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Lab 1 - Introduction to RF Digital Communication Signals and Systems

Goal:

Part 1:
Introduce two common radio-frequency communication signal formats—binary-phase-shift keying (BPSK) and quadrature-phase-shift keying (QPSK). Understand the relationship between the power density spectrum of the transmitted signal and the signal phase. Understand the relationship between signal phase, the distance between the transmitter (Tx) and the receiver (Rx). These signaling formats are generated using ***gnuradio*** in the Pluto SDRs using software that we will be using throughout the class.

Part 2:
Survey several “live” communication signals. For this part, you may be able to modify the Pluto SDR to observe a wider range of signals.

1 Digitally-generated Data Waveforms

1.1 Binary-phase-shift-keyed Signals (BPSK)

1. We will start with a digital modulation format that transmits one bit per symbol interval using a single carrier frequency. This format is called binary-phase-shift keying or BPSK.

2. Go to the Lab 1 directory ./lab1.py. The command executes python program that uses *gnuradio*. Running the program should start the BPSK modem front panel shown in Figure 1. If you have your PLUTO, set the carrier frequency to (950) MHz. If the display is "laggy", please read the handout on "Getting Started in Lab", which discusses how the virtual machine (VM) performance depends on your specific hardware, and tips on how to make your system more responsive and less "laggy".

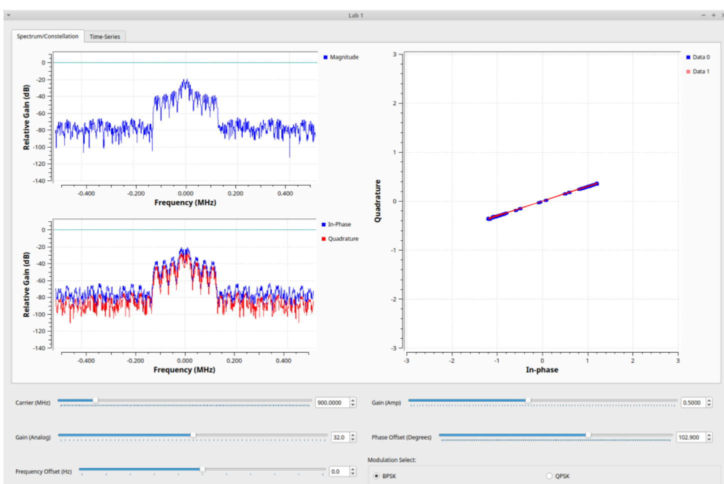


Figure 1: Front panel for BPSK for a 950 MHz carrier frequency f_c.

3. The trace on the right of Figure 1 is the measured signal constellation for the BPSK waveform with the blue points being samples that, in general, have both an in-phase (I) component and a quadrature component (Q). Depending on your local environment, the trace may "bounce" around.

4. The traces on the left of Figure 1 are three different power density spectra:

    a) The magnitude of the power spectrum of the signal is in the upper-left corner. This is the magnitude of the complex-baseband power density spectrum.
    b) The power spectrum of the in-phase component I^2 is the blue trace in the lower-left corner.
    c) The power spectrum of the quadrature component Q^2 is the red trace in the lower-left corner

5. Vary the phase offset of the local oscillator using the slider bar and observe what happens to the signal constellation and the power in the in-phase component as compared to the power in the quadrature component. Is the magnitude $\sqrt{I^2 + Q^2}$ of the power density spectrum affected by the phase? Why or why not?

- The signal constellation
    - A phase offset impairs each point in the constellation, causing a rotation in the counterclockwise direction for a positive phase offset.
    - Rotation in the clockwise direction for a negative phase offset.
- In-phase component power (in comparison to the quadrature component)
    - Decrease means the in-phase component is smaller than the quadrature component.
    - Increase means the in-phase component is larger than quadrature component.

Since when one decreases, the other increases, the average power stays the same.

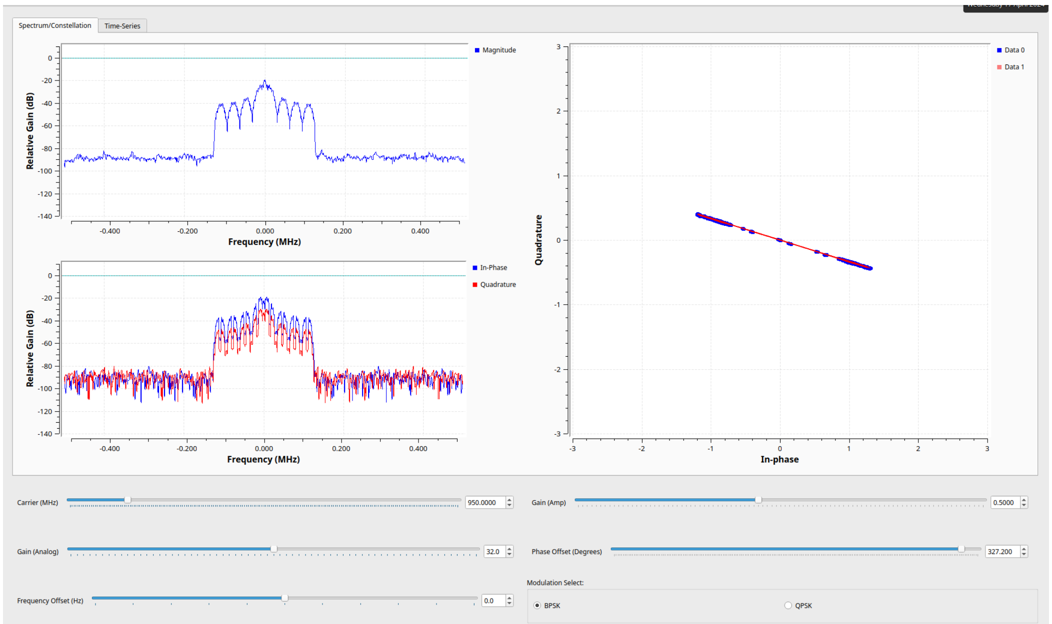


Figure 1: Positive Phase Offset

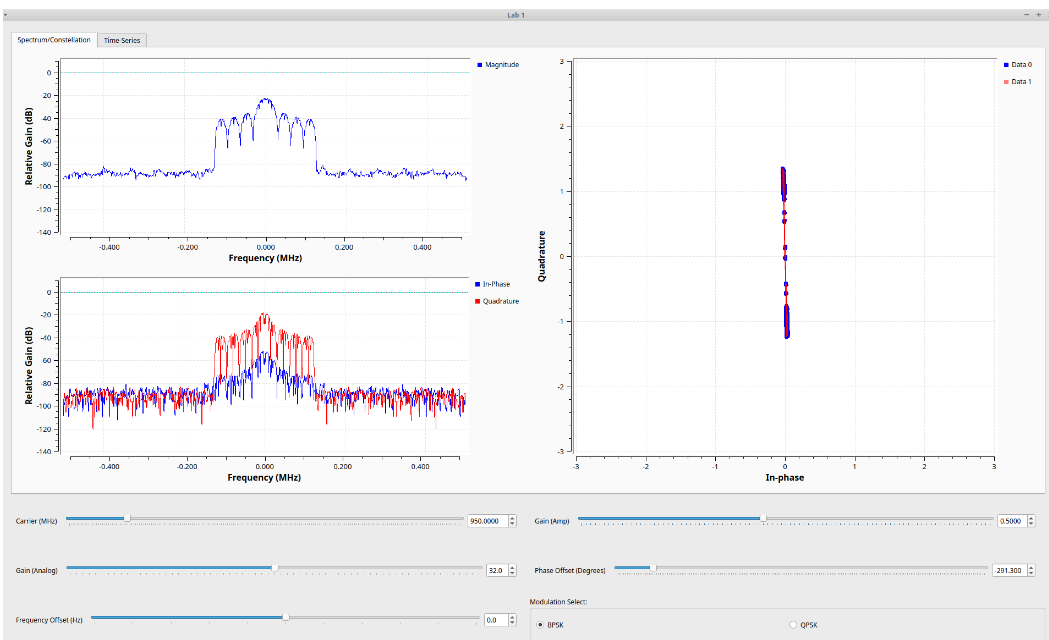


Figure 2: Negative Phase Offset

6. Adjust the phase so that the signal has only an in-phase component such that the constellation lies along the *x* axis. Record the phase and take a screenshot. Repeat for a phase offset for which the constellation has only a quadrature component. What is the phase difference between these two conditions? Why?

There is about a 90-degree phase difference because we are effectively rotating the constellation diagram by 90 degrees.

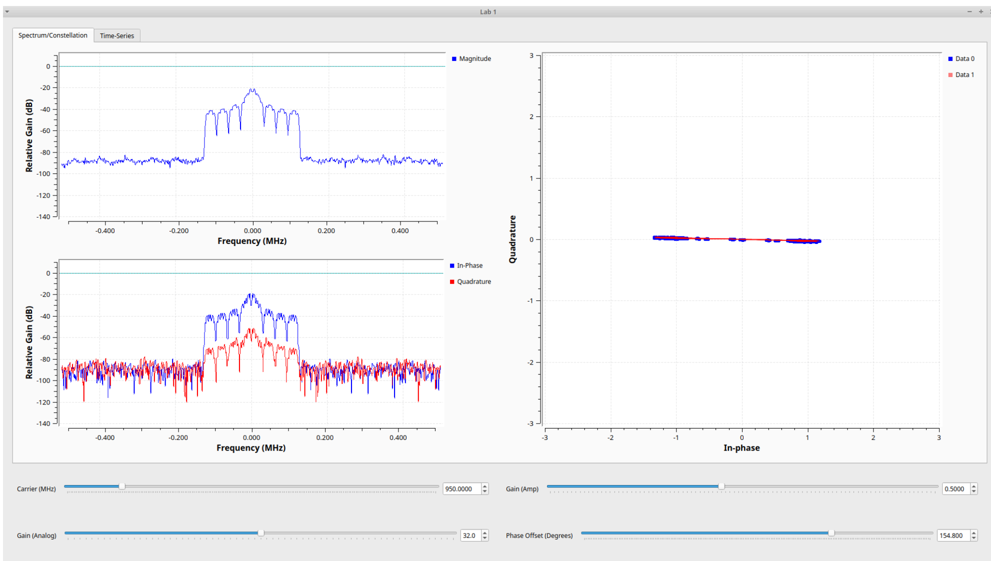


Figure 3: Only In-phase component @ 154.8 degrees

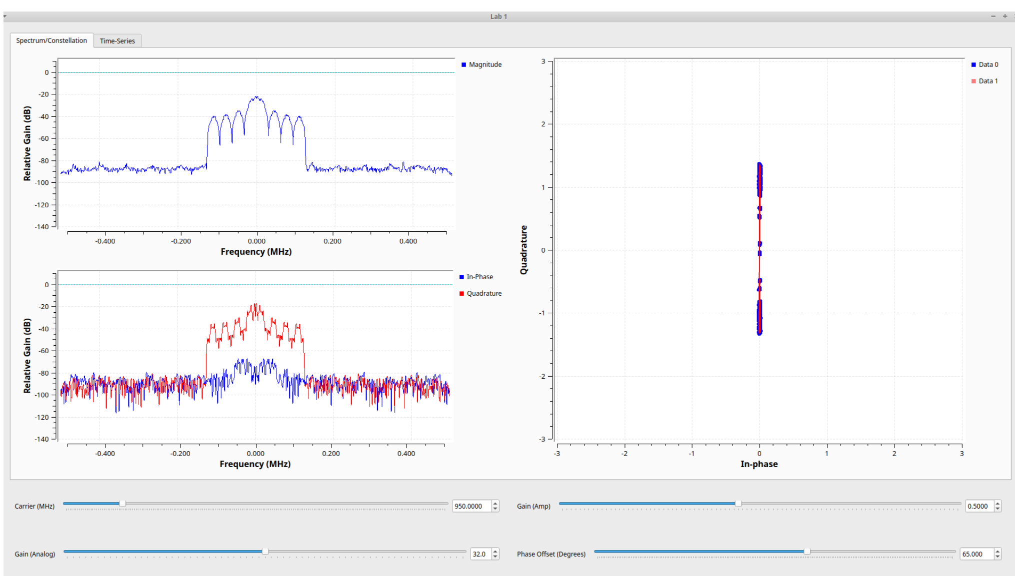


Figure 4: Only Quadrature component @ 65 degrees

7. Move the Rx antenna relative to the Tx antenna. Observe the effect of the distance *d* between the two antennas on the power density spectrum of the *I* and *Q* components and on the orientation of the signal constellation.

   - Constellations
     - Closer – counterclockwise and close together points
     - Farther – clockwise and farther apart points
       - Around at an angle we get circular point configuration (sparse)
   - Power spectrum
     - Close together = stopband attenuation decreases (ex. From -80 to -100 dB)
     - Farther apart = stopband attenuation increases (ex. From -80 to -70 dB)

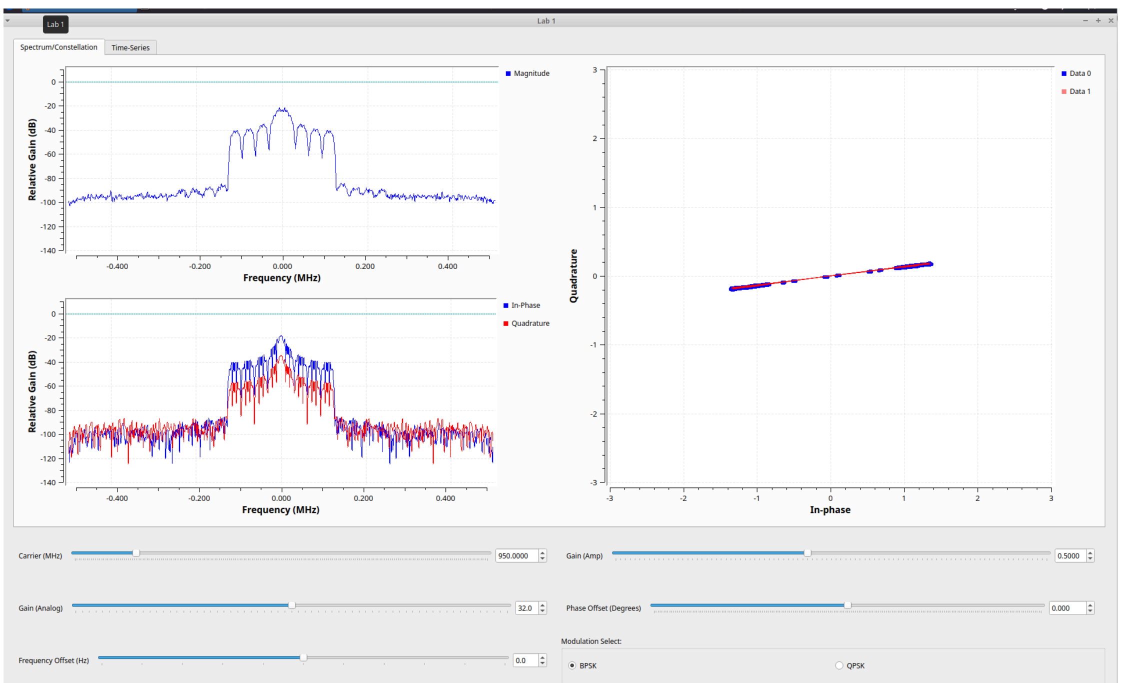


Figure 6: Close together

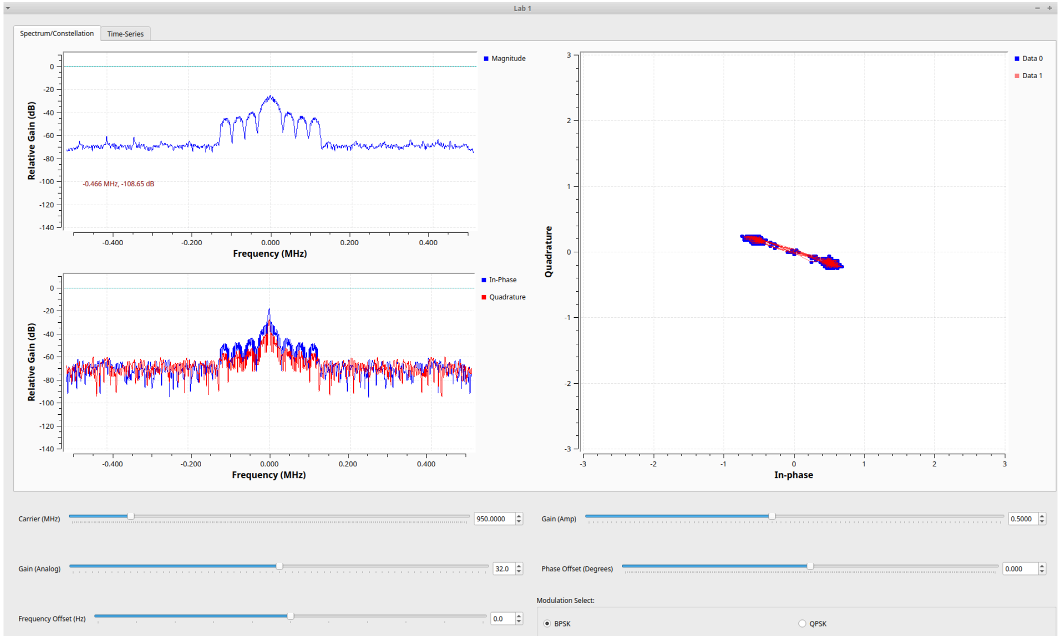


Figure 7: Farther apart

8. Increase the carrier frequency f_c by a factor of two and repeat the same motion as Step 7. Does the constellation change at the same rate? Why or why not? Using the results from Step 7, for a given frequency (or wavelength), what is the relationship between the signal phase θ and the distance d between the antennas?

The constellations change at a different rate because we only changed the carrier frequency and not the other components to compensate for this change.

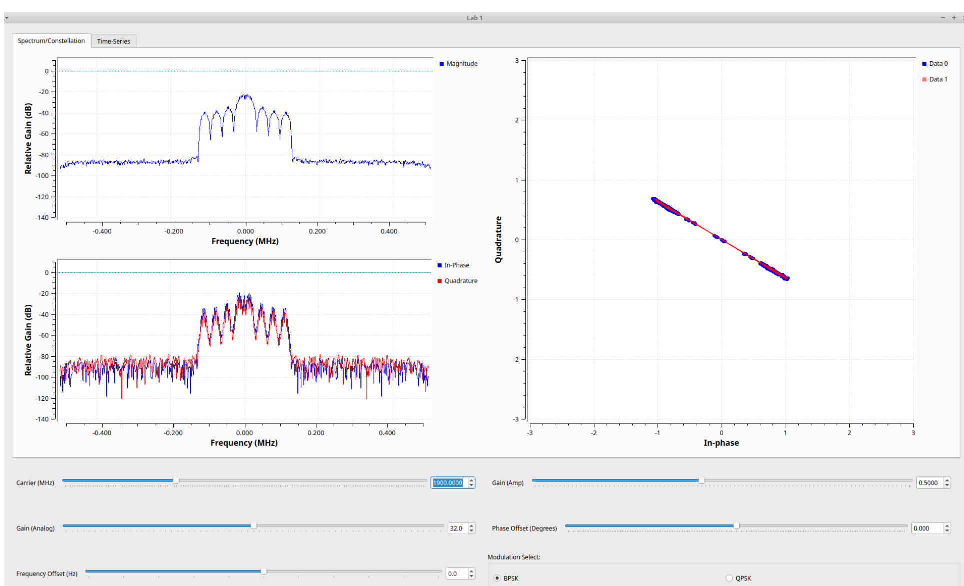


Figure 8: Close together (stopband attenuation increased versus part 7, -90 vs -100)

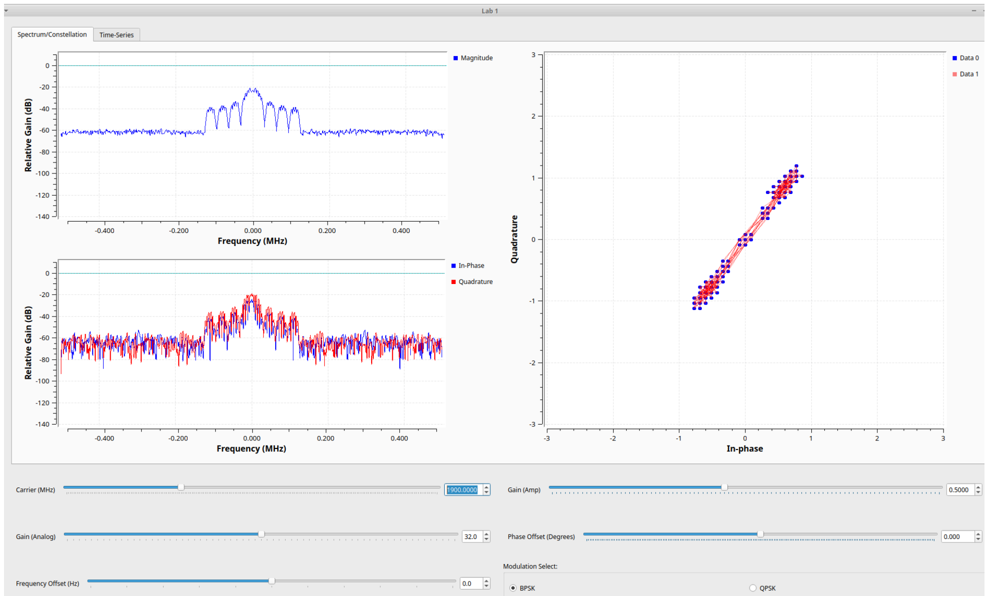


Figure 9: Farther apart (stopband attenuation increased versus part 7, -60 vs -70)

The relationship between the carrier frequency and the distance between antennas is given by the equation d = c * $\Delta\phi$ /2*pi*f or f = c* $\Delta\phi$ / 2*pi*d . This means that the frequency will increase as distance decreases or the change in phase increases.

Where: $\Delta\phi = \frac{2\pi d}{\lambda}$

$\Delta\phi$ is the phase difference in radians, d is the distance between the antennas, λ is the wavelength of the signal, and c is the speed of light.

9. Offset the carrier frequency between the transmitter and the receiver by 2 Hz (lower left part of the panel) and observe the effect on the constellation. Why does this happen?

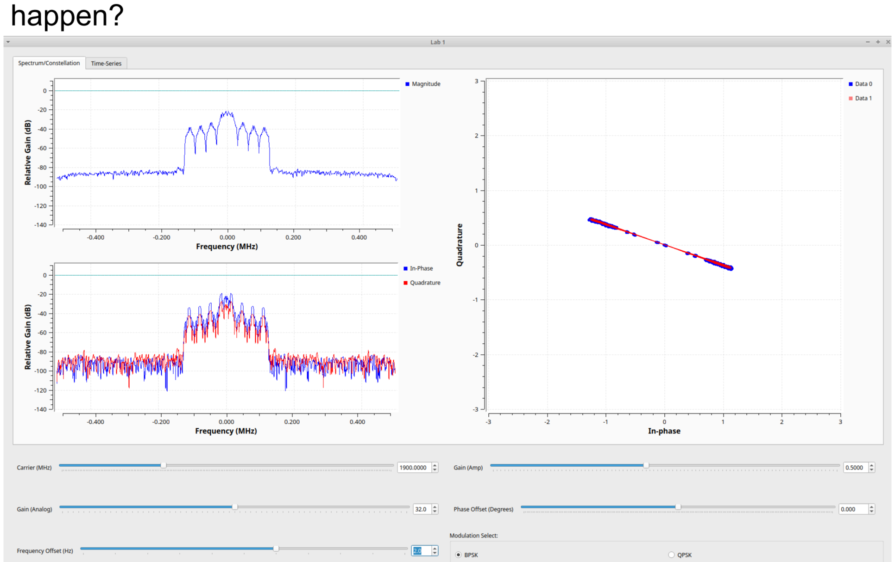


Figure 9: Carrier frequency offset of 2 Hz

Constellations are spinning in the counterclockwise direction because the offset causes the phase of the received signal to vary over time relative to the expected phase, leading to a rotation or spinning effect in the constellation diagram.

10. Now move one antenna at a constant rate toward the other antenna and observe the effect of rate that the antenna moves to the rate of rotation of the signal constellation. Repeat by moving the antenna away. Depending on your local environment, you may be able to “freeze” the rate of rotation by moving the antenna. Why does the rate slow down in one direction and increase in the other direction?

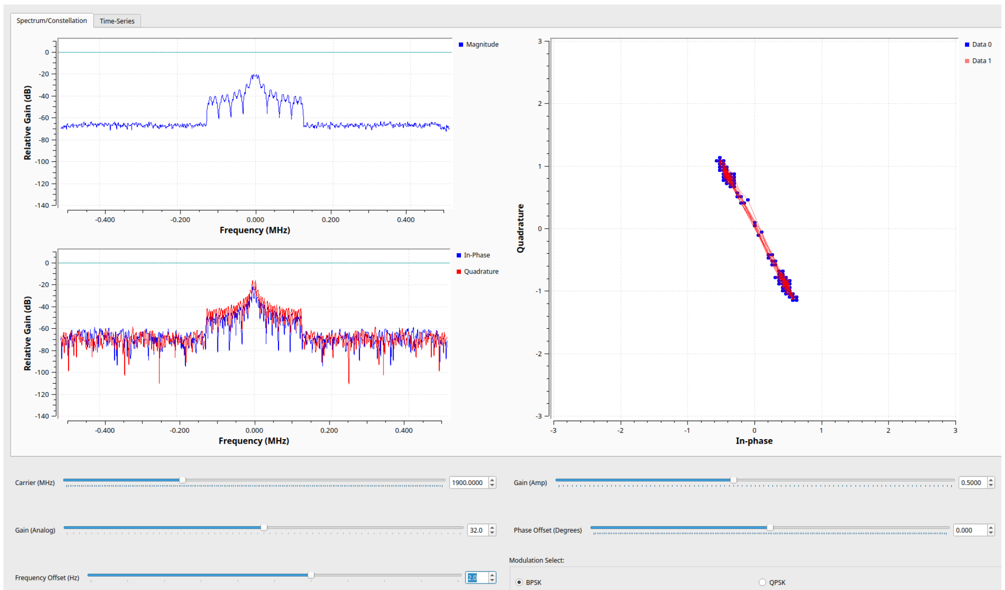


Figure 10: Moving away (faster)

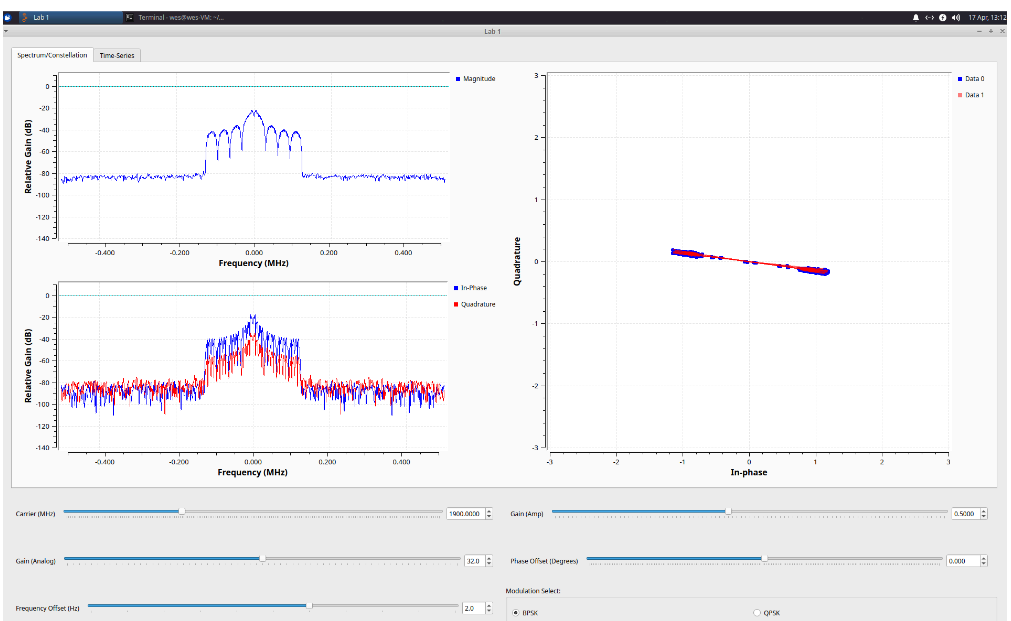


Figure 11: Moving towards (slower)

When one antenna is moved at a constant rate toward the other antenna, the speed of rotation of the signal constellation will appear to slow down and when one antenna is moved away, it appears to speed up.This is caused by Doppler shift, the frequency of a wave appears higher when the source and observer are moving toward each other and lower when they are moving away from each other. Similarly, at a certain speed, the speed of the antennas and the speed of rotation could cancel out and it would “freeze”.

1.2 Quadrature-Amplitude Modulated (QAM) Signals

1. On the lower right of the front panel select QPSK. The panel should be similar to that of Figure 2. QPSK generates a second carrier at the same frequency as BPSK that is orthogonal to the single carrier used for BPSK. This modulation format is called quadrature phase-shift-keying (QPSK). This modulation format is equivalent to two BPSK signals in phase quadrature meaning one BPSK signal has a cosine dependence while the other BPSK signal has a sine dependence.

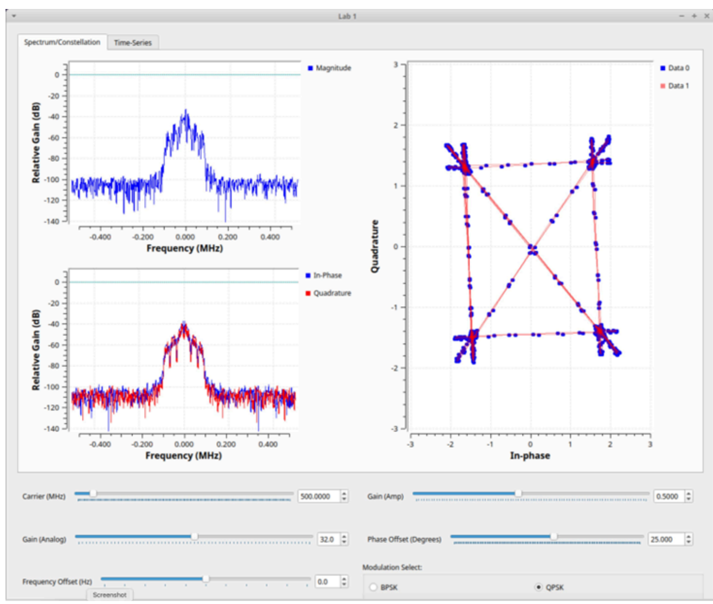


Figure 2: Front panel for QPSK.

2. Compare the spectrum of BPSK to the spectrum of QPSK. This can be easily done by toggling between the BPSK and QPSK buttons on the front panel. Does the magnitude-squared of the power density spectrum ($I^2 + Q^2$) change for QPSK as compared to BPSK? Does the power density spectrum for each component change? Why or why not? Also notice the “overshoot” in the trajectories for the constellation. This is caused by the shape of the transmit pulse and will be discussed in Lab 2.

The magnitude-squared of the power density spectrum (I^2+Q^2) changes for QPSK compared to BPSK because QPSK transmits two bits per symbol, so the symbol rate is halved compared to BPSK, but each symbol carries twice the information.

3. Repeat Steps 7-10 from Section 1.1 noting the key differences between QPSK and BPSK with respect to the average signal power and the effect of a phase offset or a frequency offset caused by relative motion.

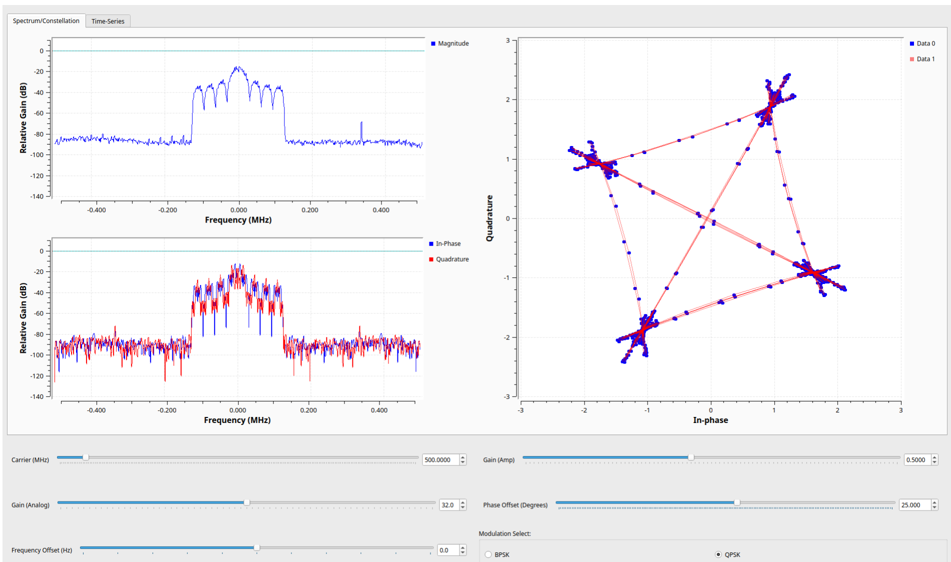


Figure 1: Rx antenna close to Tx antenna

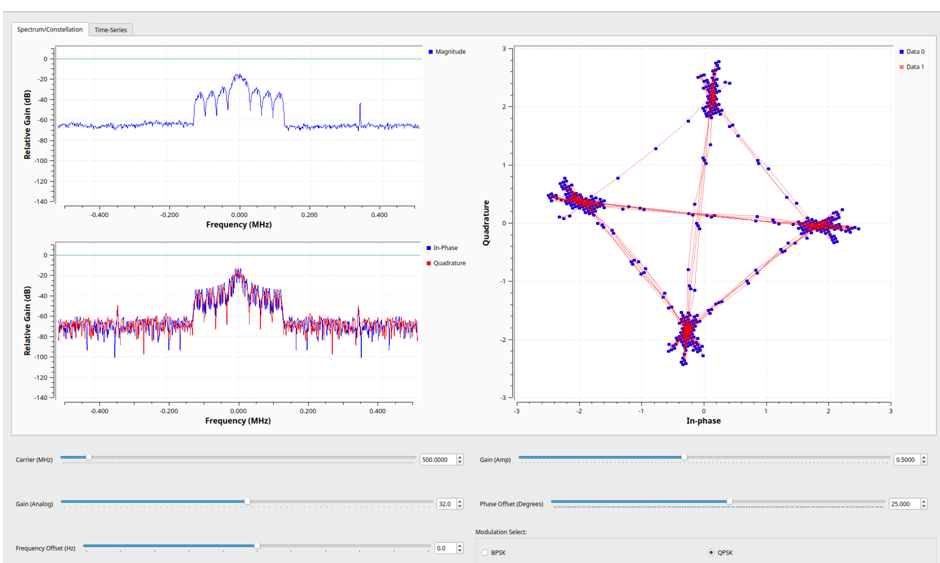


Figure 2: Rx antenna away from Tx antenna

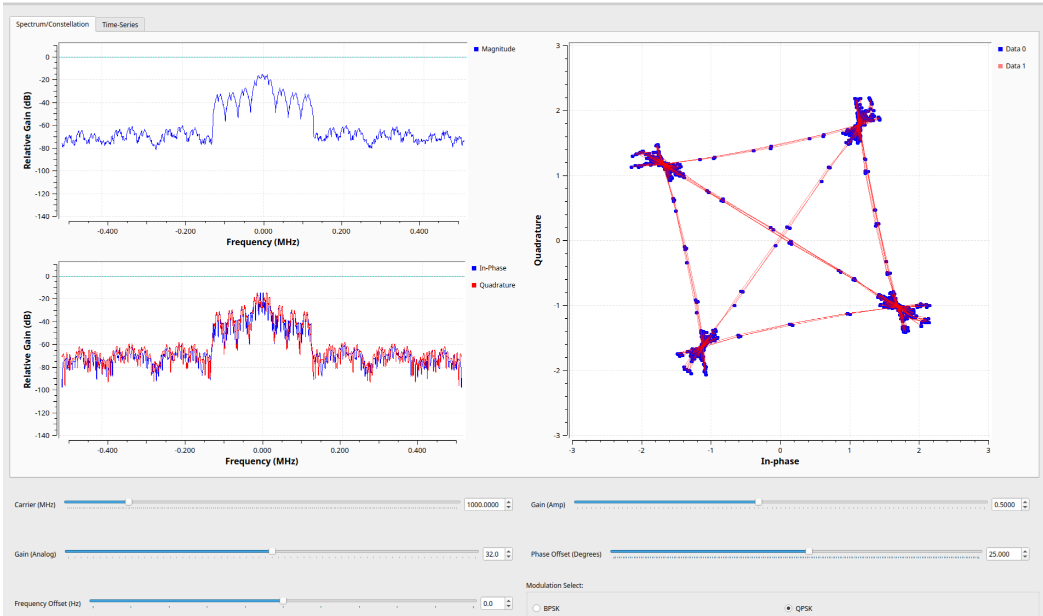


Figure 3: f_c by a factor of two, Rx antenna close to Tx antenna

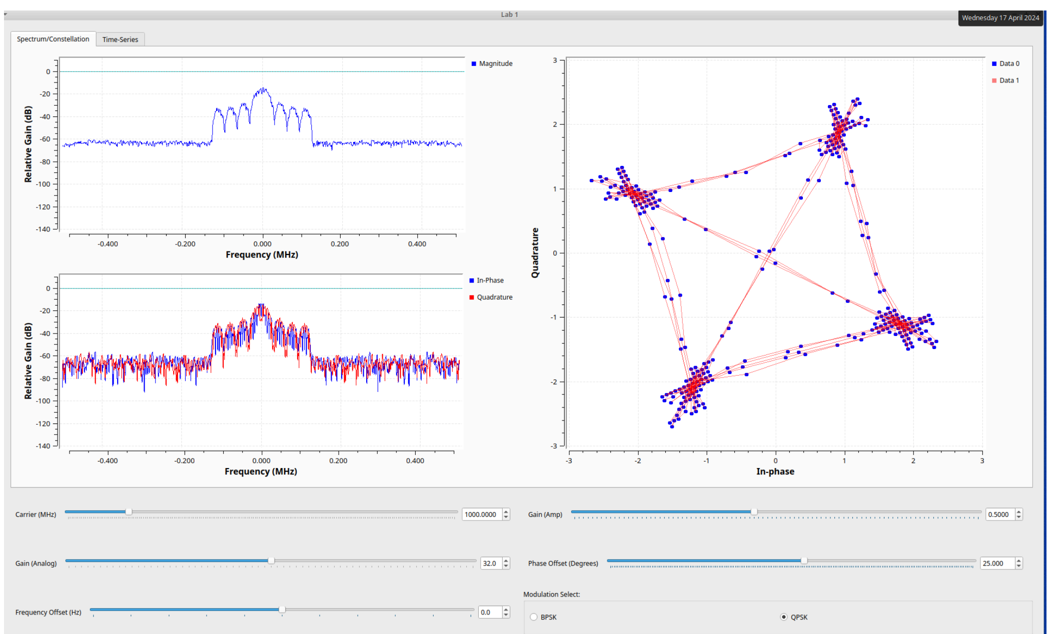


Figure 4: f_c by a factor of two, Rx antenna away from Tx antenna

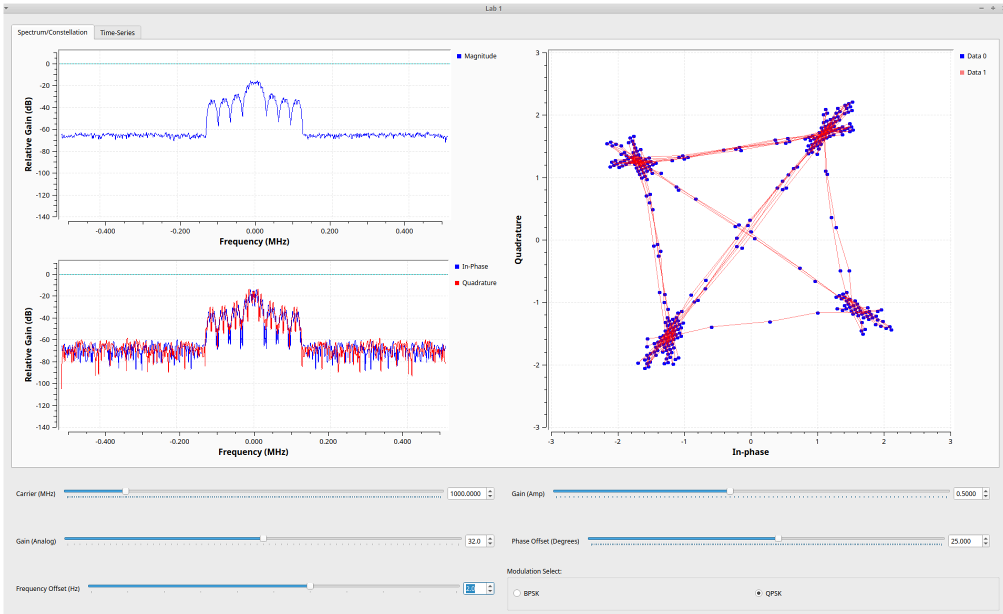


Figure 5: Carrier frequency offset of 2 Hz, moving away (faster)

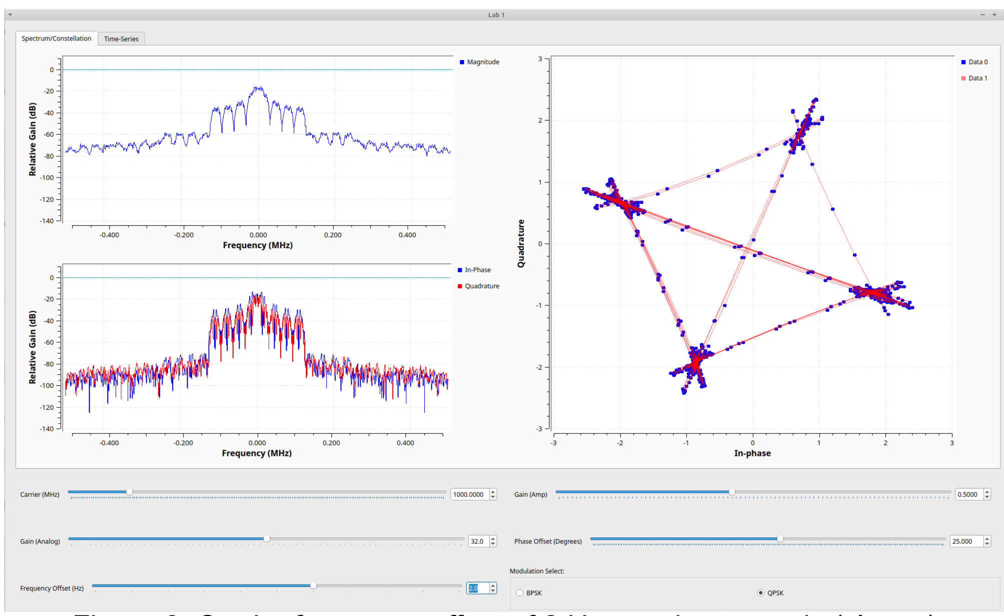


Figure 6: Carrier frequency offset of 2 Hz, moving towards (slower)

Unsurprisingly, the QPSK follows the same trends as the BPSK, moving the antennas closer causes the stopband attenuation to decrease (increasing when farther apart). Similar happens when the carrier frequency is doubled, however, the stopband attenuation level increases compared to the normal carrier frequency for both directions. However, the key difference is that the stopband is bigger for the QPSK in all scenarios. This is because the stopband attenuation level for the QPSK is often a trade-off between signal quality and complexity, the QPSK allows us to send more information per bit but we lose filter performance.

1. Using the screen shots for BPSK and QPSK, determine the average power of the constellation as measured by the (uncalibrated Pluto),

$$P_{\text{ave}} = \frac{1}{N}\sum_{i=1}^{N} |s_i|^2$$

$$|s_i|^2 = s_i\,(s_i)^*$$

where s_i is the complex value corresponding to the coordinates of each constellation point, and N is the number of constellation points used by the particular modulation format.

For BPSK:

Since BPSK consists of 2 symbols (+1 and -1) the average power is the same because it can be calculated as the average of the squares of the symbol magnitude.

$$P_{avg} = \frac{(-1)^2+(1)^2}{2} = \frac{1+1}{2} = 1$$

For QPSK:

QPSK consists of 4 symbols 1+j,1−j,−1+j,−1−j, the average power, similarly to BPSK, can be calculated by the average of the squares of the symbol magnitudes.

$$P_{avg} = \frac{|1+j|^2+|1-j|^2+|-1+j|^2+|-1-j|^2}{4} = \frac{2+2+2+2}{2} = 2$$

2. Suppose that you are using a carrier of 1 GHz.

   a) What is the corresponding wavelength λ ?

      λ = 29.9cm

   b) How far do you have to move the antenna to the phase by 180^o?

      Move the antenna half the wavelength to achieve a phase of 180^o so 15cm.

   c) Using this result, derive a procedure to determine the carrier frequency f_c from a plot of the phase θ vs distance d between the Tx and Rx antennas.

      First you will want to measure the change in phase

Next, consider change in phase by 180 degrees means a movement of half the wavelength or λ/2, use the measured change in distance and change in phase to calculate the wavelength

$$\lambda = \frac{2 \cdot \Delta d}{\Delta \theta}$$

Δd = *change distance*

$\Delta \theta$ = *change in phase*

Once you have the wavelength, you can calculate the carrier frequency using the equation:

$$f_c = \frac{c}{\lambda}$$

d) How many cycles per second of the phase change, which is a frequency offset, occur if you are moving at:

Using c= 3.8e8

i. 1 m/s (Walking)

f = fc($\frac{1m/s}{c}$) => 3.33 Hz

ii. 30 m/s (In a car)

f = fc($\frac{30m/s}{c}$) => 100 Hz

iii. 250 m/s (In a plane)

f = fc($\frac{250m/s}{c}$) => 833 Hz

Hint: You may find the doppler formula useful:

$$f = \left(1 + \frac{v}{c}\right) f_0$$

2 Survey of “Live” Communication Signals

In this part of the lab, we will measure several communication signals “in the wild” using the python program *“pluto fft.py*”, which is a “soft” spectrum analyzer. This program can display up to a 20 MHz band of a spectrum centered anywhere from 325 MHz to 3.8 GHz. For this “soft” spectrum analyzer, the *x* axis is the frequency measured from the carrier frequency f_c. The *y* axis is the (uncalibrated) power measured in dB with respect to a full scale (FS) power over a resolution bandwidth B_{res} defined below.

1. Open a terminal on the VM and change the directory to cd ~ /ece157A/grc/ or simply cd ... The reason this program is located here is because we will be using it for most labs.

2. Type ./pluto_fft.py. This should start the soft spectrum analyzer front panel shown below. The spectrum is defined by several parameters controlled on the front panel of the program.

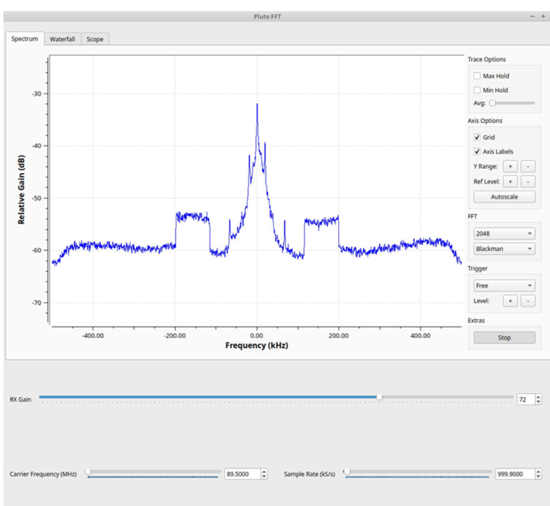


Figure 3: Front panel of the soft spectrum analyzer showing an analog FM signal at 89.5 MHz with two digital side bands.

a) The ***center*** of the spectrum is defined by the carrier frequency f_c. The frequencies shown on the trace are relative to the carrier f_c.

b) The ***span*** of the spectrum is defined by the passband bandwidth B_{pass} on the lower right of the display. The passband bandwidth is twice the baseband bandwidth B_{base}. Using the sampling theorem, the passband bandwidth is also equal to the (IQ) sampling rate f_s so that

$$B_{\text{pass}} = f_s \qquad \text{or } B_{\text{band}} = f_s/2.$$

c) The ***resolution bandwidth*** B_{res} is the number of resolvable points over the span B_{pass}. This is given by the length M of the FFT so that

$$B_{\text{res}} = B_{\text{pass}}/M.$$

For a span of 1 MHz and a 1024-point FFT, the resolution bandwidth is about 1 kHz. As more points are used in the FFT, the power in each frequency bin decreases.

d) The ***reference level*** is the maximum power displayed. It is controlled on the right of the front panel.

e) The ***y range*** controls the dB per division on the y axis. It is controlled on the right of the front panel.

f) The averaging controls the number of traces that are averaged. Moving the slider to the *left* increases the number of traces used in the average.

2.1 Commercial FM and digital radio (Require working AD9364 Modification)

The commercial FM band lies in the range of 87.5-108 MHz. Several radio channels are now broadcasting a digital signal in part of their allocated FM frequency band. The spectrum in Figure 4 is for KPBS at 89.5 MHz with a passband bandwidth of 1 MHz taken from the University City area. Your results may vary.

1. Try and find a channel that is broadcasting digitally. Take a screenshot of that channel. (It can be KPBS). Once you have acquired a signal, vary the size of the FFT and confirm the resuming change in the power per frequency bin.

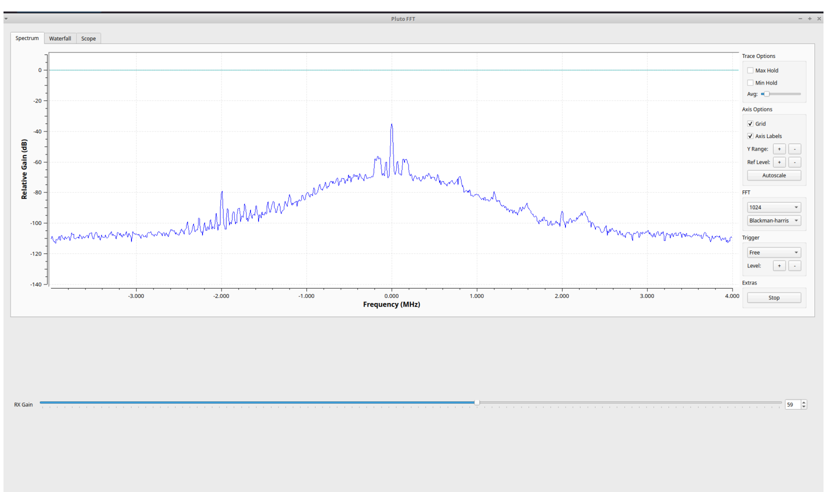


Figure 1: Digital Broadcasting Channel

We were not able to find a strong digital broadcasting channel in the Jacob's building due to being in an enclosed space made up of concrete and drywall versus what you'd get going outside.

2.2 Commercial TV

Commercial TV is in several bands. In San Diego both Channel 8 (KFMB-CBS) and Channel 10 (KGTV-ABC) are in the upper VHF band with about a 6 MHz bandwidth. Channel 8 is centered at 183 MHz and Channel 10 is centered at 193 MHz. Other channels are in the UHF band with Channel 69 centered at 803 MHz. Below is the spectrum of Channel 8 taken from the University City area. Your results will be different depending on your location.

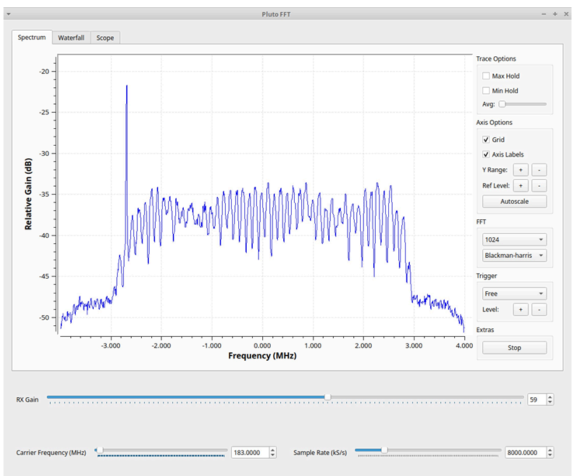


Figure 4: Front panel of the soft spectrum analyzer showing the measured spectrum of KFMB TV signal showing the carrier frequency at one edge of the passband spectrum.

1. Try and find a digital TV channel and take a screenshot of that channel. Compare the measured carrier frequency to the table published in the Web site given earlier in this section.

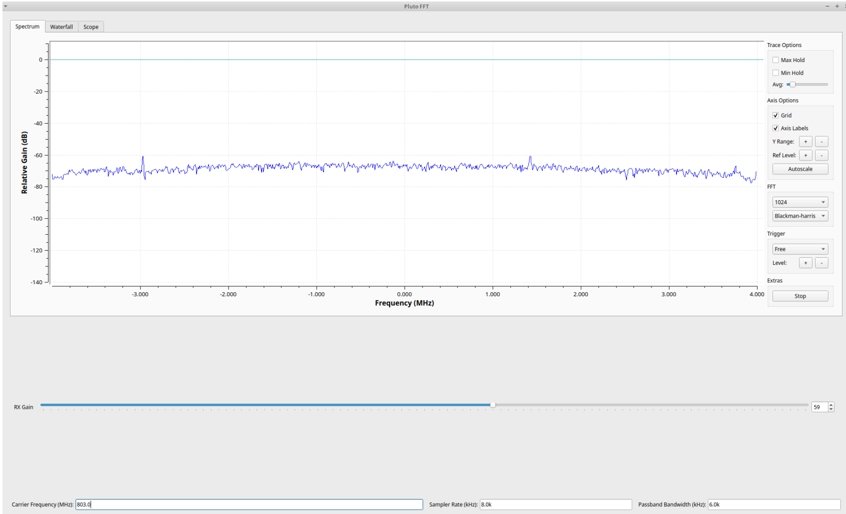


Figure 2: Digital TV Channel

2.3 Remote Keyless Systems (315 MHz Band) (Requires working AD9364 Modification)

Remote keyless systems for car entry key use signals in the 315 MHz band. Further information can be found here. The left side of Figure 5 shows the spectrum when the remote is pressed. The right side shows the time waveform showing the modulation using the “scope” tab at the top of the front panel. For this particular device, the modulation format is amplitude shift keying (ASK). Other devices may use frequency-shift keying (FSK). It will depend on your car fob.

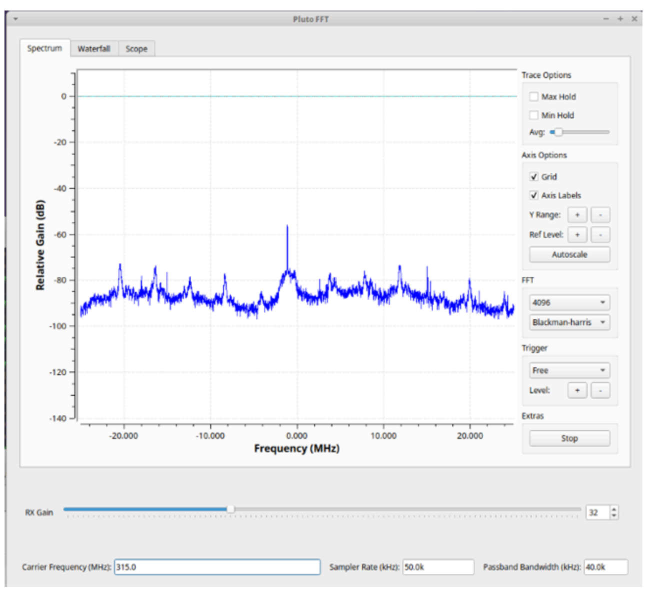


Figure 3: Remote Key Signal

When you press the button to a car remote, the signal peaks at the frequency the key is programmed at.

2.4 PCS and other cellphone bands (1.85-1.99 GHz)

Cell phone carriers transmit in bands given here.

There are several digital modulation formats that are used within this band.

1. Using as wide a bandwidth as your system will permit without being “laggy”, scan the PCS band (or another band) for cell-phone signals. This will vary with your location and the carriers. By varying the center frequency f_c, you should see several modulated signals. Save a spectrum that shows several carriers. An example of 100 MHz in four overlapping 40 MHz scans is shown in Figure 6. The blue trace is the instantaneous spectrum. The greenish trace is the maximum of the signal over the measurement interval set by the Max hold button on the front panel. Examining where the spectra overlap between the traces, it is evident that the power is not well-calibrated in the Pluto over the maximum 40 MHz band as the same signal in two different scans has different characteristics.

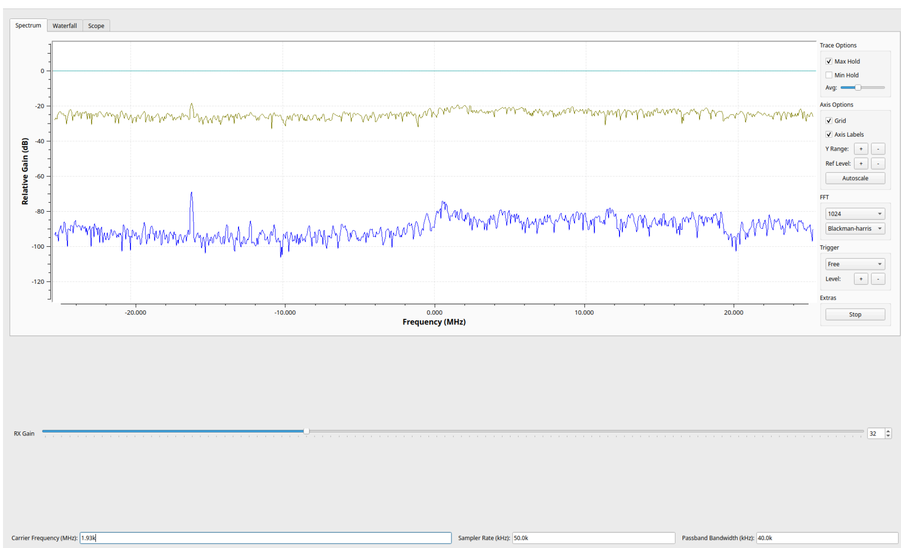


Figure 4: Cell-phone signal

Since we are in a building made up of concrete and drywall, the cell phone signals aren’t very strong at this frequency versus in an open space:

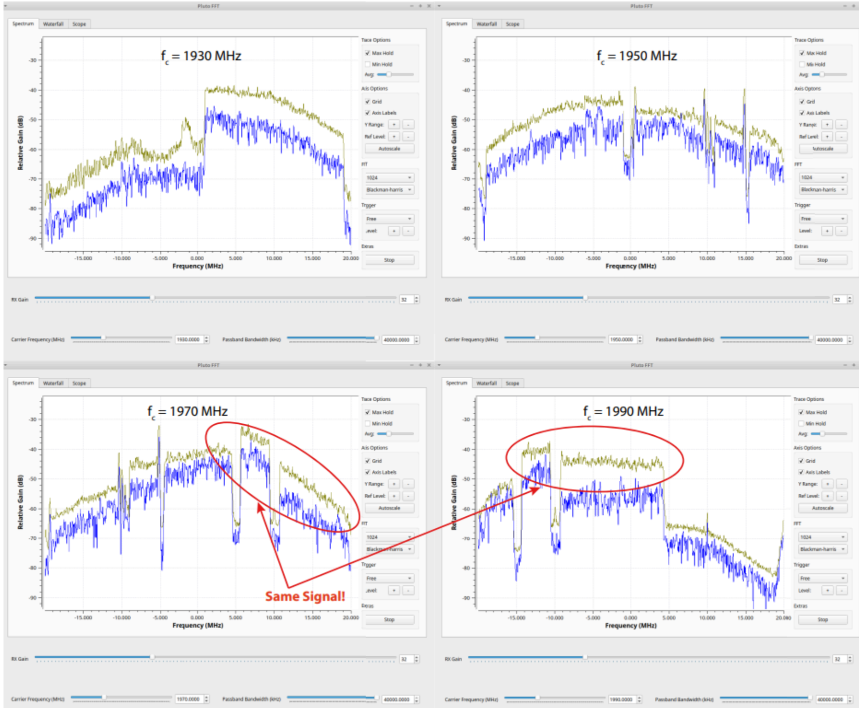


Figure 6: Four overlapping 40 MHz scans spanning 1910 MHz to 2110 Hz. The blue trace is the instantaneous spectrum. The greenish trace is the maximum of the signal over the measurement.

2. Zoom in on a modulating band and determine the bandwidth of the modulating signal.

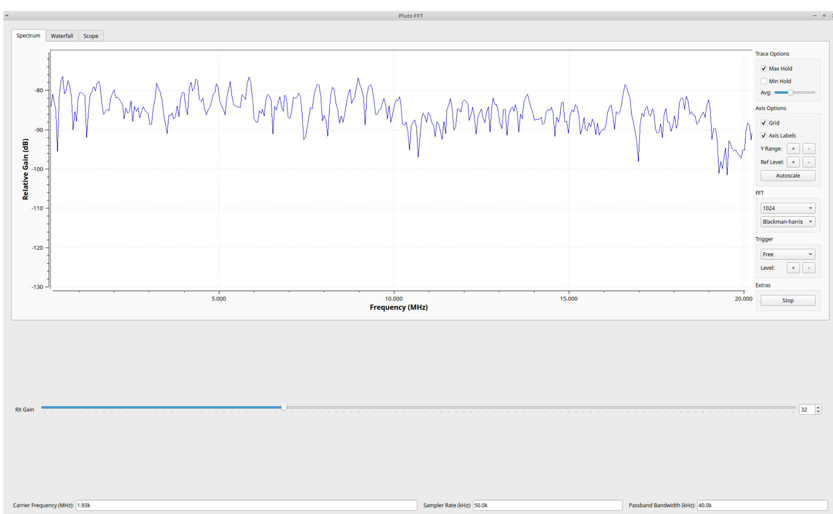
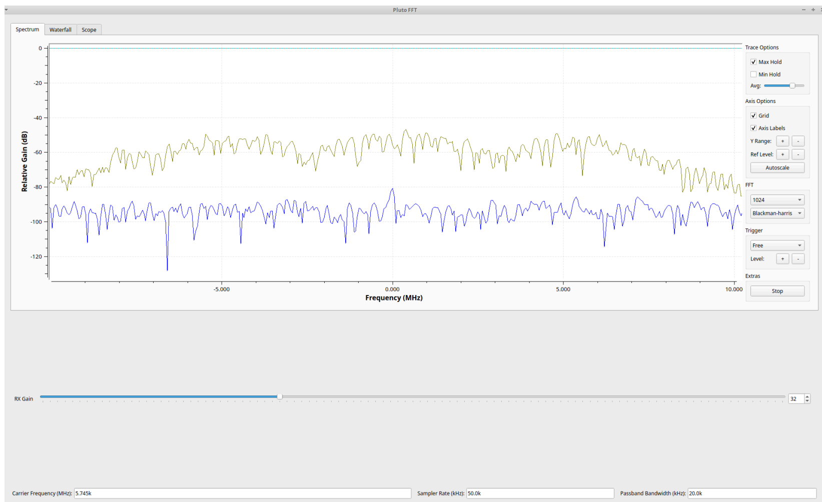


Figure 5: Modulating Band Close-up

As previously mentioned, the cell phone signals in the figure can’t be observed very well. The bandwidth is about 0 to 20MHz so 20MHz.

2.5 WiFi Bands (2.4 and 5 GHz)

The Pluto SDR can see both the 2.4 GHz and the 5 GHz WiFi bands. We transfer a file while connected to WiFi on Channel 192 in the 5 GHz band (centered at 5745 MHz) and run pluto fft with a 20 MHz-wide band. A screen shot taken during the file transfer is below.



Since we are in a building made up of concrete and drywall, the wifi signals aren't very strong at this frequency versus in an open space:

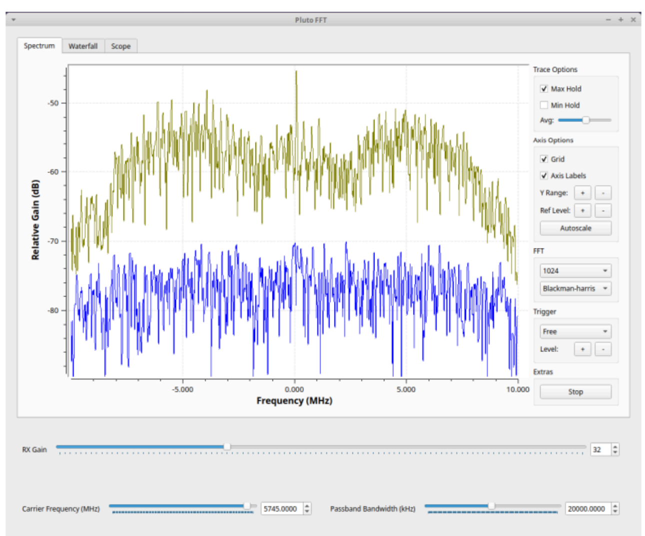
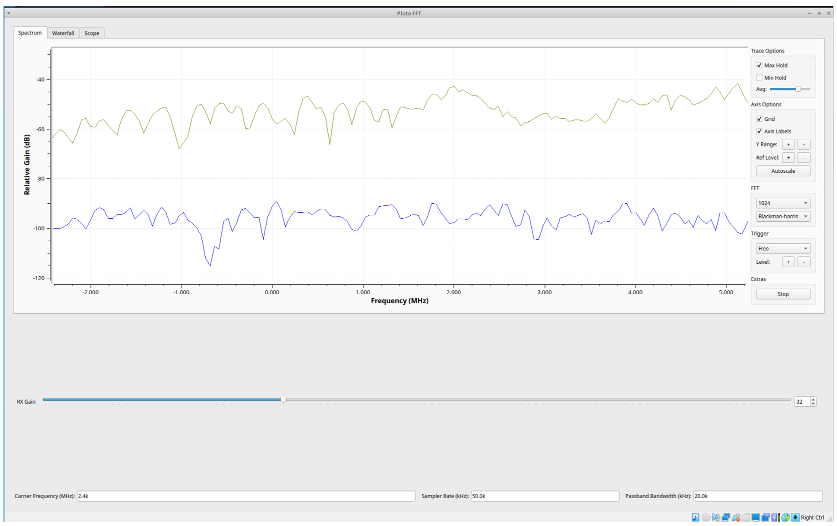


Figure 7: Blue trace: Instantaneous spectrum of Wifi Channel 192 in the 5 GHz band. Greenish trace: peak hold of trace over observation time.

2.6 ISM Bands (900 MHz and 2.4 GHz)

An unmodified Pluto-SDR can see both the 902-928 MHz ISM (Industry Scientific and Medical) and the 2.4 GHz - 2.5 GHz ISM band. Many familiar signals exist in these bands, such as Bluetooth in the 2.4 GHz band and Smart Metering Devices in the 900 MHz band. Tune to both these frequencies and capture a screenshot of any signal. Try to identify it.

Hint: If you have a bluetooth device (such as a headphone), try using it while observing a slice of spectrum at 2.4 GHz.



When we turn on a bluetooth device, it starts to oscillate faster. We can observe at certain frequencies the signal becomes stronger indicating those are the frequencies that the bluetooth device was allocated to.

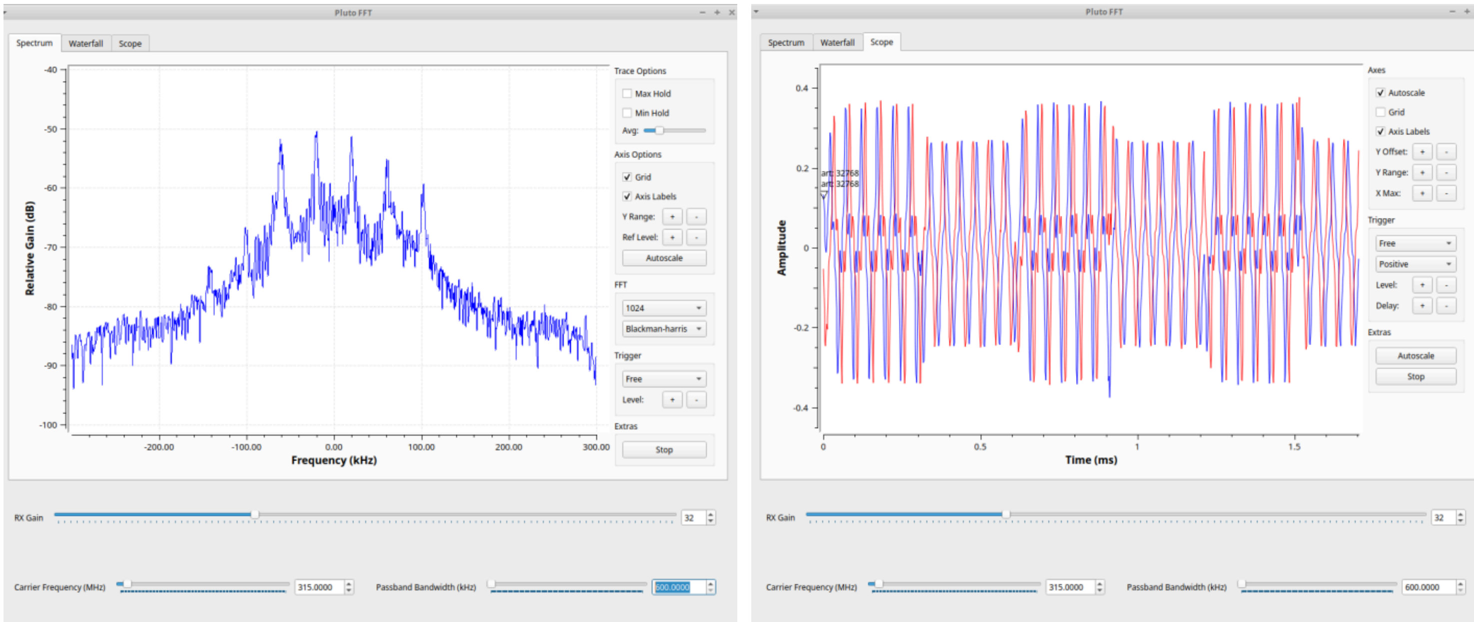


Figure 5: Top: Spectrum of remote wireless keyless entry. Bottom: Amplitude-shift-keyed time waveform using the “scope” tab on the front panel. (Note that several tries were needed to capture a clean time waveform because the signal was not synchronized.)

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[1] If your system is “laggy”, please reach out to the TA