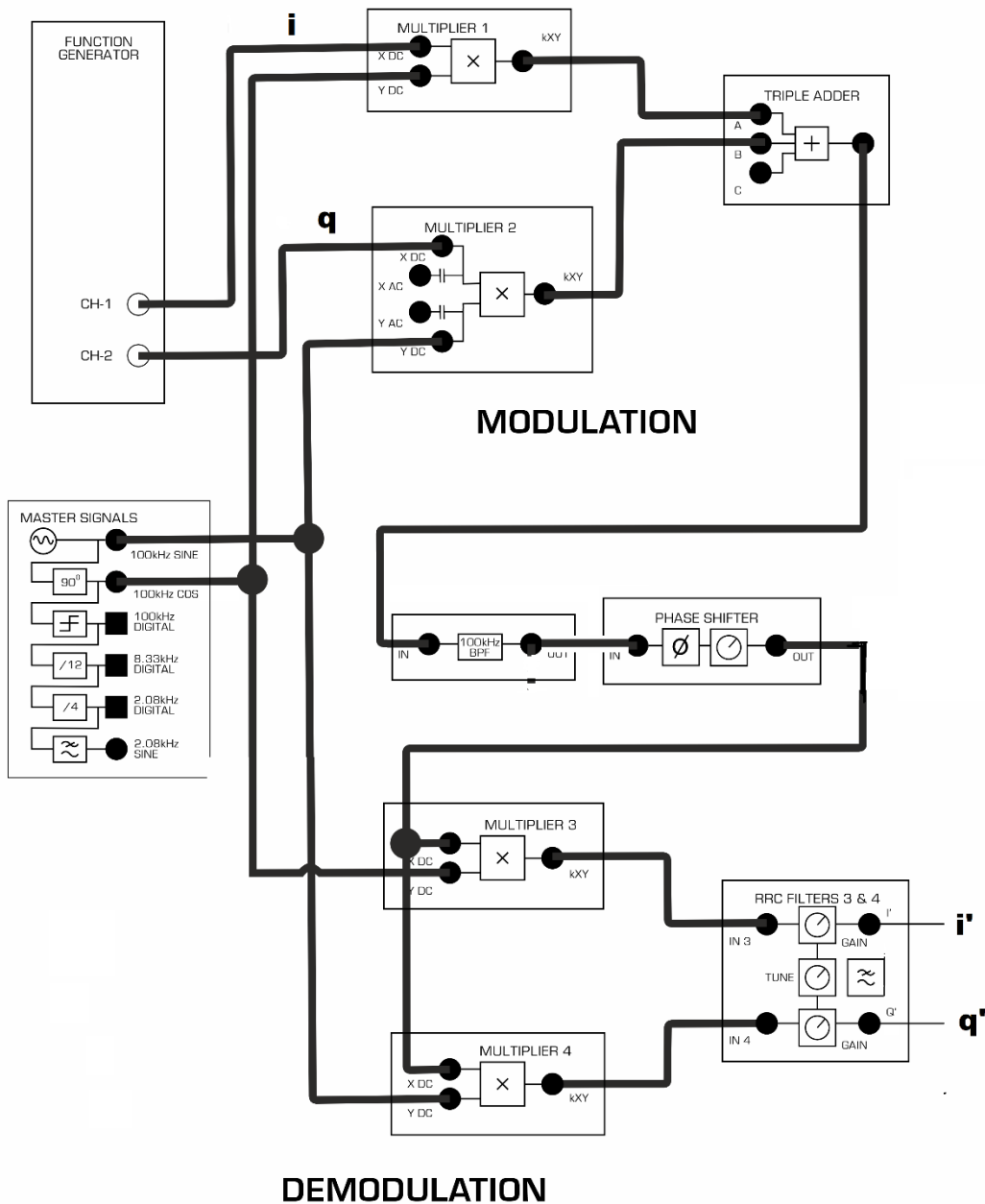


Figure 15: Patching diagram for demodulation

2. View the signals after the MULTIPLIER and after the FILTER in one arm and compare with the original I or Q signal at the transmitter.

5-1 What can you observe about the signal after the MULTIPLIER ?

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5-2 What can you observe about the signal after the FILTER ?

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3. View the original I/Q pair at the transmitter on Scope Channels 1 & 2 whilst viewing the recovered I/Q signals with Channels 3 & 4. The RRC FILTERSs main purpose is to eliminate the 200kHz component whilst passing the baseband components.

Try adjusting the PHASE SHIFTER in order to see the relationship between transmitted and received signals ? Is this easy to do as it is in a standard n-QAM experiment ?

5-3 Why is this difficult to achieve ?

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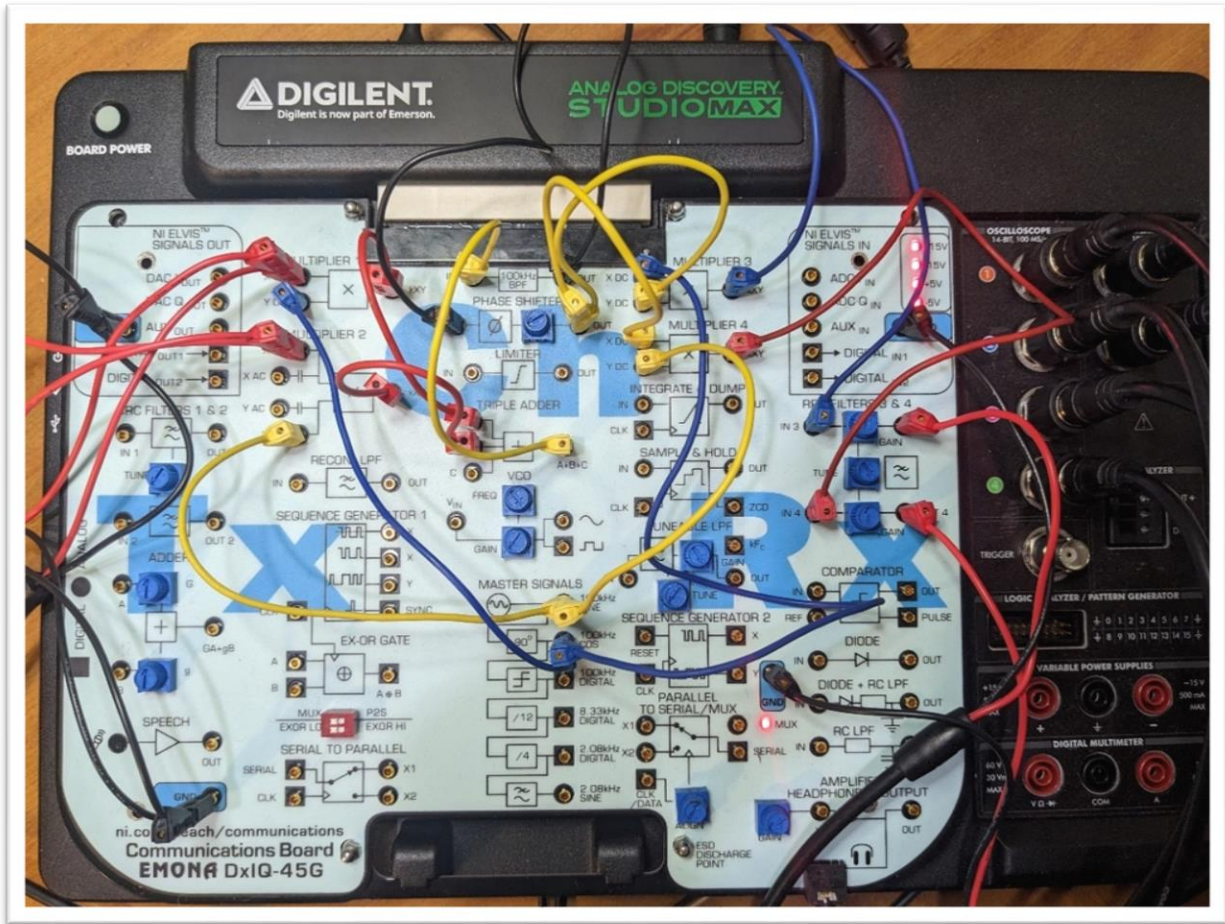


Figure 16: Patching for OFDM demodulation

## 1.6 Implement: Exploring the use of Channel Equalization

If we consider that there are many phase effects on such a complex signal such as OFDM we need to consider how to calibrate for this at the receiver.

One such way is to measure the phase response of the channel by sending a “test pattern” of distinct known parameters through the channel and measuring the channel response to this signal.

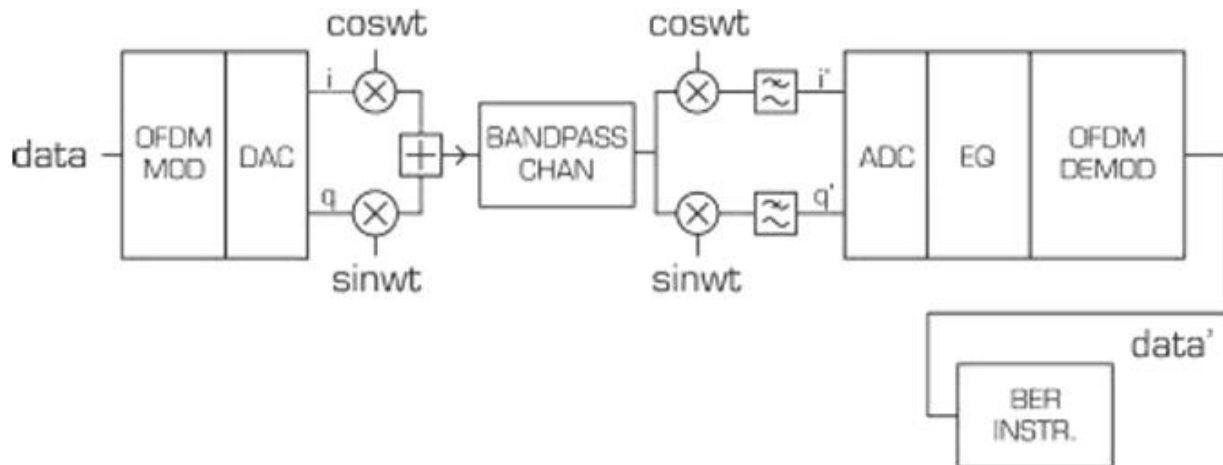


Figure 17: Generalised system block diagram showing EQ placement

An adequate “test pattern” is a signal with a known amplitude and phase at each sideband frequency. This signal can easily be constructed by an IFFT given these settings.

Instead of using a random data stream we will create an I/Q signal pair from fixed data such as all “1 1 1 1 1...” placed into each sideband slot. This is effectively creating a signal which is the sum of 8 sinusoid pairs, of length 1 ms, and repeated continuously.

Load a new Workspace whose WAVEGEN panel contains this signal pre-defined for your use. (Alternatively, you can create your own signals and upload them to the WAVEGEN instrument)

Load the **L23-setup-TestPattern\*.dwf3work** workspace and RUN ALL the FG outputs into your existing OFDM modulator/demodulator setup.

The figure below show the spectrum of this test pattern BEFORE THE CHANNEL and gives clear indication as to its purpose.

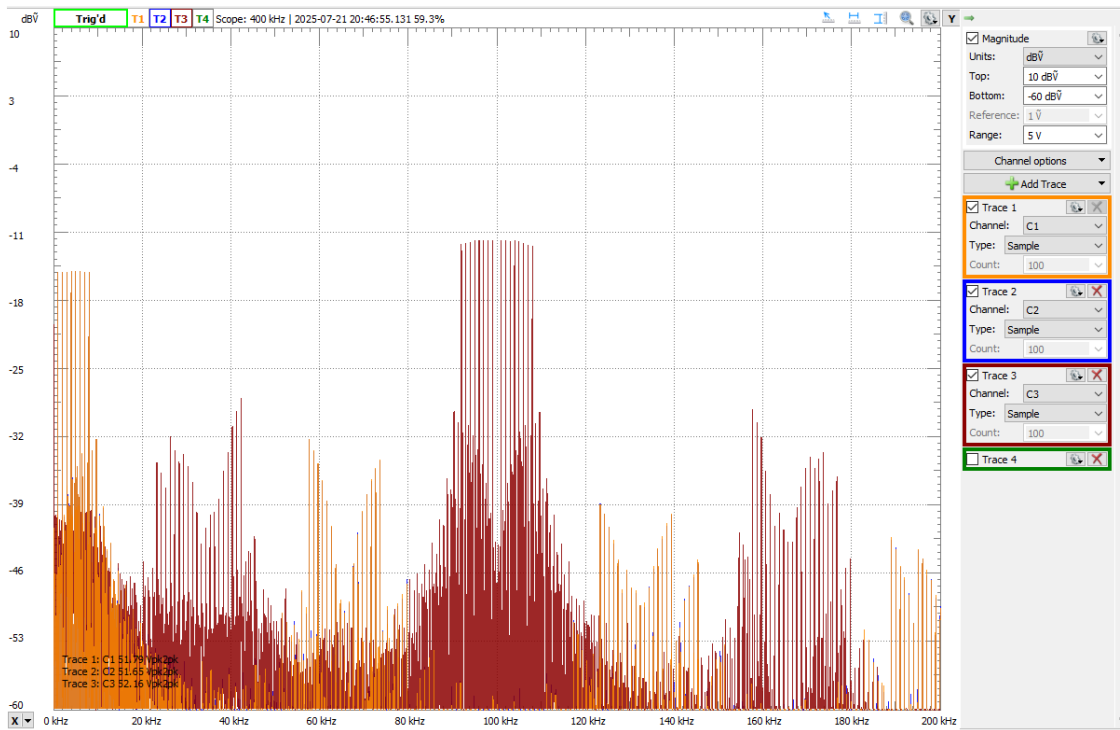


Figure 18: 8-sideband Test Pattern signal at passband

Viewing the signal after the channel and before the demodulator (comprised of MULTIPLIERS & FILTERS ) .

6-1 What effects can you notice at this point ?

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Try adjusting the PHASE SHIFTER whilst viewing the recovered I' & Q' signals. See if you can compensate for the total phase delays such that the recovered signals are similar in orientation and magnitude to the originals.

If you find that you do not have enough PHASE SHIFTER range consider adding another source of phase delay to the chain. You can include 180 degree of phase shift by inverting the signal using the AMPLIFIER (set to unity gain).

Try this and see if that helps ? Otherwise remove some delay by bypassing the 100kHz BPF which is inconsequential at this stage. Or try both or either.

You should be able to achieve “equalization” as shown below in the attached screenshot. Absolute amplitude matching is not important.

6-2 Which combination of EQ worked for your setup ?

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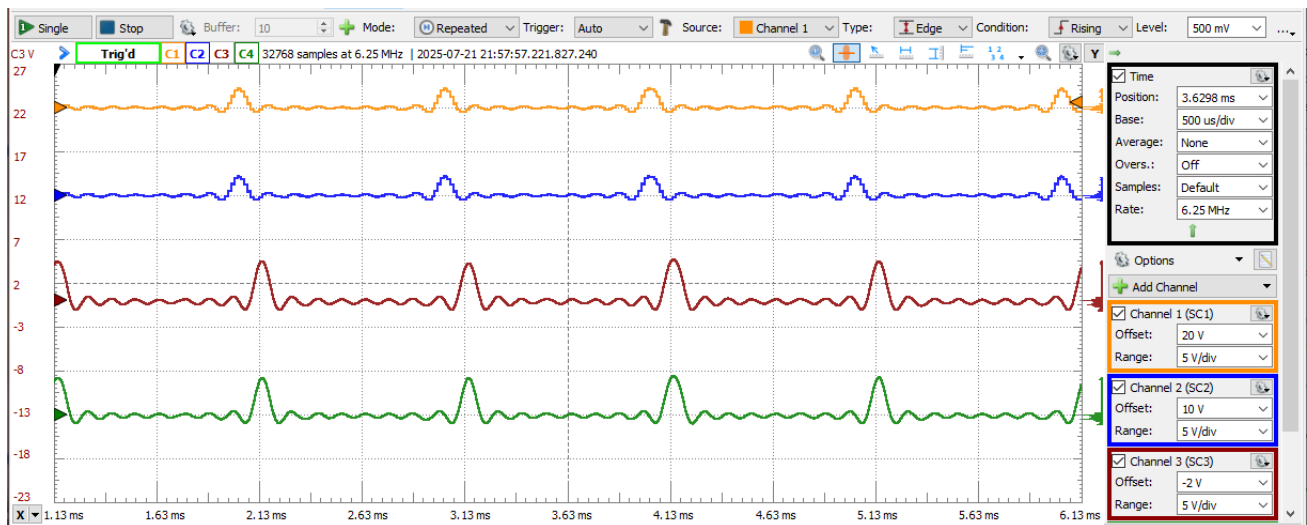


Figure 19: Equalised Tx & Rx with test pattern signal pair

To confirm that you have in fact equalized for the “channel” between transmitter and receiver, switch back to the previous Workspace with the active data streaming OFDM symbols....and do not adjust any hardware settings on the board at this point.

You should be able to visually compare the i/Q signal pairs as see that they are in fact very similar. This means you have eliminated the distortion due to phase delays.

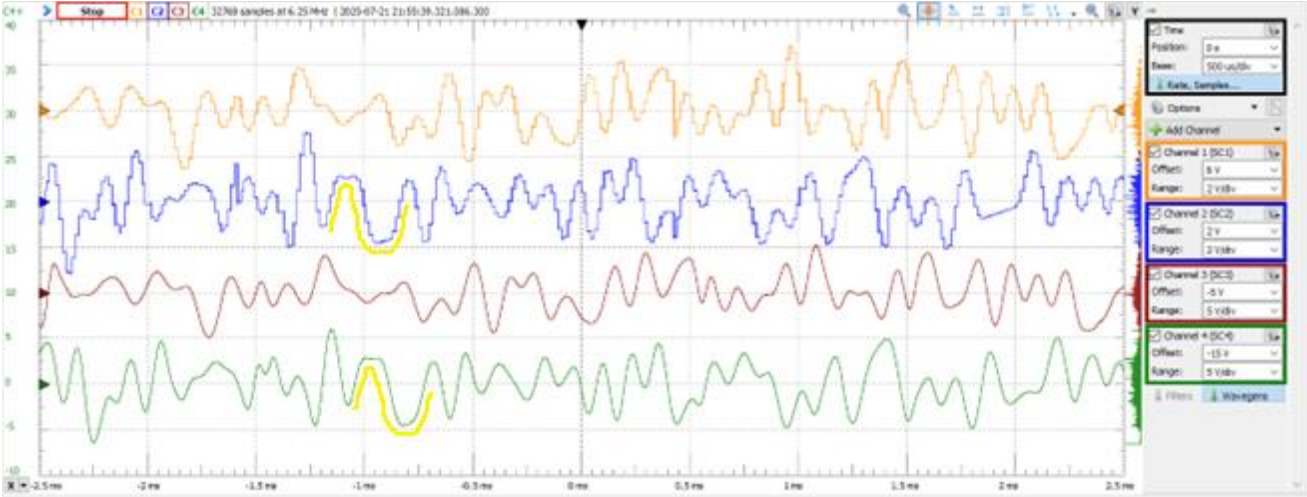


Figure 20:Equalised Tx & Rx with data streaming signal pair (alignment highlighted in yellow)

Being able to measure the actual phase of each component would allow us to also compensate with a new “EQ block” at the input to the receiver. This is beyond the scope of this experiment as we do not have configurable blocks in the system for this task...however further study could involve doing this in software with the raw data collected in the experiment.

## References and further reading

B.Le Floch, M. Alard and C.Berrou, "Coded Orthogonal Frequency Division Multiplex", Proc. IEEE, pp.982-996, Vol.83, No.6, June 1995

C. Langton, "Orthogonal Frequency Division Multiplex Tutorial", [www.complextoreal.com](http://www.complextoreal.com)

EMONA TIMS: OFDM Lab Manual [www.emona-tims.com](http://www.emona-tims.com)

## Answer Key

3-1 What can you observe about the spectrum of each signal ? Discuss negative frequencies ?

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I/Q spectrum have 8 sidebands 1 kHz apart

---

Passband has 8 sidebands oneither side of carrier

---

Negative freq resul t in lower sidebands at the carrier.

---

3-2 Why are there discontinuities ? What is the sampling rate ? How many samples per OFDM symbol ?

---

The symbols are constructed from 64 samples out of the IFFT. After which a unique symbol begins.

---

$T_s=15.6\mu s$ ,  $F_s = 64kSps$

---

There are 64 samples per symbol which corresponds ot the size of the IFFT.

---

4-1 What can you observe about the amplitude and spectrum of each signal ? Explain your findings.

---

Some amplitude change.

---

BW of BPF is wider than OFDM (according to User Manual)

---

There is phase delay from BPF

---

4-2 What can you observe about the amplitude and spectrum of each signal ? Explain your findings.

---

Significant amplitude change, esp of peaks

---

Spectrum is similar but noise level is higher due to clipped components.

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4-3 What impact do you think the jamming signal will have on the OFDM signal at the receiver ?.

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Single sidebands are severly affected one at a time.

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Since data is distributed across 8 sidebands, the error impact will be limited.

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5-1 What can you observe about the signal after the MULTIPLIER ?

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A 200kHz component is visible, form the multiplication process, as well as a baseband component

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5-2 What can you observe about the signal after the FILTER ?

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The 200kHz components have been eliminated  
The baseband signal reembles the original transmitted.

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5-3 Why is this difficult to achieve ?

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There are multiple phases in these signals so it is very difficult to tune the phase by sight.  
Unlike with a simple 4-QAM signal constellation.

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6-1 What effects can you notice at this point ?

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Apart from amplitude differences not much change is visible.

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6-2 Which combination of EQ worked for your setup ?

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We found that using Amplifier and bypassing 100kHz BPF with Phase Shifter worked as shown

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# Lab Manual: Communications Principles

Using the **EMONA Communications Explorer board**  
for **ADS MAX**

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