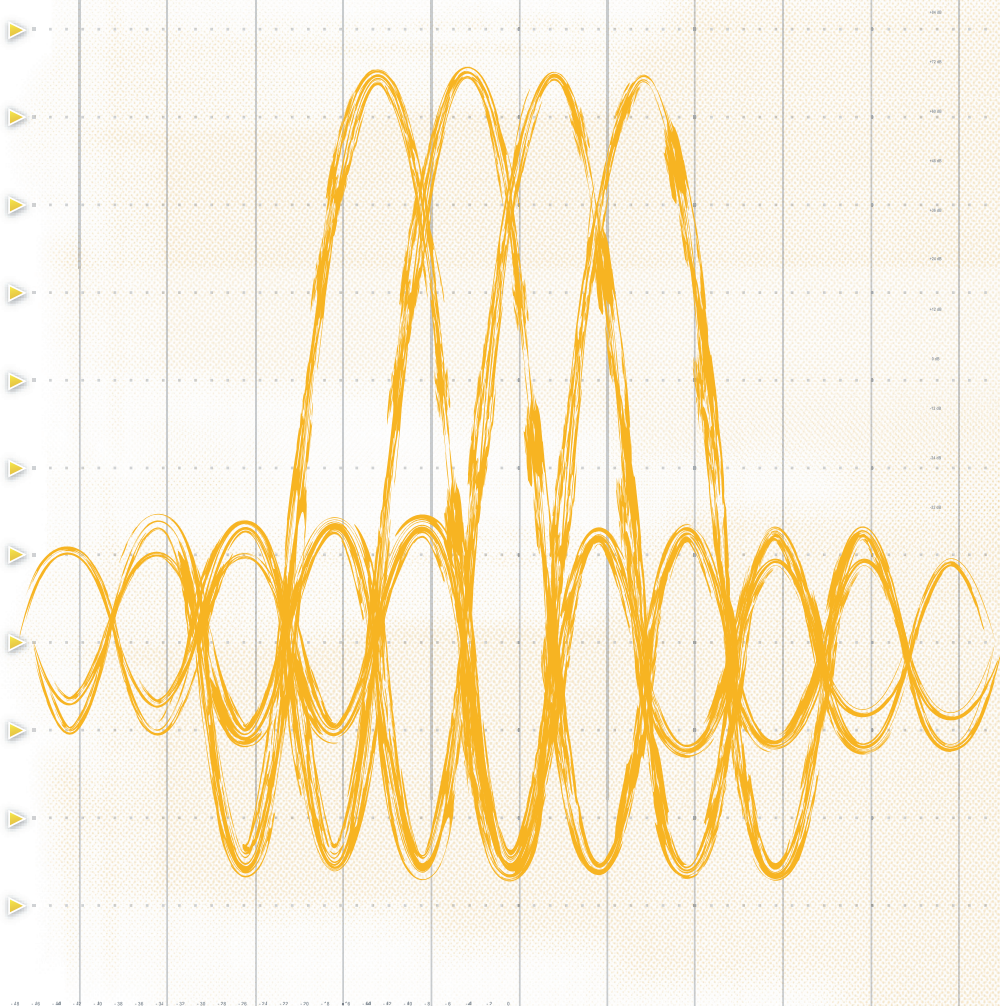


For Evaluation Only

Lab 6 Sample



DIGITAL COMMUNICATIONS

PHYSICAL LAYER EXPLORATION LAB USING THE NI USRP™ PLATFORM

Robert W. Heath Jr., Ph.D., PE.

Digital Wireless Communication

Physical Layer Exploration Lab Using the NI USRP

Student Lab Manual

Robert W. Heath Jr.

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Dedication

I dedicate this to Garima, Pia, and Rohan for their love and support,
to my parents Bob and Judy Heath for their encouragement
and to Dr. Mary Bosworth for her passion in the pursuit of higher education.

R. W. H.

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Preface

Wireless communication is fundamentally the art of communicating information without wires. In principle, wireless communication encompasses any number of techniques including underwater acoustic communication, semaphores, smoke signals, radio communication, and satellite communication, among others. The term was coined in the early days of radio, fell out of fashion for about fifty years, and was rediscovered during the cellular telephony revolution. Wireless now implies communication using electromagnetic waves—placing it squarely within the domain of electrical engineering.

Wireless communication techniques can be classified as either analog or digital. The first commercial systems were analog including AM radio, FM radio, television, and first generation cellular systems. Analog communication is rapidly being replaced with digital communication. The fundamental difference between the two is that in digital communication, the source is assumed to be digital. Modern applications of digital communication include cellular communication, wireless local area networking, personal area networking, and high-definition television.

Digital communication is widely taught in electrical engineering programs, at both the undergraduate and the graduate levels. Many digital communication courses take an abstract approach that emphasizes theory. This is no surprise—the mathematical theory of digital communication is beautiful and elegant. There has been a growing separation, however, in the abstract content of a typical course and what is implemented in practice. This difference is particularly evident in wireless communication systems, which have their own set of specific challenges. As courses are becoming more abstract, there is also increasing reliance on simulation to validate the theory. Typical simulations, though, are constructed under certain simplifying assumptions, which leaves important practical issues undiscovered. As a byproduct of the growing rift between theory and practice, and the increasing reliance on simulation, many students are not prepared to apply their knowledge immediately to a real digital wireless communication system.

This book is inspired by my own experiences as a graduate student and working at a startup company. My first summer project at Stanford University working with Arogyaswami Paulraj was to implement the physical layer of the receiver for a GSM system. The idea was to implement different space-time processing algorithms developed in Prof. Paulraj's Smart Antennas Research Group and to show practically how multiple antennas can improve system performance using real transmitted waveforms. I found the implementation of the space-time processing algorithms to be straightforward (not easy but for the most part following the theory). Most of my time was spent, however, dealing with more practical issues like channel estimation, frame synchronization, and carrier frequency synchronization. I found that the algorithms for dealing with these practical impairments were vitally important yet I had never encountered them in multiple courses on digital communication and wireless communication systems.

I used what I had learned later at a startup company then called Gigabit Wireless and later Iospan Wireless, to develop a prototype of a three transmit and three receive antenna MIMO (multiple input multiple output) communication system. This prototype was key to demonstrating the promise of MIMO communication, which in 1998 was not yet an established hot research area. Coincidentally this prototype used multichannel DAC and ADC products from National Instruments.

As a new Assistant Professor at The University of Texas at Austin, I longed to teach wireless communication from a practical perspective. I quickly found one reason why these concepts were not taught in the typical communication course—it was not included in most textbooks. As a result, I developed course notes that include these concepts and will be published in a forthcoming textbook [3]; the key concepts are included in this lab manual.

I did not just want to teach wireless communication including some theory about dealing with practical impairments. I wanted to teach a class where students would send and receive actual communication waveforms. Unfortunately, when I started developing the course materials in 2003 there were few viable solutions for the radio frequency components to create a repeatable and reliable system. All of this changed with the introduction of National Instrument's flexible RF upconverters and downconverters, which could be mated to high speed DACs and ADCs. Finally there was a way to create and process waveforms with high quality and reproducibility. Using this equipment, the students could focus on the algorithms and yet be exposed to practical wireless system engineering, without having to worry with the challenging analog front end and RF circuit design issues. The present book makes use of National Instrument's Universal Software Radio Peripheral (USRP) [12]. This low-cost hardware allows Universities to set up multiple workstations with a moderate budget. I am thrilled that this option has become available.

This book is a result of five years of development to make a complete laboratory course that teaches the principles of wireless digital communication. It consists of a series of labs with three components: a pre-lab, a laboratory experiment, and a lab report. The idea of the pre-lab is to write the essential LabVIEW code and getting it to work in a simulator before doing the laboratory experiment. This models conventional design practices where communication algorithms are tested in simulation before being tested over a wireless link. It is important to complete the pre-lab prior to starting the laboratory experiment. The laboratory experiments were designed to be completed in a time period of up to three hours. In the lab, the code from the pre-lab is run over the wireless link, some experiments are performed, and the results are recorded. The lab report is the final component of the lab. The purpose of the lab report is to discuss what was observed in the lab and to answer several questions related to wireless communication engineering. The lab report is an opportunity to synthesize what was learned.

Digital signal processing (DSP) is at the heart of the approach taken in this lab manual. No background in digital communication is assumed, though it would be helpful. The utility of a DSP approach is due to the bandlimited nature of wireless systems. Consequently with a high enough sampling rate, thanks to Nyquist's theorem, it is possible to represent the bandlimited continuous-time wireless channel from its samples. This allows the transmitted signal to be represented as a discrete-time sequence, the channel as a discrete-time linear time-invariant system, and the received signal as a discrete-time sequence.

The labs explore both single carrier and multicarrier transmission. Single carrier transmission uses quadrature amplitude modulation (QAM) and raised-cosine pulse-shaping. Over the course of the labs, complexity is added to the receiver design including functions like detection, channel estimation, equalization, frame synchronization, and carrier synchronization. In later labs, the system is extended to incorporate multicarrier modulation in the form of orthogonal frequency division multiplexing (OFDM) with coding.

This lab manual could not have been possible with the support from many graduate teaching assistants at The University of Texas at Austin including Roopsha Samanta, Sachin Dasnurkar, Ketan Mandke, Hoojin Lee, Josh Harguess, Caleb Lo, Robert Grant, Ramya Bhagavatula, Omar El Ayache, Harish Ganapathy, Zheng Li, and Tom Novlan. Some specific contributions deserve special mention. Roopsha Samanta developed the initial set of laboratory drafts and software in addition to being the first TA for the course. Ketan Mandke reworked the software to have a complete system implemented and a channel simulator, where components could be removed and replaced with software from the student. He also revised the lab manual to reflect the new system implementation. Hoojin Lee undertook the job of creating figures

for the early course material. Josh Harguess created a nice introduction to LabVIEW presentation. Robert Grant spent time seeing how to convert to an early version of the USRP platform, when it was just released. Caleb Lo, Ramya Bhagavatula, Omar El Ayache, and Tom Novlan all made important revisions to the notes and software to keep it up-to-date with current versions of LabVIEW. All the teaching assistants ran the labs, worked with the students, collected feedback, and make suggestions and revisions. I sincerely thank them for their support.

The development of this book and course was supported by several groups. National Instruments made the course possible through its establishment of the Truchard Wireless Lab at UT Austin. NI provided summer support that funded the endeavor, and contributed countless hours of employee time. Several groups from University of Texas at Austin including the Department of Electrical Engineering and the Cockrell School of Engineering provided teaching assistant support to develop and maintain the course materials. Working on the labs has inspired my research. I am pleased to acknowledge research support from the National Science Foundation, DARPA, the Office of Naval Research, the Army Research Labs, Huawei, National Instruments, Samsung, Semiconductor Research Corporation, Freescale, Andrew, Intel, and Cisco. Their support has allowed me to train many graduate students who share my appreciation of theory and practice.

I hope you enjoy this book and doing the laboratory experiments.

ROBERT W. HEATH JR.
Austin, Texas

Lab 6: OFDM Modulation & Frequency Domain Equalization

Summary

In this lab you will implement the key features of the orthogonal frequency division multiplexing (OFDM) multicarrier modulation technique. OFDM is a transmission technique with a special structure that permits low complexity linear equalization at the receiver. Several commercial wireless systems have adopted OFDM modulation including wireless LAN standards like IEEE 802.11g, IEEE 802.11a, and IEEE 802.11n; broadband wireless access including IEEE 802.16 (WiFi); mobile broadband wireless known as IEEE 802.20; digital video broadcasting DVB (used in Europe); as well as several releases of the 3GPP cellular standards. The OFDM system considered in this lab is illustrated in Figure 1.

Although the design of an OFDM system has several important differences from the single carrier system considered in previous labs, it must still perform many of the same functions (e.g., channel estimation, equalization, and frequency offset estimation). In this lab you will still perform all functions related to synchronization and channel estimation in the time domain using the same training sequence discussed in Lab 5. The framing structure considered in this lab is illustrated in Figure 2.

For the pre-lab submission, you have to turn in the three VIs described in Section 2 (*OFDM_modulate.vi*, *OFDM_demodulate.vi*, and *FEQ.vi*). Further, you have to submit the answers to questions in Section 2.

1 Background

1.1 OFDM Modulation

Figure 1 shows a block diagram of the basic OFDM modulator you will be implementing in this lab. OFDM is a type of digital modulation where information is modulated into discrete-time sinusoids. With OFDM, the symbols after the constellation mapping are considered to start in the frequency domain. OFDM operates on groups of symbols, the resulting group of symbols being called an OFDM symbol. To begin the explanation, we assume $K = 0$ and that there are N frequency-domain symbols in one OFDM symbol. The number of subcarriers is given by N , typically a power of 2. The transmitter operates as follows. Given $\{s[n]\}_{n=0}^{N-1}$ and cyclic prefix of length L_c , the

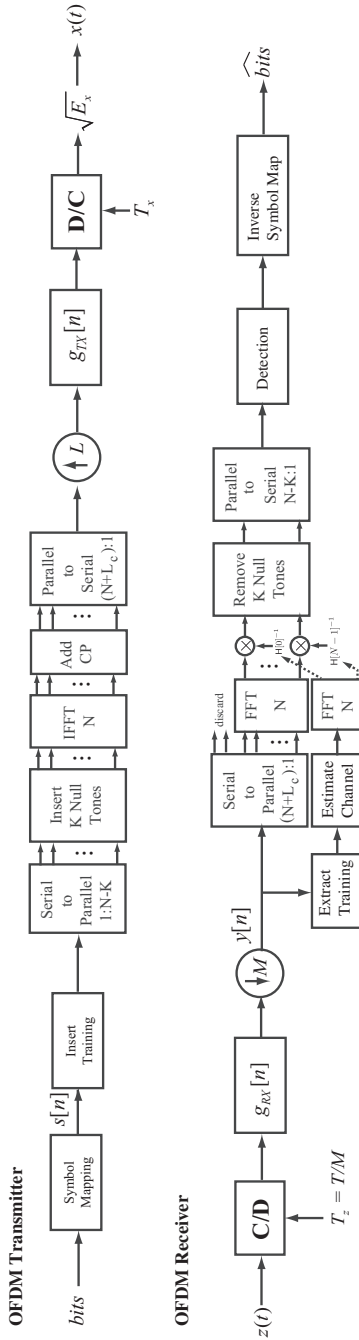


Figure 1: The OFDM system considered in this lab. The transmitter sends groups of $N - K$ symbols where N is the number of subcarriers and K the number of null subcarriers. Null symbols are inserted into groups of $N - K$ transmit symbols, which are transformed from frequency to time domain, then prepended with a cyclic prefix of length L_c at the transmitter. The receiver processes blocks of length $N + L_c$, discarding the first L_c samples of each block. Single tap equalization is performed in the frequency domain. The operations of carrier frequency synchronization and frame synchronization are omitted for simplicity.

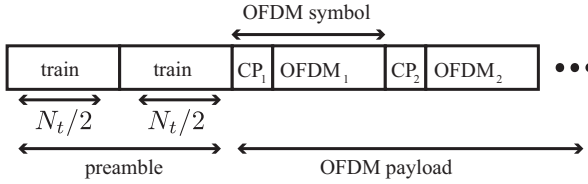


Figure 2: The framing structure considered in this lab. The preamble consists of two repeated training sequences from Lab 5 (a total of four Barker codes). The preamble is sent using the usual complex pulse amplitude modulation. Subsequent data is sent using OFDM modulation, which is a block-based modulation technique.

transmitter produces the sequence

$$w[n] = \frac{1}{N} \sum_{n=0}^{N-1} s[m] e^{j2\pi \frac{m(n-L_c)}{N}} \quad n = 0, \dots, N + L_c - 1$$

that is passed to the transmit pulse-shaping filter. The samples from $n = L_c, L_c + 1, \dots, N + L_c - 1$ are the output of the inverse discrete Fourier transform (DFT) of the input symbols $\{s[m]\}_{n=0}^{N-1}$, which could be implemented using the fast Fourier transform (FFT).

Now observe that

$$w[n] = w[n + N]$$

for $n = 0, 1, \dots, L_c - 1$. This means that the first L_c samples of $w[n]$ are the same as the last L_c samples. The first L_c samples are known as a cyclic prefix. The length of the cyclic prefix L_c should be at least as long as L_h . This will ensure that there is no intersymbol interference between adjacent OFDM symbols (i.e., the CP “guards” against ISI). The cyclic prefix serves another important purpose. It helps convert (part of) the linear convolution into a circular convolution.

In OFDM rectangular pulse-shaping is common; windowing of the symbols is used to shape the frequency spectrum. This is not considered in this lab.

Assuming carrier frequency synchronization and frame synchronization have been accomplished, the receiver observes the following signal after matched filtering, symbol timing, frame synchronization, and downsampling

$$y[n] = \sum_{\ell=0}^L h[\ell] w[n - \ell] + v[n].$$

The receiver operates on blocks of data.

Note: This exposition implies that to recover multiple blocks of symbols (i.e., the input to the OFDM modulator), you will need to process multiple OFDM symbols, each of length $N + L_c$. Assuming that the indexing starts at the first OFDM symbol, the receiver discards the first L_c samples to form for $n = 0, 1, \dots, N - 1$ (neglecting noise) $\bar{y}[n] = y[n + L_c]$. With some mathematical manipulations it can be shown that

$$\begin{aligned}
 \bar{y}[n] &= \sum_{l=0}^L h[l]w[n + L_c - l]n = 0, \dots, N - 1 \\
 &= \frac{1}{N} \sum_{l=0}^L h[l] \sum_{m=0}^{N-1} s[m] e^{j2\pi \frac{m(n+L_c-L_c-l)}{N}} \\
 &= \frac{1}{N} \sum_{l=0}^L h[l] \sum_{m=0}^{N-1} s[m] e^{j2\pi \frac{mn}{N}} e^{-j2\pi \frac{ml}{N}} \\
 &= \frac{1}{N} \sum_{m=0}^{N-1} \left(\sum_{l=0}^L h[l] e^{-j2\pi \frac{ml}{N}} \right) s[m] e^{j2\pi \frac{mn}{N}}.
 \end{aligned}$$

The receiver then takes the DFT (or FFT) of these samples to produce (after some simplification)

$$\begin{aligned}
 \bar{Y}[k] &= DFT[\bar{y}[n]] \\
 &= H[k]s[k] + V[k],
 \end{aligned} \tag{1}$$

where

$$H[k] = \sum_{l=0}^L h[l] e^{-j2\pi \frac{kl}{N}},$$

which is just the DFT of the zero padded channel. The frequency domain interpretation of OFDM comes from Eq. (1). Essentially information is sent on discrete-time sinusoids, or carriers. The information on the k^{th} discrete-time sinusoid experiences the channel response determined by $H[k]$. Equalization simply requires dividing $\bar{Y}[k]$ by $H[k]$. We refer to this as the frequency domain equalizer (FEQ).

The following parameters are useful when discussing OFDM.

- T is sample period.
- $T(N + L_c)$ is the OFDM symbol period.
- The guard interval, or cyclic prefix duration, is $L_c T$.

- The passband bandwidth is $1/T$ assuming use of a sinc pulseshaping filter.
- The subcarrier spacing $\Delta_c = \frac{BW}{N} = \frac{1}{NT}$.

The length of the cyclic prefix L_c should be the same as or exceed the order of the channel response L_h . Recall that the length of a channel of order L_h is $L_h + 1$. This will ensure that there is no intersymbol interference between adjacent OFDM symbols (i.e., the CP “guards” against ISI). The guard interval is a form of overhead. This reduces the effective data rate that is transmitted (i.e., for an OFDM system with OFDM sample rate R_s and M bits/symbol, the effective data rate $R_d < R_s$).

The guard interval serves to separate different OFDM symbols thus the name. In practice the guard interval is determined by the maximum delay spread. As the bandwidth increases, L_c must increase to compensate. The subcarrier spacing refers to the spacing between adjacent subcarriers as measured on a spectrum analyzer. The larger the N , the smaller the subcarrier spacing. The subcarrier spacing determines the sensitivity to Doppler and residual carrier frequency offset.

The subcarrier spacing is inversely proportional to the number of subcarriers N . This means that as N increases you will get higher spectral efficiency, but at the cost of increased sensitivity to frequency offsets.

It is common for not all subcarriers to be used in an OFDM system. Some subcarriers are usually “nulled” or “zeroed out” in the frequency domain (i.e., the null tones). The zero frequency or DC is commonly nulled due to RF distortion at DC. Also, guard bands (i.e., frequencies at the edges of the frequency response corresponding to those around $s[N/2]$) are commonly nulled to prevent interference with signals in adjacent frequency bands. In the lab we assume that K subcarriers are zeroed with the zero locations being specified separately.

2 Pre-Lab

In this lab you will implement the OFDM modulator and demodulator as described in the background section. You are required to build two VIs: *OFDM_modulate.vi* and *OFDM_demodulate.vi*. These VIs will implement the appropriate transmit and receive operations from Figure 1.

Before discussing the details of these VIs, you will learn about a set of helper VIs which have been provided to you in *OFDM_comm1.0.llb*, a new digital communications library for processing related to OFDM. The VIs described in Table 1 are located in *OFDM_comm1.0.llb* and may be helpful in your implementations of OFDM modulation and demodulation.

Name of VI	Description
<i>S2P.vi</i>	converts serial input stream (1-D array) to parallel blocks structure (2-D array in which each row represents M consecutive elements from the input stream)
<i>P2S.vi</i>	converts parallel input stream (2-D array) to a serial output stream (1-D array which contains successive rows of input concatenated together)
<i>OFDM_insert_null_tones.vi</i>	insert columns of zeros into 2-D input array at specified locations
<i>OFDM_add_CP.vi</i>	prepends last C columns of 2-D input array to start of array
<i>OFDM_remove_null_tones.vi</i>	remove specified columns from 2-D input array
<i>OFDM_remove_CP.vi</i> <i>OFDM_FEQ.vi</i>	remove first L_c columns from 2-D input array computes frequency domain equalizer based on channel estimate and equalizes parallel input stream

Table 1: Helper VIs located in *OFDM_comm1.0.llb*.

To efficiently process parallel inputs, these VIs use a parallel block structure represented in a 2-D array. In this structure, each row of the 2-D array corresponds to a single block of data. Thus, the number of rows corresponds to the number of blocks that are being processed.

Note: For-Loops in LabVIEW provide an auto-indexing feature which can be used to extract the i^{th} element of a 1-D array. Auto-indexing can also be used on a 2-D array to extract the i^{th} row of the 2-D array.

Tables 2 and 3 describe the VIs that you must construct. Many of the OFDM related parameters you will need to use (such N , L_c , and *null tones*)

Table 2: Description of *OFDM.modulate.vi*

<i>OFDM.modulate.vi</i> - implements the OFDM modulator described in Section 1.1			
INPUTS	<i>input symbols</i>	1-D array of CDB (complex doubles)	input symbol stream to be modulated using OFDM
OUTPUTS	<i>output samples</i>	1-D array of CDB	output sample stream after OFDM modulation; one OFDM symbol corresponds to $(N + L_c)$ samples

Table 3: Description of *OFDM_demodulate.vi*

<i>OFDM_demodulate.vi</i> - implements the OFDM demodulator described in Section 1.2			
INPUTS	<i>input samples</i>	1-D array of CDB	input sample stream to be demodulated using OFDM; one OFDM symbol corresponds to $(N + L_c)$ samples
	<i>channel estimate</i>	1-D array of CDB	channel estimate computed prior to demodulation (used for FEQ)
	<i>number of data symbols</i>	I32	number of data symbols to be recovered ¹
	<i>equalize channel?</i>	Boolean	determines whether or not you should apply FEQ to OFDM demodulated symbols; set this value to TRUE by default
OUTPUTS	<i>demodulated symbols</i>	1-D array of CDB	stream of output symbols after OFDM modulation and FEQ (when appropriate)
	<i>FD channel estimate</i>	1-D array of CDB	frequency domain response of channel estimate computed taking DFT of channel estimate

can be found unbundled from the *OFDM parameters* in cluster. After building your VIs, insert your code into *OFDM_transmitter.vi* and *OFDM_receiver.vi* as shown in Figure 3 and 4 respectively.

You have been provided with templates for the VIs you need to create for this lab that already have all the inputs and outputs wired for you. What is required of you is to finish constructing the block diagram to provide the functionality of the VIs.

Throughout the course, several of the VIs you will create will have a *modulation parameters* cluster passed into and out of them. The *modulation parameters in* contains many of the parameters needed by your VIs and will be unbundled from them. This has already been done for you in the template VIs if necessary. Some VIs will also have *modulation parameters out*, so that the cluster can be passed on through to the VIs that follow. Please ensure

¹ Figure 1 implies that the output of the OFDM demodulator produces multiples of N symbols. You should truncate the array to the appropriate size (as dictated by *number of data symbols*).

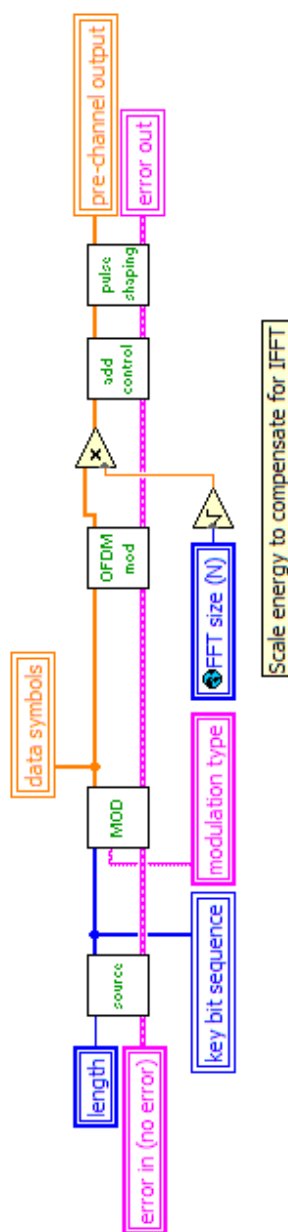
Figure 3: Block diagram for *OFDM_transmitter.vi*.



Figure 4: Block diagram for *OFDM_receiver.vi*.

that these clusters remain wired the way they are in the template VIs, as changing how they are wired will cause VIs further down the line to break. In addition, you will now have access to the *OFDM parameters* cluster for OFDM-specific parameters you will need for your VIs. These are accessed in the same way that parameters from the *modulation parameters* cluster are.

After inserting your code into the simulator provided to you, verify that your code is working properly by observing that the transmitted and received constellations reflect the appropriate PSK modulation scheme you have chosen.

Pre-Lab Turn In

1. Submit your implementation of *OFDM_modulate.vi* and *OFDM_de-modulate.vi*. Remember, you will be penalized if you do not wire error cluster inputs and outputs. *Note: If you need to generate additional subVIs for this or any future labs, please submit these subVIs along with your other pre-lab VIs.*
2. **EXTRA CREDIT (20pts)** - implement *FEQ.vi* (i.e., your own version of *OFDM_FEQ.vi*). Table 4 describes the details of this VI. Submit your implementation of *FEQ.vi* with your other VIs. Remember to wire error clusters.

Table 4: Description of *FEQ.vi*

<i>FEQ.vi</i> - performs frequency domain equalization as described in Section 1.3			
INPUTS	<i>input</i>	2-D array of CDB	parallel block structure of symbols (i.e., output of DFT); each row corresponds to a block of N symbols (i.e., $\{Y[k]\}_{k=0}^{N-1}$)
	<i>channel estimate</i>	1-D array of CDB	channel estimate computed prior to demodulation
OUTPUTS	<i>equalized output</i>	2-D array of CDB	equalized symbols; each row corresponds to a block of N symbols (i.e., $\{\tilde{X}[k]\}_{k=0}^{N-1}$ where $\tilde{X}[k] = Y[k]/\hat{H}[k]$)
	<i>FD channel estimate</i>	1-D array of CDB	frequency domain response of channel estimate computed by taking DFT of channel estimate (i.e., $\hat{H}[k] = DFT\{h[l]\}$)

3 Lab Experiment

A single carrier system operating with symbol rate $1/T$ would transmit one symbol every symbol period T . Thus in time NT , the single carrier system would transmit N symbols; maintaining orthogonality (or separation) between symbols through time division multiplexing (or TDM). As you have learned in previous labs, a frequency selective channel can undo this orthogonality, making some form of equalization necessary.

Multicarrier systems use a cyclic prefix to enable digital frequency domain equalization. An interpretation is that OFDM divides a frequency selective channel into N flat fading subchannels. Thus OFDM can be seen as N parallel flat fading channels, (each of bandwidth $1/NT$), multiplexed in the frequency domain. Hence, a simple zero-forcing equalizer can be applied to each subchannel in order to equalize channel impairments. In this lab you will examine the frequency selectivity of wireless channels and explore when it might be advantageous to use OFDM to forgo the complexities of linear equalization.

Along with the advantage of low complexity equalization, OFDM systems also provide a framework which allows for many advanced digital communication techniques such as adaptive modulation and power control. Additionally, the frequency domain interpretation of OFDM (i.e., as a set of N parallel flat fading subchannels) allows for many clever techniques with regard to error control coding by taking advantage of frequency diversity (topics that are outside of the scope of this course). All of these advantages do not come for free. There are a number of tradeoffs associated with single and multicarrier systems. In this lab you will explore one particular tradeoff, the sensitivity of OFDM systems to frequency offsets.

In this lab you will run your implementation of *OFDM_modulate.vi* and *OFDM_demodulate.vi* over a real wireless link. As in previous labs, you will complete the framework for the transmitter and receiver blocks in lab using your code from this and previous labs. Insert your code into this framework as you did in the pre-lab. You will then perform two experiments to explore the previously mentioned topics: 1) the frequency selectivity of wireless channels and 2) the sensitivity of OFDM systems to frequency offsets.

3.1 Insert Your Code

Figure 5 depicts the dependencies between files in the new OFDM framework you will be using in lab. Note that this new framework still leverages many of the blocks in the original digital communications library (*digital_comm.llb*), but also includes some of the elements from the new OFDM digital communications library (*OFDM_comm1.0.llb*).

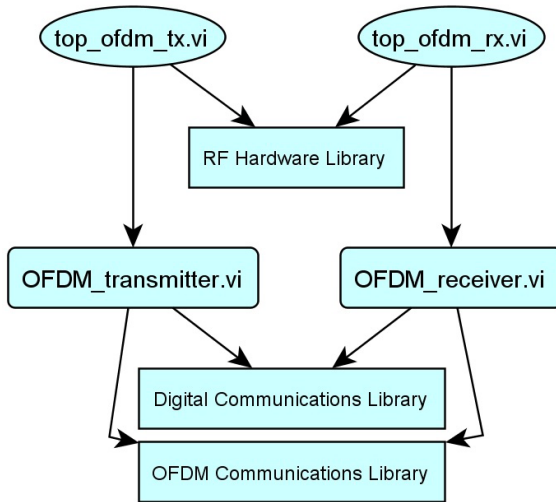


Figure 5: Hierarchy of files for OFDM framework.

Once you have inserted your code for *OFDM_modulate.vi* and *OFDM_demodulate.vi* into *OFDM_transmitter.vi* and *OFDM_receiver.vi* respectively, you will need to set up the parameters listed below. These parameters are located on the front panels of *top_tx.vi* and *top_rx.vi*. Leave any unspecified parameters set to their default value.

- Packet length = 500 bits
- Modulation type = QPSK
- Channel estimate length = 4
- FFT size (N) = 64
- Length of CP (L_c) = 8
- Null tones = {0, 31, 32, 33}

3.2 Frequency Selectivity of Wireless Channels

In this first experiment you will observe the frequency response of narrowband and wideband channels. Set up the following parameters for a narrowband system.

- TX sample rate = 4 MSamp/sec

- TX oversample factor = 20
- RX sample rate = 4 MSamp/sec
- RX oversample factor = 20
- Capture time = 2.4 msec

After transmitting a packet successfully, observe the frequency response of the narrowband channel, using the *Channel Response* graph located on the front panel of *OFDM_receiver.vi*. Also examine the instantaneous power-delay profile using the appropriate graph on the front panel of the same VI. Take note of the effective length of the channel response (i.e., the number of nonzero taps in the channel).

Next, you will observe the frequency response of a wideband channel. To set up a wideband system, set the following parameters in your OFDM system.

- TX sample rate = 20 MSamp/sec
- TX oversample factor = 4
- RX sample rate = 10 MSamp/sec
- RX oversample factor = 2
- Capture time = 100 μ sec

For this part of the experiment it is critical that you place your antennas at an elevated height so that all reflected paths in the lab environment reach the antennas. After transmitting a packet successfully observe the frequency response and power-delay profile of the wideband channel in *OFDM_receiver.vi*. Also, take note of the effective length of the channel response.

Questions

Answer the following questions regarding the frequency selectivity of wireless channels.

1. According to the parameters above, what is the respective OFDM symbol rate in the narrowband and wideband systems you have set up (i.e., the reciprocal of the OFDM symbol period as previously defined)?
2. What are the effective lengths of the narrowband and wideband channels respectively?
3. Describe the frequency responses of each channel. In particular, are the frequency responses of these channels frequency selective or flat?

4. Consider the multipath channel model in the absence of noise

$$y[n] = \sum_{l=0}^{L_h} h[l]x[n-l], \quad (2)$$

where $h[n] = 0, \forall n \notin (0, 1, \dots, L_h)$.

- Show that in an OFDM system, when $L_h = 0$ the frequency response of the channel is necessarily flat fading. In other words, show that the frequency response of all subchannels is the same (i.e., $H[n] = H[m], \forall n, m$, where $H[k] = DFT\{h[l]\}$).
- Show that when $L_h > 0$ the frequency response of the channel is frequency selective (i.e., show that $L_h > 0 \Rightarrow H[n] \neq H[m]$ for at least one different n and m).

Submit your answers to these questions as part of your lab report.

3.3 Sensitivity to Frequency Offsets

In this experiment you will observe how the performance of an OFDM system degrades in the presence of a frequency offset. Set up the following parameters in your system.

- TX sample rate = 20 MSamp/sec
- TX oversample factor = 20
- RX sample rate = 4 MSamp/sec
- RX oversample factor = 4
- Capture time = 500 μ sec
- Frequency offset (Hz) = 200 Hz

To observe how a frequency offset impacts your system, you will need to disable the frequency offset correction algorithm implemented in the synchronization block. To do this, simply set *Correct Frequency Offset* on the front panel of *top_ofdm_rx.vi* to FALSE. Now you will consider two OFDM systems which use different values for N . First, consider a system which uses $N = 64$ subcarriers. Set up the following OFDM parameters.

- FFT size (N) = 64
- Length of CP (L_c) = 8

- Null tones = {0, 31, 32, 33}

Observe how a frequency offset impacts the received signal constellation. Also make note of the impact of a frequency offset on BER performance. Increase the amount of frequency offset in your system in increments of 200 Hz and observe how the signal constellation and BER performance vary. Now consider a system which uses $N = 1024$ subcarriers.

- FFT size (N) = 1024
- Length of CP (L_c) = 32
- Null tones = {0, 511, 512, 513}

Again, observe how a frequency offset of just 200 Hz impacts the received constellation and BER performance of your system. To understand how a frequency offset impacts OFDM systems, it is convenient to think of a frequency offset as a shift in the frequency domain. This shifting can cause what is known as inter-carrier interference (or ICI).

Questions

Answer the following questions about the sensitivity of OFDM systems to frequency offsets.

1. Recall from the Lab 5 that in a single carrier system, a frequency offset causes a time varying phase offset which effectively “smears” the received constellation as it rotates it. How is the impact of a frequency offset in OFDM systems different from that of single carrier systems? In particular, how is the impact on the signal constellation different?
2. What is the subcarrier spacing Δ_c of your system when $N = 1024$ and 64 respectively?
3. Which of the systems (i.e., $N = 1024$ or 64) is more severely impacted by a 200 Hz frequency offset? Why?
4. As mentioned, frequency offsets can be interpreted as shifts in the frequency domain. There is a duality between the effect of this shifting in a multicarrier system and symbol timing error in a single carrier system (discussed in Part 2 of Lab 2).

Discuss this relationship between the effect of symbol timing error in single carrier systems and frequency offset in OFDM systems. Be sure to include in your discussion the effect of each impairment on the received signal constellation. *Hint: Think about the impact of each type of error on the orthogonality (or separation) between symbols.*

Submit your answers to these questions as part of your lab report.

3.4 Lab Turn In

Show the instructor that you have replaced the OFDM modulator and demodulator in lab with your own code. Demonstrate to the instructor that your code is working properly. Also show the instructor that your OFDM system “breaks” down when you have frequency offsets greater than the subcarrier spacing that are not corrected for (i.e., when $f_{\text{offset}} > \Delta_c$). Answer all of the questions above and submit your answers in your lab report.

DIRECTIONS FOR LAB SUBMISSION

Your lab report should include the following.

1. Answer all questions from the lab experiment (i.e., do not reanswer pre-lab questions).
2. Discuss any problems you might have encountered and how you overcame these obstacles.
3. In this lab you observed how an OFDM system operates over a real wireless link. Answer the following questions about your experience in lab.
 - (a) OFDM systems have an inherent overhead due to the need for a cyclic prefix. Assuming QPSK modulation, in terms of N , L_c , T , and the number of null tones K (all as previously defined), what is the effective data rate of the OFDM system in lab?
 - (b) Based on your experience in lab, discuss why or why not you might use an OFDM system in a wideband and narrowband system respectively. Include in your discussion some of the benefits/costs of each scenario.
 - (c) OFDM systems in general have a large degree of flexibility. Name at least three parameters of OFDM systems which contribute to this flexibility and comment on how they do so.