LABORATORY MANUAL

EE 504. Software-Defined Radio.

California Polytechnic State University, San Luis Obispo

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0 Course Information

0.1 Catalog Description

EE 504. Software-Defined Radio. 4 units

Prerequisite: EE 314; and EE 328 or CPE 327; or graduate standing.

Introduction to software defined radios, including architectures of software defined radio receivers and transmitters, design principles and trade-offs, signal processing techniques, and applications of the technologies. 3 seminars, 1 laboratory.

0.2 Learning Objectives

- Become familiar with the configuration of software-defined radios.
- Develop an understanding of communication system components.
- Leverage understanding of communication systems to use MATLAB's Communication, LTE, and 5G toolboxes.
- Investigate a relevant topic of interest and present findings during seminar or lab session.

0.3 Laboratory Activities

Week	Lecture Topic	Lab Activity
1	Intro	Plutos and Links
2	Comm Systems	FM, Nyquist, and Antennas
3	Sampling Theory	Barker Codes, QPSK, Constellation Diagrams, and BER
4	Digital Filters	I/Q Imbalance, SNR, EVM, and more BER
5	Timing/Contingency	TBD
6	Probability	TBD
7	Channel Encoding	project work
8	Channel Encoding	project work
9	Special Topics	project work
10	Special Topics	project presentations
F	final exam	submit report

1 Plutos and Links

"Pluto is not a planet"— M. Rodriguez.

1.0 Learning Objective

The purpose of this session is to introduce the software-defined radio (SDR) unit that will be used in this course, install the necessary software on your machine, and establish communication links.

1.1 The ADALM-PlutoSDR

For this course, we will be using the Analog Devices Active Learning Module (ADALM) PlutoSDR. This is a bit of a mouthful so we will just refer to them as **plutos**. The plutos are equipped with a transmit (Tx) port, a receive (Rx) port, a Micro-USB 2.0 data port, a power port (also Micro-USB 2.0), an indicator LED, and uncountably infinite configuration possibilities via software. The radio frequency (RF) ports, Tx and Rx, are SubMiniature version A (SMA) female connectors, so an attaching antenna will need to have an SMA male connector. The RF ports can be set to either half duplex, either talk or listen, or full duplex, talk and listen at the same time. I tend to operate better in half duplex so if you have a question try to send an interrupt first so my brain can make a context switch (bad software joke).

1.1.1 Specifications

The previous TA, Julio Tena, put together a wonderful presentation to outline the capabilities of the pluto. Some specifications of interest pulled from Analog Devices website are listed below:

- RF coverage from 325 MHz to 3.8 GHz
- Up to 20 MHz of instantaneous bandwidth
- 12-bit ADC and DAC
- One transmitter, one receiver, half or full duplex
- MATLAB and Simulink support

1.1.2 Kit Components

Your kit should come with the pluto shown in Figure 1, a USB data cable, an SMA male-male connector shown in Figure 2, and two antennas shown in Figure 3.

Figure 1: Pluto au naturel

Figure 2: Pluto kit SMA male-male connector

Figure 3: Pluto kit antennas

1.2 Lab Activity

We will install the necessary software components, run an example transmit-and-receive (tx and rx, respectively) script, and test a few communication links.

1.2.1 Equipment

- pluto kit
- laptop with MATLAB and Simulink

1.2.2 Procedure

Be sure to document your findings (pictures and screenshots) along the way for your lab notebook.

- Sign into MathWorks.
- Install MATLAB if you don't already have it on your machine.
- Install the ADALM-PLUTO Radio Support from Communications Toolbox.
- Follow the hardware installation and connect the pluto to your computer via USB.
- Open MATLAB and hack your pluto by running the following line in the command window:

  ```
  configurePlutoRadio('AD9364')
  ```

  This will expand the operating frequency range by configuring the pluto to the AD9364 RF transceiver architecture which supports frequency tuning from 70 MHz to 6 GHz. The pluto by default will follow the AD9363 architecture which has the advertised operating range of 325 MHz to 3.8 GHz.
- Verify that the receive-and-transmit MATLAB script works.

1.2.3 Deliverables

Document your set-up and results in your lab notebook and post next week before class.

1. (25 pts) Screenshot of transmitted signal from tx-and-rx example MATLAB script.
2. (25 pts) Screenshot of spectrum analyzer output from tx-and-rx with bare RF ports.
3. (25 pts) Screenshot of spectrum analyzer output from tx-and-rx with a hard-wire link.
4. (25 pts) Screenshot of spectrum analyzer output from tx-and-rx with an antenna air link.

2 FM, Nyquist, and Antennas

"Marconi plays the mamba, listen to the radio"— Starship.

2.0 Learning Objective

The purpose of this session is to review concepts of frequency modulation (FM), implement an FM receiver in software, construct an antenna, compare antenna performance of audio fidelity, and observe the Nyquist-Shannon sampling theorem in the frequency spectrum.

2.1 Before the Lab Session

1. Read all sections up to the lab activity.

2.2 FM Theory

Imagine you are at a party. Music is playing, everyone is either laughing, talking, or screaming across the room, and it seems impossible to have an intelligible conversation. You want to talk to your friend so you walk over to another room with them where it is quieter. Well this is the same idea behind signal modulation. We just walk our **message** to a different space in the frequency spectrum. The **carrier frequency** of our modulated signal is where we want to stand. A **channel** is the room that we are in which is inside some building, or **frequency band**. The **bandwidth** of our message is the range (varying timbre) of our voices. You and your friend can hear all the people in the party room still so their bandwidth extends the **guardband**, walls, and prohibits complete **channel separation**. FM is one technique we can use to relocate our message.

2.2.1 Definition

We define an FM signal as Eq. 1. Modulated signals are typically represented as $\phi(t)$ with some subscript describing the nature of modulation. An FM signal can be described as a sinusoid with constant carrier amplitude and time-varying frequency that is proportional to some integral gain of the message signal.

$$\phi_{FM}(t) = A_c \cos\left[\omega_c t + k_f \int_{-\infty}^{t} m(\lambda) d\lambda\right] \tag{1}$$

2.2.2 Modulation Index

The FM modulation index β, also known as the frequency deviation ratio, is defined as the ratio of the frequency deviation, of the modulated signal, to the message signal bandwidth as given by Eq. 2. The frequency deviation describes how far our modulated signal can be displaced from the carrier which effectively constrains the spectrum.

$$\beta = \frac{\Delta f}{B} = \frac{\Delta\omega}{2\pi B} \tag{2}$$

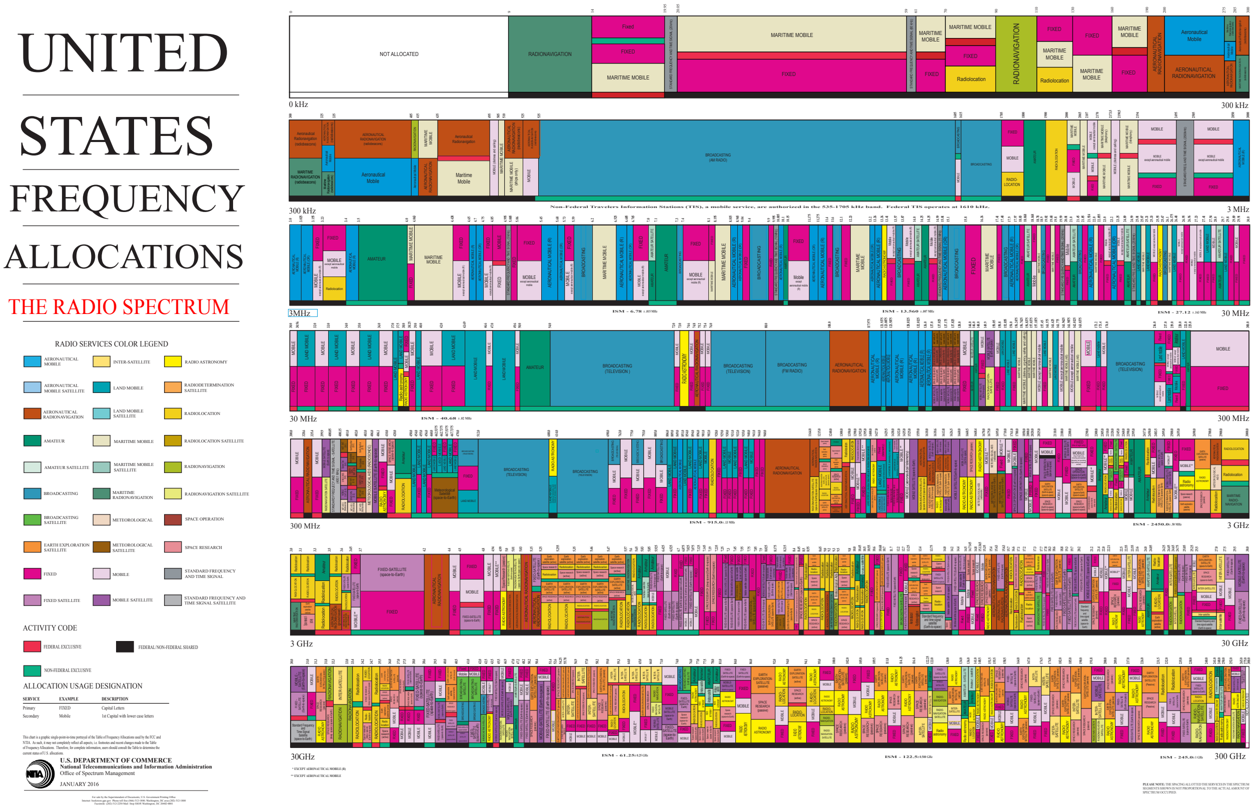

Figure 4: United States Frequency Allocations, Federal Communications Commission (FCC)

2.3 Antenna Theory

We are not going to worry too much about antenna theory here since this is a study of software-defined radio. You might notice that the antennas provided in your kit are fairly small. There are many types of antenna and in general the length of an antenna is inversely proportional to its intended operation frequency. Recall that the frequency operating range of plutos goes from 324 MHz to 3.8 GHz. The antennas that are provided in our kit were designed for the range of operation specified, but we want to *hack* the pluto to go to the lower frequency FM broadcast band. We might achieve better performance by creating an antenna that is designed for the lower frequency. There are a number of different antenna parameters that we can measure to characterize performance such as: gain, bandwidth, radiation pattern, polarization, and impedance. You should have some familiarity with gain and impedance concepts from prerequisite coursework, so we will stick to observing gain in the frequency spectrum and impedance in the antenna construction.

2.3.1 Whip Antenna

We will create a whip, or monopole, antenna. Recall from circuit theory that maximum power transfer occurs when the impedance of the source and load are matched. For a monopole topology, we can approximate an impedance inverter by creating an antenna that is of quarter-wave length, $\lambda/4$, for reasons that are beyond the scope of this class (electromagnetism and our good friend Maxwell). The quarter-wave length of our monopole antenna is given in meters by Eq. (3) where f is our target frequency in Hertz and c is the speed of light, approximately $3 \times 10^8 m/s$.

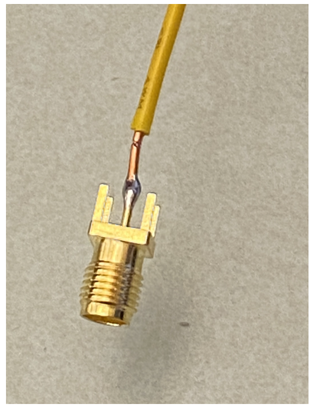

Figure 5: Whip antenna construction

$$l = \frac{c}{4 \times f}(meters) \tag{3}$$

There is a ten-week treatment of antenna theory offered at Cal Poly, EE 533 usually taught by Professor Arakaki in the spring, if you are interested in expanding your mind.

2.3.2 Antenna Construction

The antenna that I intend for us to design is composed of an insulated copper wire soldered to the center conductor of an SMA female connector. The copper wire is cut to a length such that the total length of the copper wire matches the monopole quarter-wave antenna length. Again this is probably not the greatest antenna ever made, but it does a fair job of showing us the importance of the length of an antenna. My whip antenna is shown in Figure 5.

2.4 Nyquist-Shannon Sampling Theorem

You should know by now that if we do not sample a signal at least twice the highest frequency present then we introduce the possibility for aliasing. In the frequency spectrum, this manifests itself as a remapping of content. To observe this effect, we will downsample the received signal until we notice changes in the frequency spectrum. Due to signal processing constraints, I have provided a Simulink model to capture the signal and a separate model for the spectrum analysis.

2.5 Lab Activity

We will create an FM broadcast receiver using a pluto, MATLAB, Simulink, one of the provided antennas, and a whip antenna that you create. Our target frequency will be Cal Poly's radio station KCPR, which is 91.3 FM in the San Luis Obispo area and has a carrier of 91.3 MHz.

2.5.1 Equipment

- pluto kit
- laptop with MATLAB and Simulink
- SMA connector and insulated copper wire
- solder and soldering station

2.5.2 Procedure

Be sure to document your findings (pictures and screenshots) along the way for your lab notebook.

- Connect the antenna from your kit to the Rx port of your pluto.
- Download the lab 2 source files and open the example FM capture Simulink model.
- Double-click the ADALM-PLUTO Receiver and tune the center frequency to KCPR.
- Lower the volume on your device so as to not damage your speakers and ears.
- Run the program and observe audio fidelity of the pluto kit antenna for FM band receiving.
- Determine the antenna length for a whip antenna optimized for 91.3 MHz, cut a piece of wire to approximately that length, and solder it onto the center conductor of an SMA.
- Connect your whip antenna to the Rx port and try running the Simulink model again.
- Try to get a good audio sample to use for spectrum analysis.
- Using the FM baseband plotter model, adjust the downsample factor until aliasing occurs.
- Discuss your findings in your lab notebook (set-up, results, conclusion).

2.5.3 Deliverables

1. (25 pts) Whip antenna length calculation and picture of hardware set-up with whip antenna.
2. (25 pts) Comparison of audio fidelity between antennas. You can tune in to KCPR here.
3. (25 pts) Spectrum analyzer screenshot of original signal and of aliased signal.
4. (25 pts) Feedback on the activity. Maybe there is something that you want changed or you came up with a simple hack that improved antenna performance. Or maybe you found the assignment fun, or too short/long.

3 Barker Codes, QPSK, Constellation Diagrams, and BER

"Are you paying attention?"— Benedict Cumberbatch as Alan Turing in *The Imitation Game.*

3.0 Learning Objective

The purpose of this session is to generate and analyze Barker codes, modulate a signal using QPSK, to learn how to use a constellation diagram to visualize data of a digital modulation scheme, and to simulate bit error rate across an additive white Gaussian noise channel.

3.1 Barker Codes

If we have a radio system, how can we tell the receiver to start listening for a packet of data? Well Ronald Hugh Barker invented constraints for a pattern of digital values with the property of ideal autocorrelation in an attempt to achieve this so-called group synchronization of binary digital systems. Only nine Barker codes are known to exist. They have a length of 13, at most, can only contain '-1' or '+1', and can be elementally symmetric. For example, a known barker code of length 7 is $\{+1, +1, +1, -1, -1, +1, -1\}$ and performing element-wise multiplication by -1 yields another sequence. The Barker code resembles a discrete version of a chirp signal and in general the synchronization performance increases with the code length. We define a Barker code as a finite sequence of N values of $+1$ and -1, a_{ij} for $j = 1, 2, ..., N$ such that the magnitude of Eq. (4) is inclusively bounded by unity for all $1 \leq v < N$.

$$c_v = \sum_{j=1}^{N-V} a_j a_{j+v} \tag{4}$$

3.2 QPSK

Recall that the barker codes can only contain '-1' or '+1'. This implies that there exists a binary phase shift as the two values, or symbols, can be expressed as differing by 180°. Quadrature phase shift keying (QPSK) extends this idea by separating symbols by 90°. Phase shift keying is a digital modulation process whereas frequency modulation that was observed in lab last week is analog modulation.

3.3 Constellation Diagrams

We can use a constellation diagram to visualize the received values of a digital system in a scatter plot. The incoming signal has an in-phase component, I, and a quadrature component, Q. The location of a symbol is fixed and samples are then plotted in I-Q space. A sample is thus determined to be whatever symbol it is closest to in space. For example if we have a digital system with symbols at '-1' and '+1' in I-Q space and we receive a '0', it might be best to throw away that sample because it is maximally ambiguous as it is equidistant from the symbols.

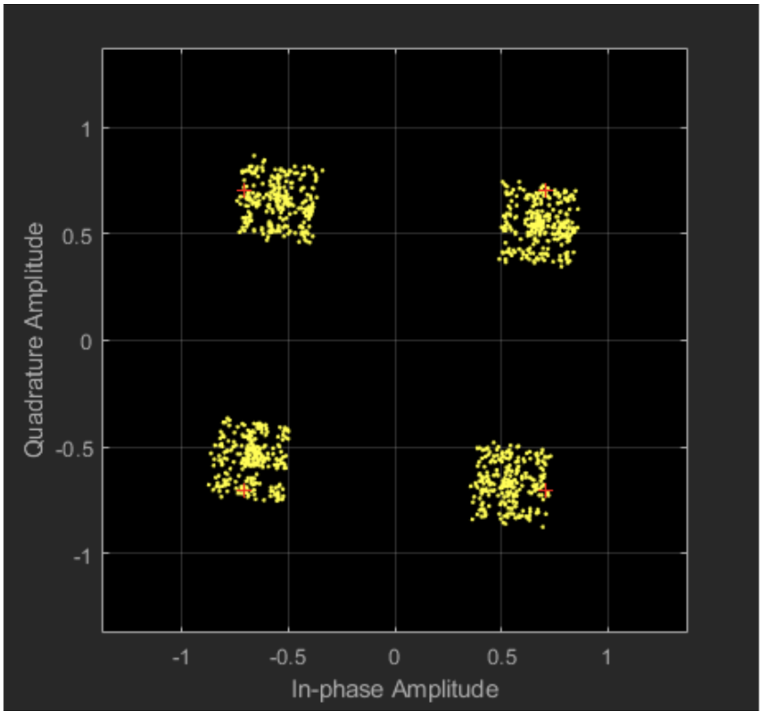

Figure 6: I-Q constellation, QPSK symbol location marked by red +'s, samples scattered in yellow, from my lab notebook last year

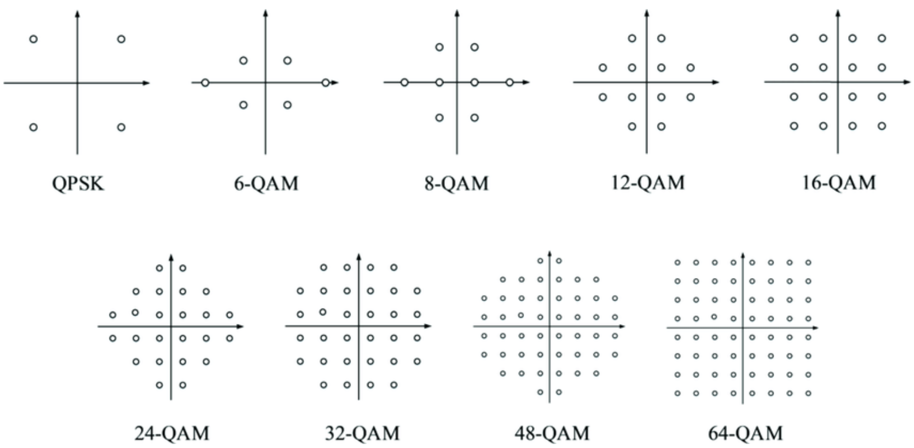

Figure 7: Examples of constellation symbol locations, "Loss weight adaptive multi-task learning based optical performance monitor for multiple parameters estimation", Yu et al.

3.4 BER

The bit error rate (BER) is a common quantitative performance metric for a digital system that describes the rate at which incorrect bits are received as shown in Eq. (5).

$$BER = \frac{N_{error}}{N_{total}} \tag{5}$$

The constellation diagram is a great way to get a sense of the BER as incoming values are determined to be the symbol that they are closest to. In I-Q space, it is common to use the Euclidean norm to determine the closest neighboring symbol, but as you might know other distance measures exist.

3.5 Communication System Simulation

As you might imagine, it can be helpful to simulate a system to analyze its performance before proceeding to implementation. There are a few things worth considering: the channel model, the modulation scheme, the symbol decoding process, and the error rate.

3.5.1 Channel Model

The channel model is used to describe the medium in which our signal propagates. Many channel models exist, but we will consider the additive white Gaussian noise (AWGN) model as it is common for naturally occurring random processes. The AWGN model follows a Gaussian distribution and is additive in the sense that you can simply add it to your "transmitted" signal to get what the receiver sees. You should be familiar with a Gaussian, or normal, distribution which has a PDF modeled by Eq. (6). Notice that this is a function of x, so the mean, μ, and variance, σ^2, are constant parameters for a given distribution.

$$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \tag{6}$$

3.6 Modulation Scheme

The modulation scheme should be a familiar concept. FM is a type of analog modulation, while QPSK is a type of digital modulation, and both are examples of modulation schemes. In Figure 7 you can see the constellation of some digital modulation schemes in I-Q space. An example MATLAB script will be provided that compares the BER of 4-PAM (pulse amplitude modulation), 4-QAM, and QPSK, across an AWGN channel.

3.6.1 Symbol Decoding

As mentioned previously, we decode a received signal by mapping it to the nearest symbol using some distance measure. The example script uses the Euclidean norm.

3.6.2 Error Rate

We will simulate a digital system which means that the data propagating across our channel is a stream of bits. Thus, we will use BER to determine the error.

3.7 Lab Activity

3.7.1 Equipment

- pluto kit
- laptop with MATLAB and Simulink

3.7.2 Procedure

Be sure to document your findings (pictures and screenshots) along the way for your lab notebook.

- Download the lab 3 source files.
- Start a blank Simulink model, save it as barker_codes.slx. Design a model that:
  - Generates a Barker code using the **Barker Code Generator** block
  - Allows us to view the code in the time domain using the **Scope** block
  - Converts the Barker code to binary with a **Relational Operator** and a **Constant** block
  - Uses BPSK to modulate the binary with the **M-PSK Modulator Baseband** block
  - Transmits the modulated data with the **ADALM-PLUTO Transmitter** block
  - Receives the modulated data with the **ADALM-PLUTO Receiver** block
  - Demodulates the BPSK to baseband with the **M-PSK Demodulator Baseband** block
- Run plutoLoopback.m and observe what happens as tau_hat changes. Run the simulation with a hard-wire link, with an air link, and again with the bare RF ports.
- Run Modulation_schemes_BER.m and watch the stars align.

3.7.3 Deliverables

1. (20 pts) Screenshot of your model, Barker code of length 7, and the demodulated signal.
2. (20 pts) The Barker code that the Simulink model generated (i.e. $\{B_1, B_2, ..., B_7\}$).
3. (20 pts) Discussion on the relationship between signal strength and constellation diagrams.
4. (20 pts) Screenshot of the three constellation diagrams from Modulation_schemes_BER.m and the BER plot.
5. (20 pts) Adjust a parameter, or multiple parameters in Modulation_schmes_BER.m, provide a discussion on the impact on BER, provide screenshots of the constellation diagrams, and BER plot again. Some examples of things to change include:
   - The variance, stored as nvar
   - The symbol location, stored as symb_ followed by the modulation scheme
   - The channel model, uses AWGN with complex Gaussian noise
6. (Extra credit) Create a Barker code of length 8. Or provide some feedback on the assignment.

4 IQ Imbalance, SNR, EVM, and more BER

"Does anyone actually read this?"— RJ.

4.0 Learning Objective

The purpose of this session is to introduce IQ imbalance, review SNR, measure EVM and BER, and learn to cope when the stars do not align.

4.1 IQ Imbalance

Recall the loopback test from last week where the constellation shifted in phase and amplitude with a change in tau_hat. When the symbols appear to be properly spaced but shifted in phase and/or amplitude, this can be attributed to IQ imbalance. The receiver of a radio system should include measures to control this imbalance so as to limit errors in the demodulated signal.

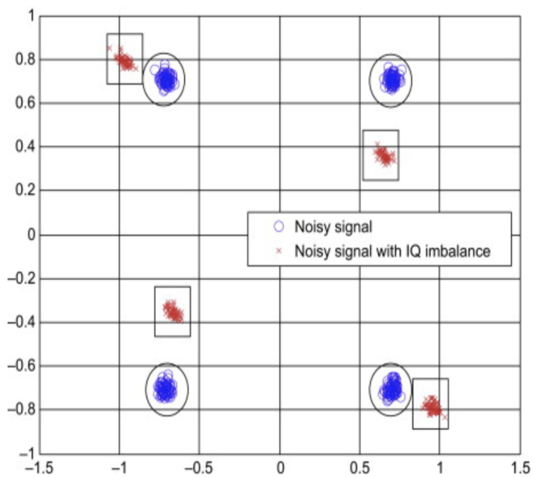

Figure 8: QPSK Signal with Phase and Amplitude IQ Imbalance

4.2 SNR

You should hopefully be familiar with the idea of signal-to-noise ratio (SNR). Signal comes first in the ratio, so higher SNR means that the power of the signal is greater than that of the noise.

4.3 EVM

The error vector magnitude (EVM) measures how close symbols are received with respect to the desired constellation. The EVM is given in decibels by Eq. (7). Whenever you have an error signal it must be with respect to a desired reference. In our case, the desired constellation will be whatever is generated before the channel distortions (IQ imbalance, noise model, and path distortion) occur. EVM is an industry standard measurement for cellular phones, cable television, and Wi-Fi.

$$EVM_{dB} = 20 \log_{10} \frac{EVM_{\%}}{100\%} \tag{7}$$

4.4 Lab Activity

4.4.1 Equipment

- pluto kit
- laptop with MATLAB and Simulink

4.4.2 Procedure

Be sure to document your findings (pictures and screenshots) along the way for your lab notebook.

- Design a Simulink model to measure the EVM and BER of a stream of random integers modulated with 16-QAM, cascaded through IQ imbalance an AWGN channel, and the pluto hard-wire link. Also grab the constellation at both ends of the channel (i.e. directly after modulation and before demodulation).
- Some useful blocks include: Random Integer Generator, Rectangular QAM Modem Baseband, I/Q Imbalance, AWGN channel, and EVM Measurement.

4.4.3 Deliverables

1. (25 pts) A screenshot of your Simulink model and hardware set-up.
2. (25 pts) Average EVM, BER, and constellations for a system with an IQ imbalance of 1dB at 15° across an AWGN channel with an SNR of 0dB.
3. (25 pts) Observe two other cases of IQ imbalance and SNR and tabulate the results.
4. (25 pts) Repeat the deliverables with a different modulation scheme.

