

Lab Manual:  
Communications Principles  
  
Using the EMONA Communications board for NI ELVIS III



Lab 15: Principles of OFDM

List of Updates

|  |  |
| --- | --- |
| **Date** | **Details** |
| 4/13/2019 | Completed final document |
|  |  |
|  |  |

**© 2018 EMONA Instruments Pty Ltd**

All Emona TIMS/ETT-Series/DxIQ user manuals, experiment manuals and supplied software   
are (C) Copyright to Emona Instruments Pty Ltd and its related entities. All rights reserved.

LIMITED AUTHORITY TO COPY TIMS MANUALS

This License Agreement grants a limited authority only to those educational institutions who have purchased the Emona TIMS/ETT/DxIQ laboratory learning equipment, to reproduce (in whole or in part,), and/or to give away copies of any of Emona Instrument’s published TIMS/ETT/DxIQ User Manuals and Experiment Manuals for the exclusive use of their own enrolled students.

No licensing fees are payable to Emona under this limited Authority.

Emona Instruments Pty Ltd retains the copyright of any edited and/or derivative documents.

**SOFTWARE**

EMONA Instruments Pty Ltd respects the intellectual property of others, and we ask our readers to do the same. This resource is protected by copyright and other intellectual property laws.

LabVIEW and National Instruments are trademarks of National Instruments.

All other trademarks or product names are the property of their respective owners.

**ADDITIONAL DISCLAIMERS**

The reader assumes all risk of use of this resource and of all information, theories, and programs contained or described in it. This resource may contain technical inaccuracies, typographical errors, other errors and omissions, and out-of-date information. Neither the author nor the publisher assumes any responsibility or liability for any errors or omissions of any kind, to update any information, or for any infringement of any patent or other intellectual property right.

Neither the author nor the publisher makes any warranties of any kind, including without limitation any warranty as to the sufficiency of the resource or of any information, theories, or programs contained or described in it, and any warranty that use of any information, theories, or programs contained or described in the resource will not infringe any patent or other intellectual property right. THIS RESOURCE IS PROVIDED “AS IS.” ALL WARRANTIES, EITHER EXPRESS OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, ANY AND ALL IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF INTELLECTUAL PROPERTY RIGHTS, ARE DISCLAIMED.

No right or license is granted by publisher or author under any patent or other intellectual property right, expressly, or by implication or estoppel.

IN NO EVENT SHALL THE PUBLISHER OR THE AUTHOR BE LIABLE FOR ANY DIRECT, INDIRECT, SPECIAL, INCIDENTAL, COVER, ECONOMIC, OR CONSEQUENTIAL DAMAGES ARISING OUT OF THIS RESOURCE OR ANY INFORMATION, THEORIES, OR PROGRAMS CONTAINED OR DESCRIBED IN IT, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, AND EVEN IF CAUSED OR CONTRIBUTED TO BY THE NEGLIGENCE OF THE PUBLISHER, THE AUTHOR, OR OTHERS. Applicable law may not allow the exclusion or limitation of incidental or consequential damages, so the above limitation or exclusion may not apply to you.

Table of Contents

[Lab 15: Principles of OFDM 5](#_Toc8039917)

* [Learning Objectives 5](#_Toc8039918)
* [Prerequisites 5](#_Toc8039919)
* [Required Tools and Technology 6](#_Toc8039920)
* [Expected Deliverables 7](#_Toc8039921)
* [Section 1: The Orthogonality Property 8](#_Toc8039922)
* [1.1 Theory and Background 8](#_Toc8039923)
* [1.2 Implement: Setting up a single subcarrier 12](#_Toc8039924)
* [1.21 Implement: Running the subcarrier generation software 13](#_Toc8039925)
* [1.3 Implement: Recovering a single subcarrier 17](#_Toc8039926)
* [1.4 Implement: Adding more subcarriers 20](#_Toc8039927)
* [1.5 Implement: Extracting single subcarrier data from OFDM 22](#_Toc8039928)
* [References and further reading 25](#_Toc8039929)

[Figure 1: Orthogonal subcarriers in frequency domain 9](#_Toc6951193)

[Figure 2: Subcarriers in time domain 10](#_Toc6951194)

[Figure 3: Subcarriers in frequency domain 10](#_Toc6951195)

[Figure 4: Individual subcarriers; and summed together 11](#_Toc6951196)

[Figure 5: Block diagram for IDFT implementation 11](#_Toc6951197)

[Figure 6: Equation for IDFT 12](#_Toc6951198)

[Figure 7: System block diagram 15](#_Toc6951199)

[Figure 8: Patching for 1kHz subcarrier only 15](#_Toc6951200)

[Figure 9: Scope display of subcarriers & BPSK for SC1 (time & FFT) 16](#_Toc6951201)

[Figure 10: 1kHz symbol clock; input and output to INTEGRATE & DUMP module 18](#_Toc6951202)

[Figure 11: Complete patching diagram for all subcarriers 20](#_Toc6951203)

[Figure 12: OFDM signal in time & frequency domains 21](#_Toc6951204)

[Figure 13: Sample scope screenshot: original X1 data; single SC1 input to I&D module; output from S&H module; symbol clock 22](#_Toc6951205)

[Figure 14: Sample scope screenshot: original SC3 data, complete OFDM signal; output from I&D module; symbol clock 24](#_Toc6951206)

# 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

## Prerequisites

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

## Required Tools and Technology

|  |  |
| --- | --- |
| Platform: NI ELVIS III Instruments used in this lab:   * Oscilloscope-Time * Oscilloscope-FFT * Function Generator | * Access instruments   <https://measurementslive.ni.com>   * View User Manual   <http://www.ni.com/en-us/support/model.ni-elvis-iii.html>   * View tutorials [www.ni.com](http://www.ni.com) |
| Hardware: Emona Communications Board Components used in this lab:   * Four BNC to 2mm banana-plug leads * Assorted 2mm banana-plug patch leads * Set of headphones or earbuds | * View User Manual   <http://www.ni.com/en-us/support/model.emona-communications-board-for-ni-elvis-iii.html> |
| Software: LabVIEW Version 18.0 or Later  Toolkits and Modules:   * LabVIEW Real-Time Module * LabVIEW FPGA Module * NI ELVIS III Toolkit   Files used in this lab:  Lab15\_OFDM.vi from  L15\_OFDM.lvproj | * Before downloading and installing software, refer to your professor or lab manager for information on your lab’s software licenses and infrastructure * Download & Install for NI ELVIS III   <http://www.ni.com/academic/download>   * View Tutorials   <http://www.ni.com/academic/students/learn-labview/> |

## 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: The Orthogonality Property

## Theory and Background

Multicarrier modulation allows the transmission of multiple modulated signals (or carriers) simultaneously over a single communication channel. It is used in several applications that are at present mass markets. These include wireline systems such as digital subscriber lines (DSL), where it is often referred to as discrete multitone (DMT), and wireless systems, where it is commonly referred to as orthogonal frequency-division multiplexing (OFDM).

OFDM (Orthogonal Frequency Division Multiplexing) is a combination of modulation and multiplexing, and more specifically, is a special case of Frequency Division Multiplexing, as the name implies.

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, 10kHz, 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 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.

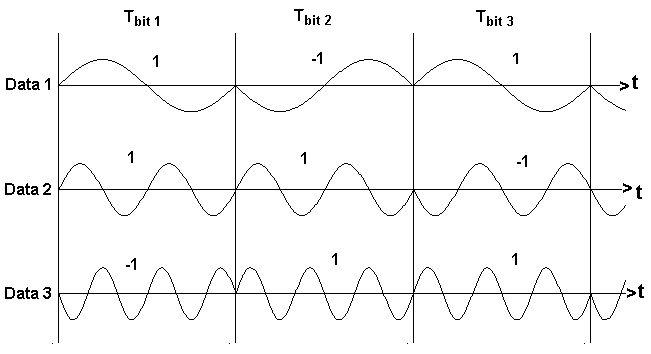


Figure 2: Subcarriers in time domain



Figure 3: Subcarriers in frequency domain

To implement the DFT in analog form, these three BPSK signals are then added together in accordance with Figure 6. In this way the parallel bits together form a set of coefficients of all the sub-carriers at each instant in time.

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 5.

rotTEK00004

Figure 4: Individual subcarriers; and summed together



Figure 5: Block diagram for IDFT implementation



Figure 6: Equation for IDFT

The m(t) term is the many (N) multiplexed data streams and the sin(2..nt) is the many (N) orthogonal sub-carriers. This multiple multiplication and addition of signals and data can be seen to be of the same form as an Inverse Discrete Fourier Transform (IDFT).

The IDFT is easily, and normally, implemented by DSP processors as is the preliminary multiplexing.

In this experiment we will effectively implement this IDFT function with discrete circuit modules and thus gain some insight into this important process for its own merit and for its use within OFDM generation. Since the IDFT is implemented using analog technique, at the receiver a forward DFT is not necessary. A simple noncoherent demodulation for every subcarrier will be used.

## 1.2 Implement: Setting up a single subcarrier

In most OFDM experiments a number of subcarriers will be used simultaneously. These signals are modulated by a DSP algorithm so that the total data stream is mapped to the multiple subcarriers by a single IDFT process. In this introductory experiment you will use individual data streams for each subcarrier and all the subcarriers are then added together later. This allows full attention to be paid to the creation of the multi-subcarrier signal.

Issues to do with alignment with the data symbol in the recovery process are investigated and the correct recovery of the data from each subcarrier channel is confirmed visually. The use of the INTEGRATE & DUMP module is also studied.

It should take you about 45-60 minutes to complete this experiment.

**Powering up the ELVIS III + EMONA Communications Board**

|  |  |
| --- | --- |
| 1. | Ensure that the NI ELVIS III 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 NI ELVIS III ensuring that it is fully engaged both front and back. |

|  |  |
| --- | --- |
| 3. | Ensure that you have connected the NI ELVIS III 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 Instrument Launcher software in your browser and select and RUN the following instruments. |

Scope Configuration

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

## 1.21 Implement: Running the subcarrier generation software

In this particular experiment we need three synchronized sinusoidal signals to act as our subcarriers. Since they are harmonically related it is a simple matter to have them all synchronized with zero phase difference between them and between the bit clock to be used in this experiment.

In fact, the bit clocks used in this experiment are derived from the zero crossing of the respective sinusoid so as to guarantee that they are synchronized and aligned.

These signals are generated to run on the FPGA of the NI ELVIS III unit as this allows us to create the signals exactly as we need them for this application, and they are output from the NI ELVIS SIGNALS OUT module on the Emona Communications board.

After you have downloaded the .lvproj file required for this experiment, open it in project Explorer as shown below. The program which creates the signal is “OFDM\_intro\_signals.vi”, and this is compiled to create the FPGA bitfile which is loaded into the FPGA.

As this has already been compiled, to run this software you must :

a) Configure the IP Address of your own NI ELVIS III from 0.0.0.0 to your actual IP Address

b) Run the program “Lab15\_OFDM.vi”. This is a simple “wrapper” program which will load the FPGA bitfile and run it.

c) Press STOP when you are finished.

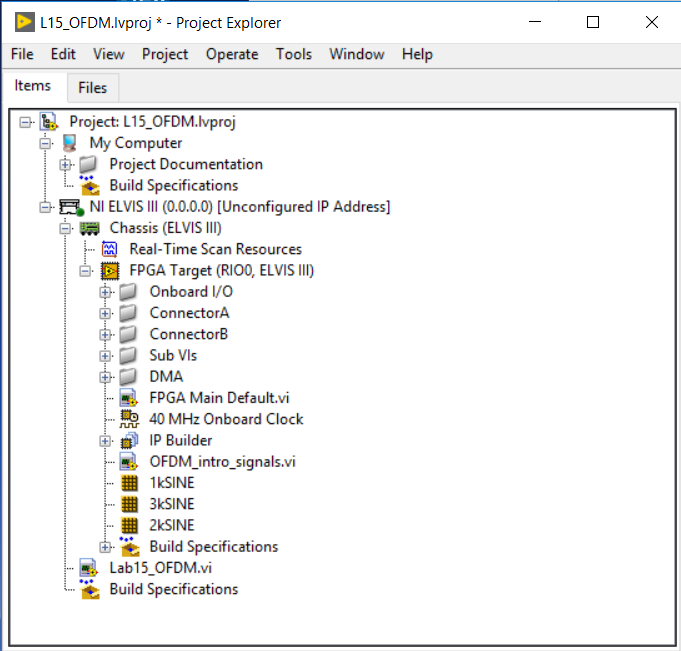


Figure 7: Project Explorer window for experiment software

To create our 3 subcarrier (SC) OFDM we will implement the block diagram of the system as shown below.

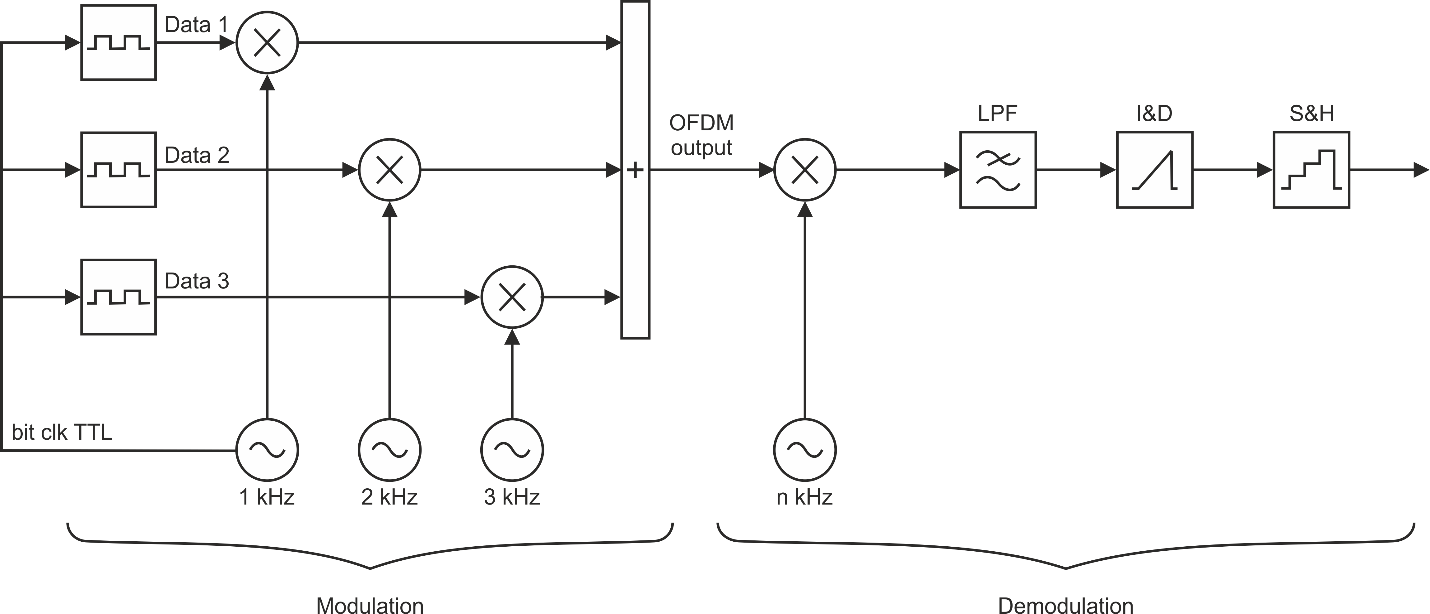


Figure 8: System block diagram

|  |  |
| --- | --- |
| 1. | Begin by patching together the first SC at 1kHz, as shown in the patching diagram in Figure 8. |

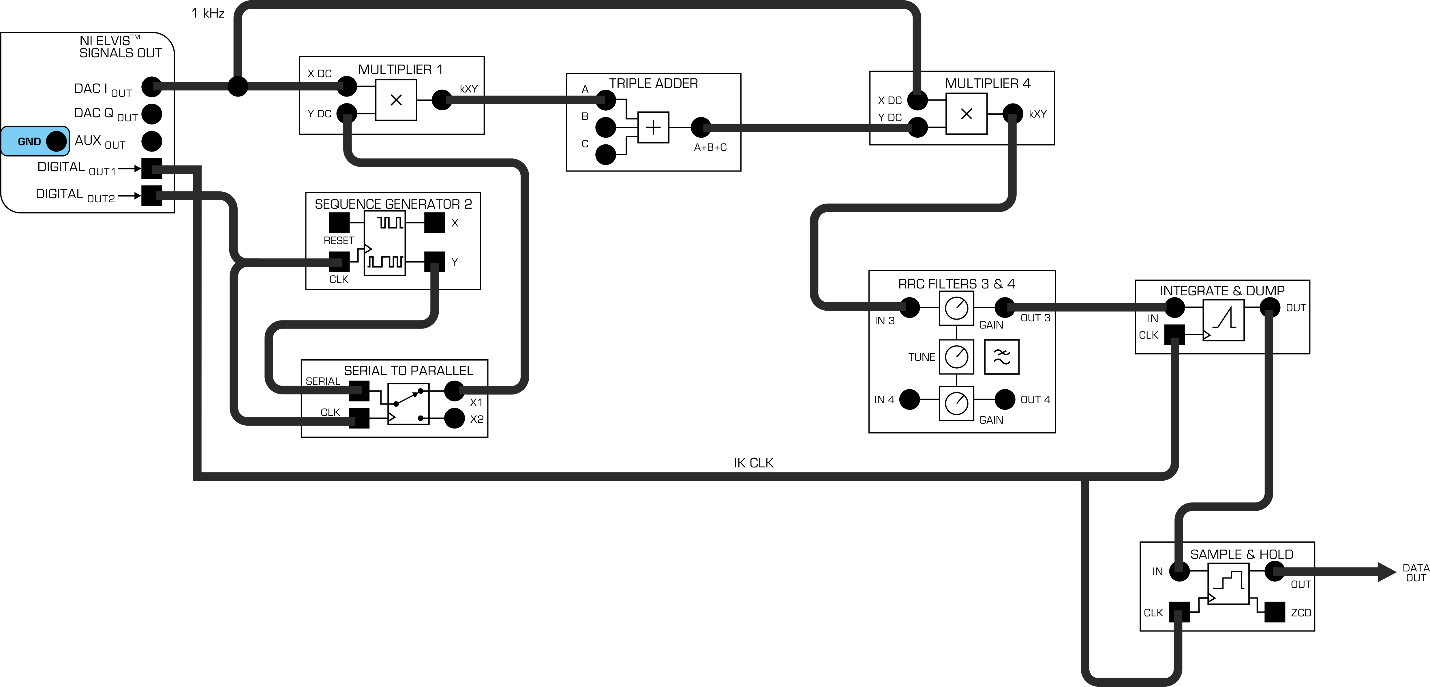


Figure 9: Patching for 1kHz subcarrier only



Figure 10: Scope display of subcarriers & BPSK for SC1 (time & FFT)

|  |  |
| --- | --- |
| 2. | View both the X1 & X2 signals output from the SERIAL TO PARALLEL module, as well as the 1kHz bit clock output from DIGITAL OUT1 of the NI ELVIS SIGNALS OUT module with scope channels. Confirm that each bipolar data stream has a symbol period of 1 ms, even though the input clock to the SERIAL TO PARALLEL module is 2kHz. |

1-1 Why are the symbol periods of X1 & X2 1 ms, and not 0.5 ms?

|  |
| --- |
|  |
|  |
|  |

The transitions of X1 & X2 are on different edges of the 1k symbol clock, however this has no impact at this point. Note that we refer to the X1 and X2 bipolar signals as “symbols” and not “bits” due to their now being bipolar, having been converted from a digital bit stream by the SERIAL TO PARALLEL module.

|  |  |
| --- | --- |
| 3. | View the first BPSK subcarrier at the output of the TRIPLE ADDER module. Confirm that this is a BPSK signal centered at 1kHz by using the FREQUENCY mode on the scope. |

## 1.3 Implement: Recovering a single subcarrier

Now we will observe the demodulation process for this single subcarrier.

|  |  |
| --- | --- |
| 1. | View the output from MULTIPLIER 4 with the scope, using the X2 channel which is no longer needed. Notice the expected familiar double frequency component as well as distinct DC levels. |

1-2 Why are 2kHz and DC components present ?

|  |
| --- |
|  |
|  |
|  |

|  |  |
| --- | --- |
| 2. | View the output from RRC FILTER 3 with this same channel on the scope. Set the GAIN controls to max (fully clockwise) and the TUNE control to max (fully clockwise) also. |

At this point there are two tasks which need to be accomplished when tuning the RRC FILTER. One is to reduce the filter bandwidth to about 1kHz, to eliminate the 2kHz “sum” frequency. The other is to align the recovered signal with the 1kHz bit clock being used by the next stage of demodulation: the INTEGRATE & DUMP module.

|  |  |
| --- | --- |
| 3. | Using the scope, view the 1kHz bit clock at the CLK input to the INTEGRATE & DUMP module on one channel. Also view the output of the RRC FILTER 3 on another channel. And also, on a third channel view the OUT signal from the INTEGRATE & DUMP module. You will see a similar display as shown in Figure 10. |

|  |  |
| --- | --- |
| 4. | Slowly adjust the TUNE control anti-clockwise until the 2kHz component is eliminated. At that point, even more slowly adjust the control such that the recovered signals zero crossings are aligned with the positive edge of the 1kHz bit clock as shown in Figure 10. This can be difficult, so it is helpful to (i) trigger the scope on the bit clock; (ii) use “Single” mode on the scope in between each tiny adjustment ie: adjust, view single shot, adjust, bview single shot, and so on, until you have it. |

|  |  |
| --- | --- |
| 5. | Capture a scope screenshot of this aligned signal for your lab report. |

It is essential that the recovered symbol is correctly aligned with the 1kHz symbol clock so that an entire symbol is integrated from start to end, rather than taking in part of an adjacent symbol. In Figure 10 you can see the integrated output is maximized by doing this correctly.

The INTEGRATE & DUMP module has powerful noise rejection capabilities as noise is averaged out during this integration period, whereas the “signal” is maximized.

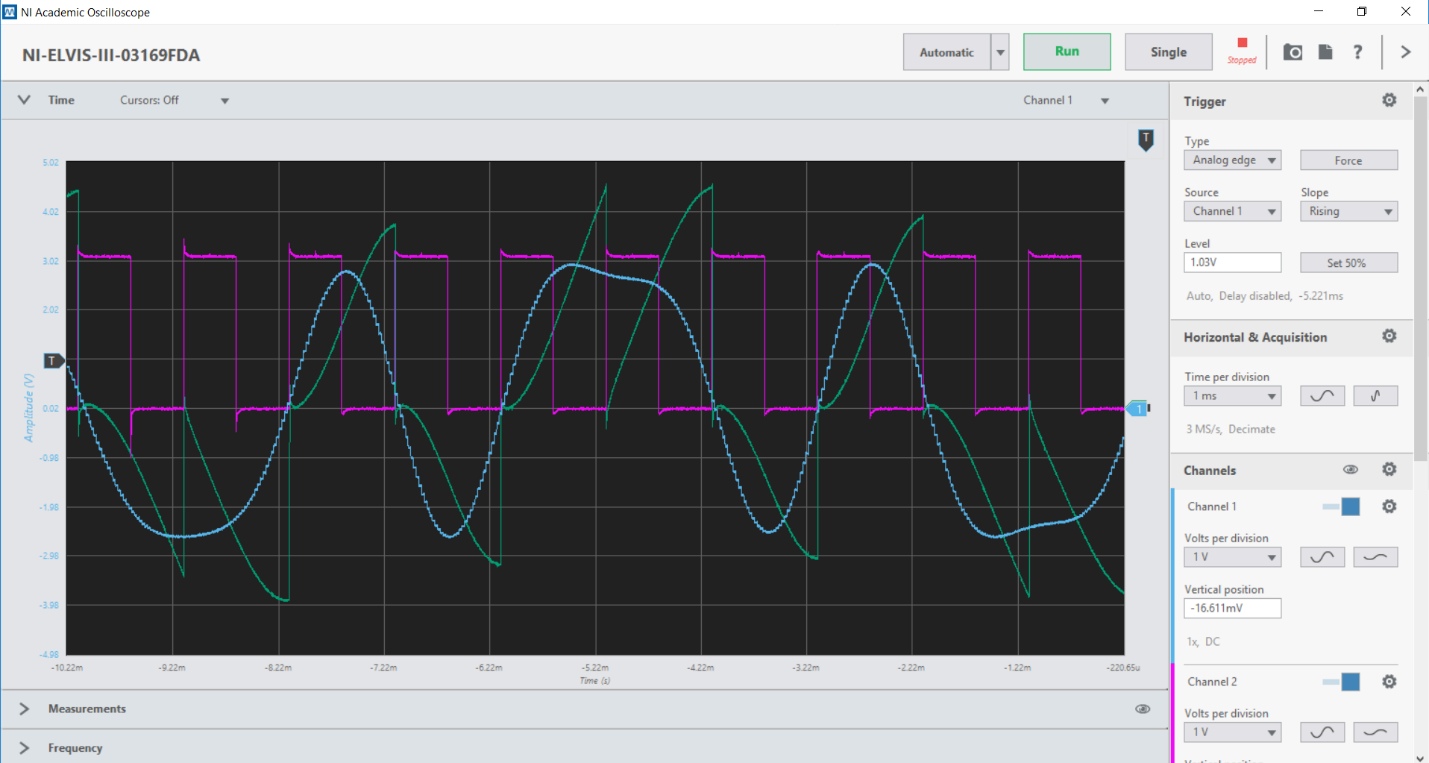


Figure 11: 1kHz symbol clock; input and output to INTEGRATE & DUMP module

|  |  |
| --- | --- |
| 6. | Use the 4th channel of the scope to also view the original data signal X1 from the SERIAL TO PARALLEL module and confirm that you can see the relationship between this original signal and the output from the INTEGRATE & DUMP. |

|  |  |
| --- | --- |
| 7. | Switch the scope channel you are using for the INTEGRATE & DUMP signal to view the output from the SAMPLE & HOLD module. Confirm the correspondence between X1 and this bipolar signal. |

|  |  |
| --- | --- |
| 8. | Capture a scope screenshot of these recovered signals for your lab report. |

## 1.4 Implement: Adding more subcarriers

1. Complete the whole system block diagram by adding the patching as shown below, which includes the other two subcarriers.

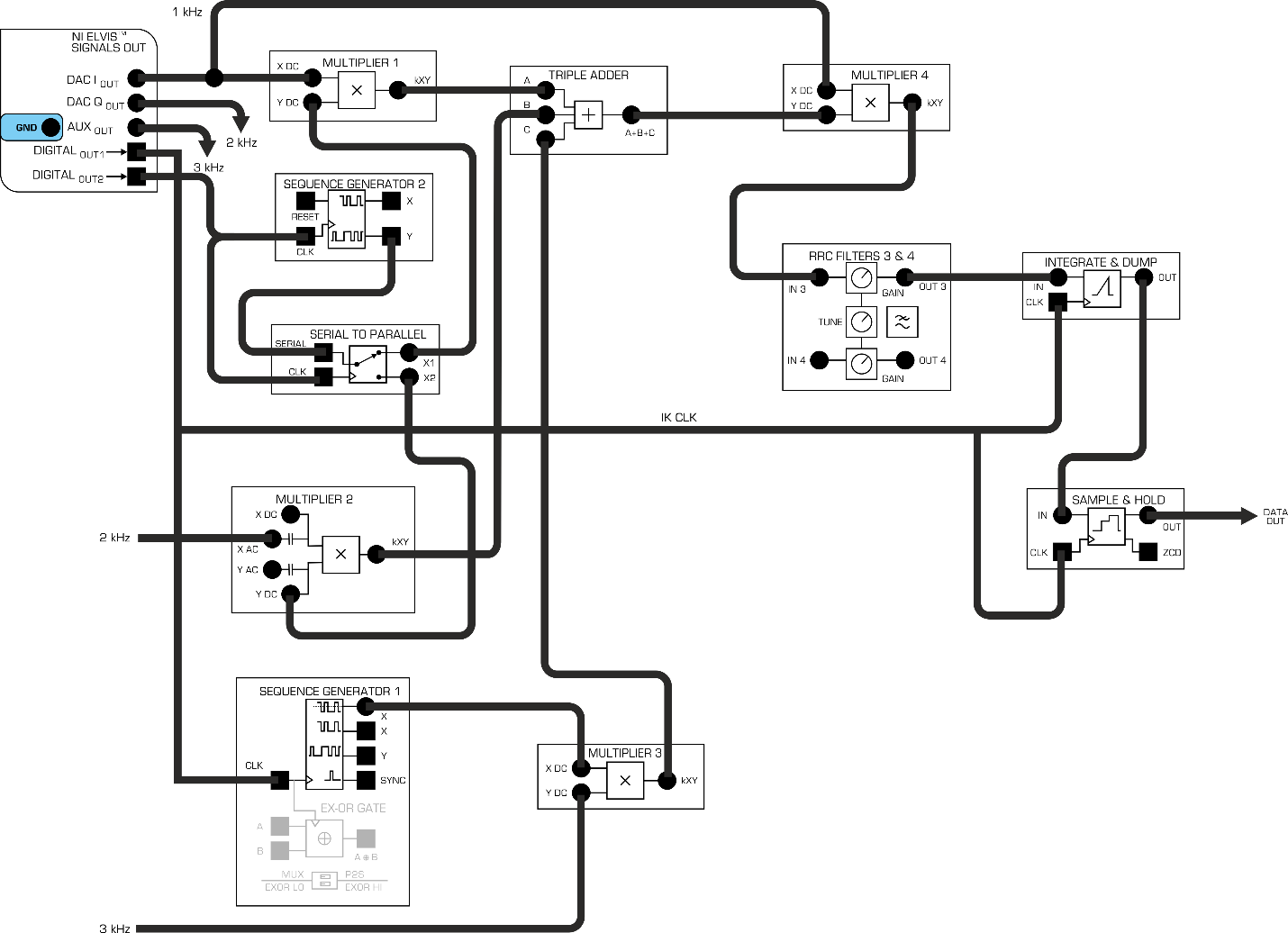


Figure 12: Complete patching diagram for all subcarriers

2. View the complete OFDM signal at the output of the TRIPLE ADDER module in both time and frequency displays. Remove subcarrier signals at the TRIPLE ADDER input as required and see the remaining subcarriers individual contribution to the output in both the time and frequency domains.

1-3 List the center frequency for each subcarriers BPSK component, as viewed in the FFT display.

|  |
| --- |
|  |
|  |
|  |

Notice that although a constant-envelope modulation scheme such as BPSK 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 x V*. This maximum will be achieved when all the carriers are aligned, which, in general, when *N* is large occurs very rarely.



The high PAPR is the biggest 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.

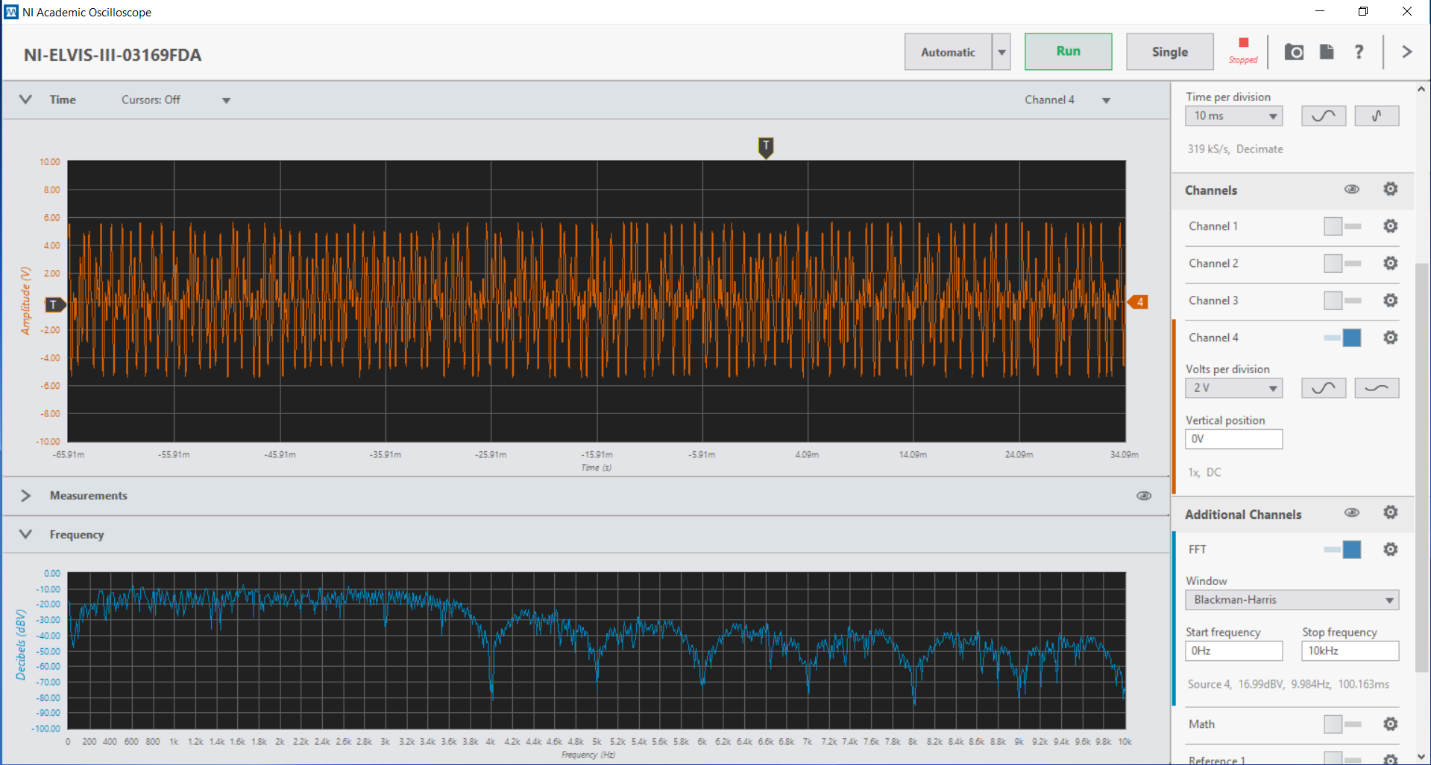


Figure 13: OFDM signal in time & frequency domains

## 1.5 Implement: Extracting single subcarrier data from OFDM

A DSP based OFDM system would extract the data from individual subcarriers simultaneously by using a FFT function, which converts the frequency domain to the time domain.

In this part of the experiment the user will extract a single subcarriers data one at a time, manually.

1. View the input to the INTEGRATE & DUMP module and the 1kHz symbol clock. Trigger the scope on the 1kHz symbol clock.

2. Remove inputs B & C from the TRIPLE ADDER and adjust the RRC FILTER so that the symbol period is aligned with the bit clock. This is the same as you did for Section 1.3 earlier in this experiment. Follow the same procedure for alignment.



Figure 14: Sample scope screenshot: original X1 data; single SC1 input to I&D module; output from S&H module; symbol clock

Notice the latency between stages from transmitter to receiver to recovery in Figure 13.

3. Insert the other two subcarriers B & C again and as well, view the original 1kHz data X1 and the output from the SAMPLE & HOLD. You are now working with the complete 3 subcarrier OFDM signal. You should be able to see that the recovered data is similar to the original data (X1) except for some latency.

1-4 Why does this latency occur ?

|  |
| --- |
|  |
|  |
|  |

4. Repeat this process for the 2kHz subcarrier. This time, be sure to use the 2kHz carrier for demodulation into MULTIPLIER 4. Remove inputs A & C. Align the symbol. Insert A & C again and compare the data streams (X2). You are now working with the complete 3 subcarrier OFDM signal. The recovered data stream may be inverted.

1-5 Why might the recovered data be inverted ?

|  |
| --- |
|  |
|  |
|  |

5. Repeat this process for the 3kHz subcarrier. This time, be sure to use the 3kHz carrier for demodulation into MULTIPLIER 4. Remove inputs A & B. Align the symbol. Insert A & B again and compare the data streams (bipolar X from SEQUENCE GENERATOR 1.) Again, you are now working with the complete 3 subcarrier OFDM signal from which you are recovering one data stream of the 3 data streams being transmitted.

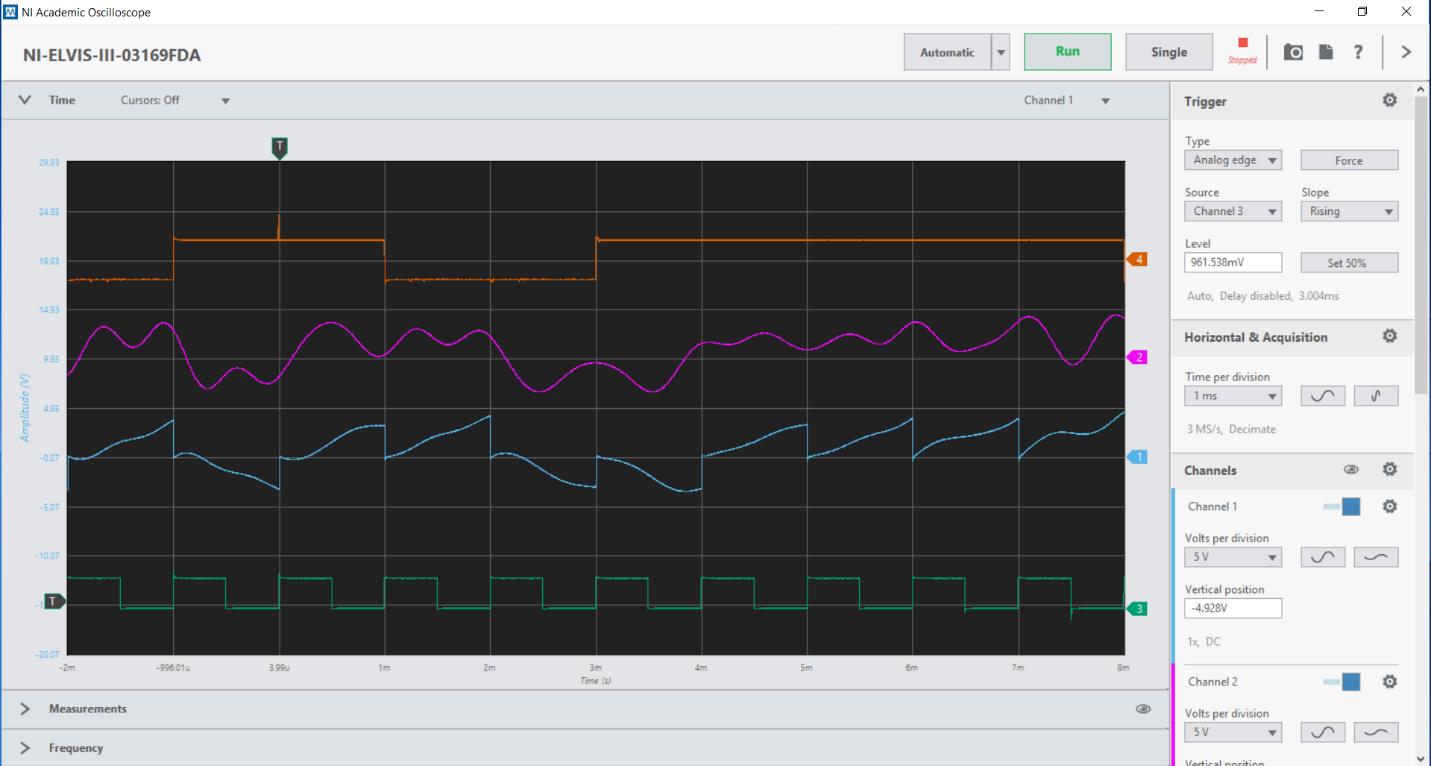


Figure 15: Sample scope screenshot: original SC3 data, complete OFDM signal into I&D module; output from I&D module; symbol clock

At this point you will have recovered the data stream from each subcarrier of the composite OFDM signal, essentially implementing a manual DFT function to reverse the IDFT used to create the OFDM signal at the transmitter.

With this knowledge, you should be able to understand how the use of many more subcarriers can be used to increase the noise resistance of this modulation scheme by distributing the data across the available spectrum.

## 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)