George Davis - Design Project 2

E157 Radio Frequency Circuit Design - Fall 2024

1. Summary information:

The secret message that was being transmitted in a frequency-modulated encoding converted from binary to ASCII was **HMC.**

The maximum range at which we could discern the logical high value from the noise was at approximately **22.56 [m]** or **74 [ft]**. We calculated the range to be 31.2 m but this is likely optimistic since many factors could contribute to this signal not traveling as far as ideal conditions allow.

Max Range of Antenna

Link Budget eq:

$$S_{21} = G_{TX} + G_{RX} + 20\log\left(\frac{\lambda}{4\pi r}\right)$$

where S_{21} = noise floor = 90.1 dBm for WIFI antennas

$G_{TX} = -29.457$

$G_{RX} = 9\,\mathrm{dBi}$

$\lambda = \frac{c}{f} = \frac{3}{2.296} \times 10^{-1}$

$r = 31.2\,\mathrm{m}$

The system temperature was analytically calculated to be 1.85*10^21 Kelvin based on the LPF BW and the powered LNA gain.

Measured*	input Tone 1	input Tone 2
Frequency [GHz]	2.2595	2.2965
IIP3 [dB]	-30.5718	-31.0577
Analytical*	21.61044397	21.66052155

*see section 8 for an explanation of the large discrepancy between Analytical and Measured.

2. Pictures of received data

3m Pictures:

Figure 1: Picture of the setup at 3m range

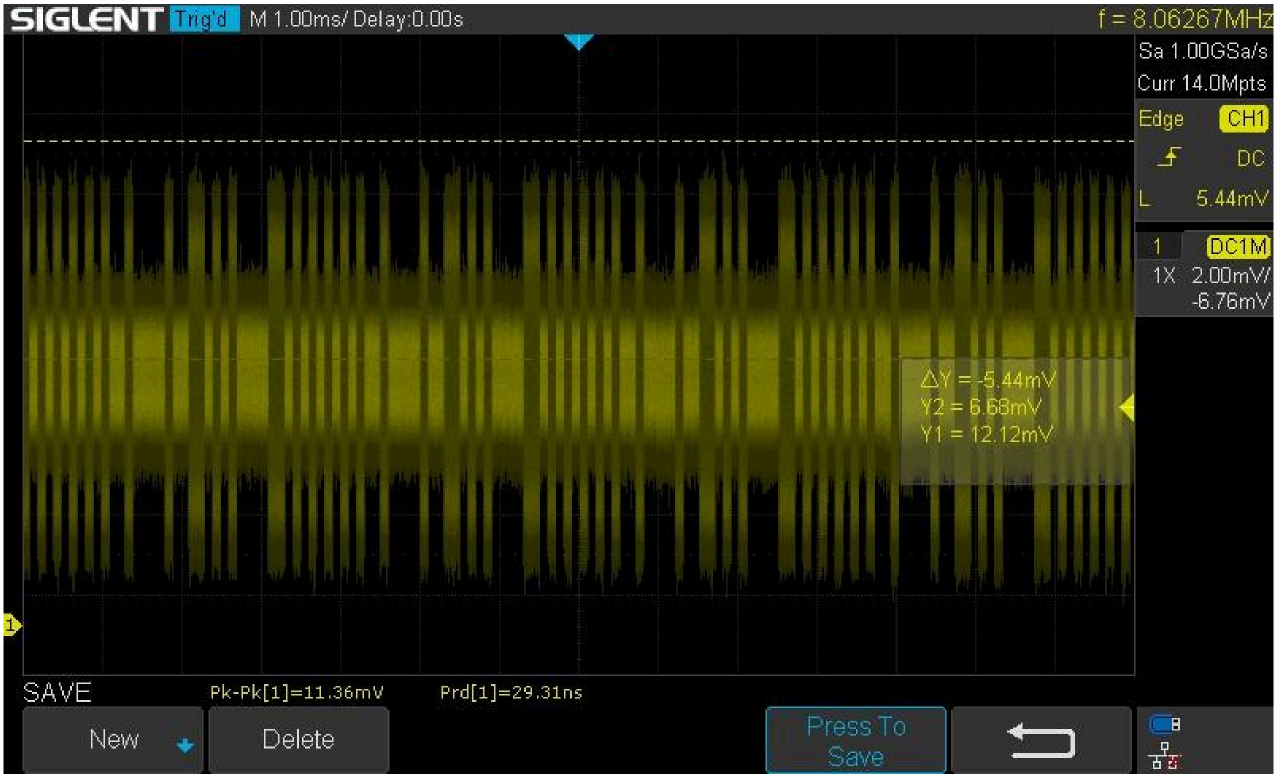


Figure 2: Oscilloscope trace of the receiver output at 3m range

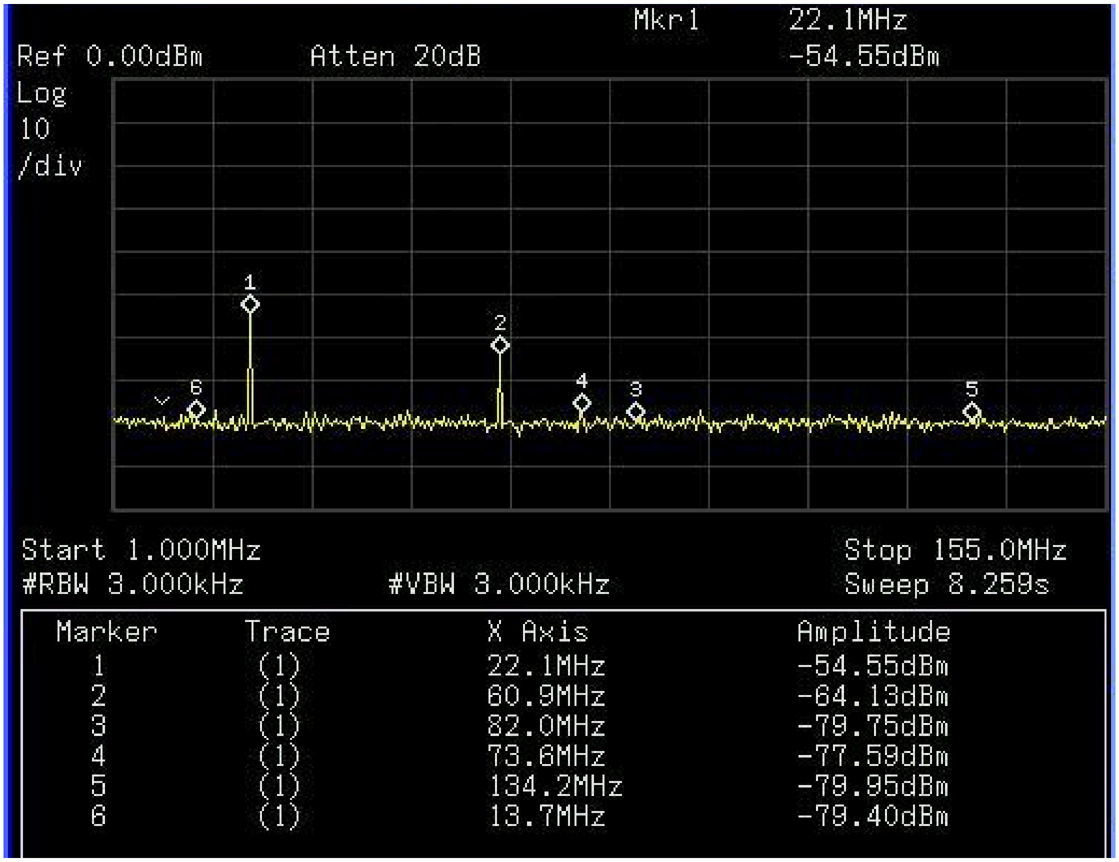


Figure 3: Spectrum of the receiver output at 3m range

MAX range Pictures:

Figure 4: Picture of the setup at max range

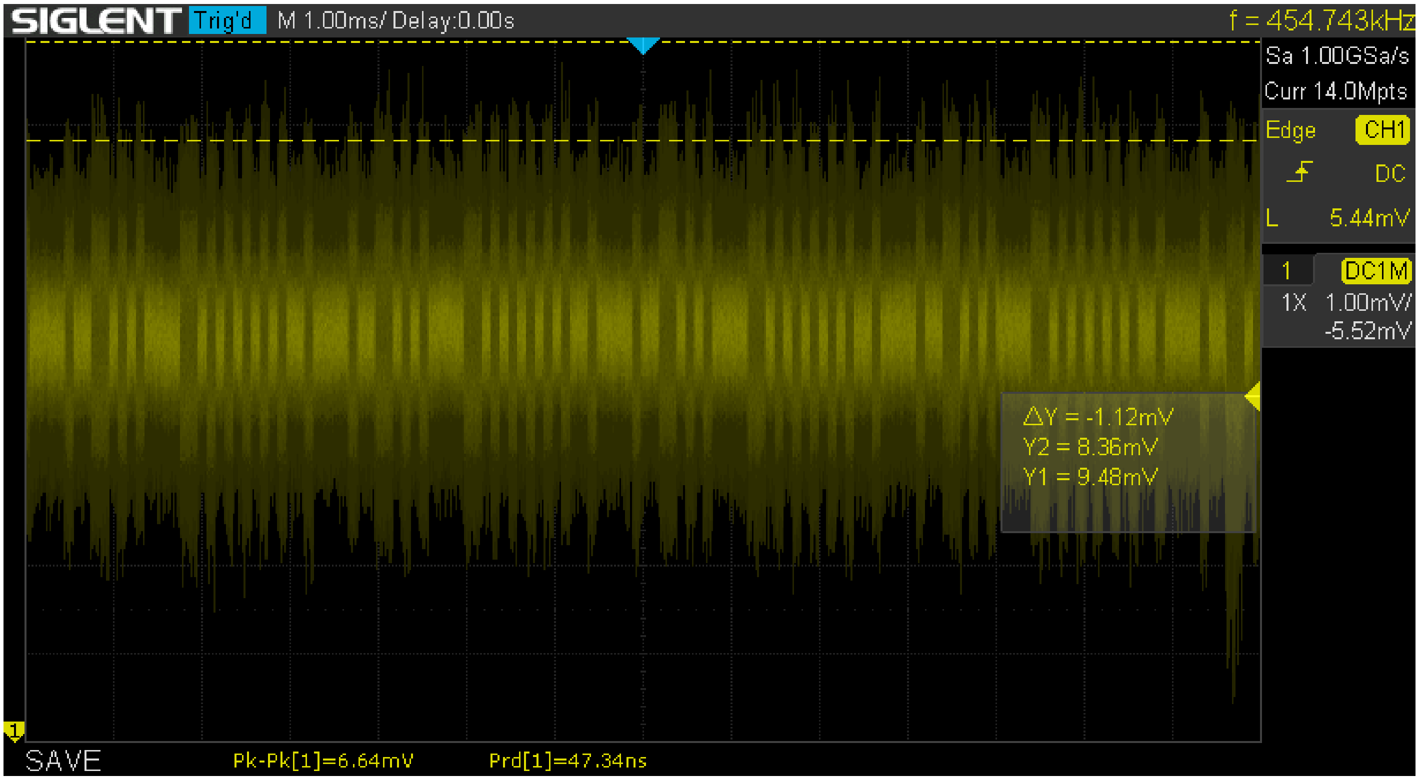


Figure 5: Oscilloscope trace of the receiver output at max range

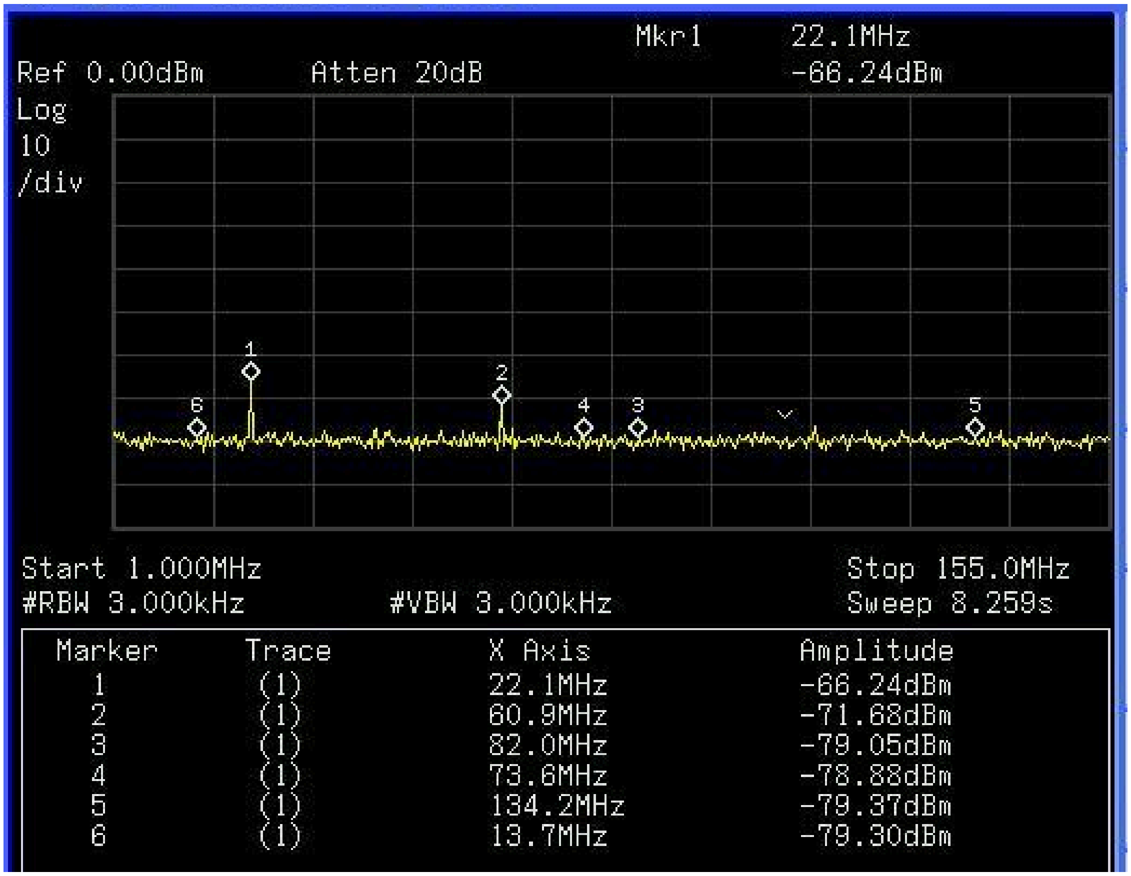


Figure 6: Spectrum of the receiver output at max range.

3. Decoding

One-page discussion of how to decode the oscilloscope trace to extract the secret message, possibly using an annotated copy of the oscilloscope trace to help explain your decoding scheme.

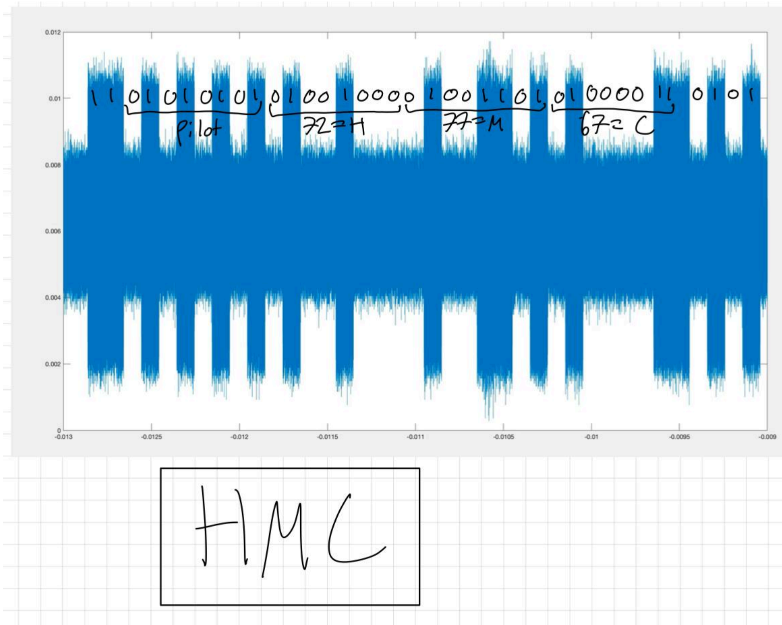


Figure 7: Binary encoding of the oscillating frequencies reads HMC

The logical high and low that the transmit antenna was emitting corresponded to 2.296 and 2.256 [GHz] respectively. The mixer we implemented used an LO that shifted these signals down to 22.1 and 60.6 [MHz] again, respectively. Finally, the LPF was used as a slope detector that kept the logical high frequency and attenuated the logical low 60.6 [MHz] signal. Plugging that output into the ADC inside the oscilloscope gave us the trace seen in Figure 1. With this plot we were able to decode the modulating frequencies using the pilot code '01010101' followed by three 8-bit ASCII encoding binary numbers.

4. Antenna Characterization

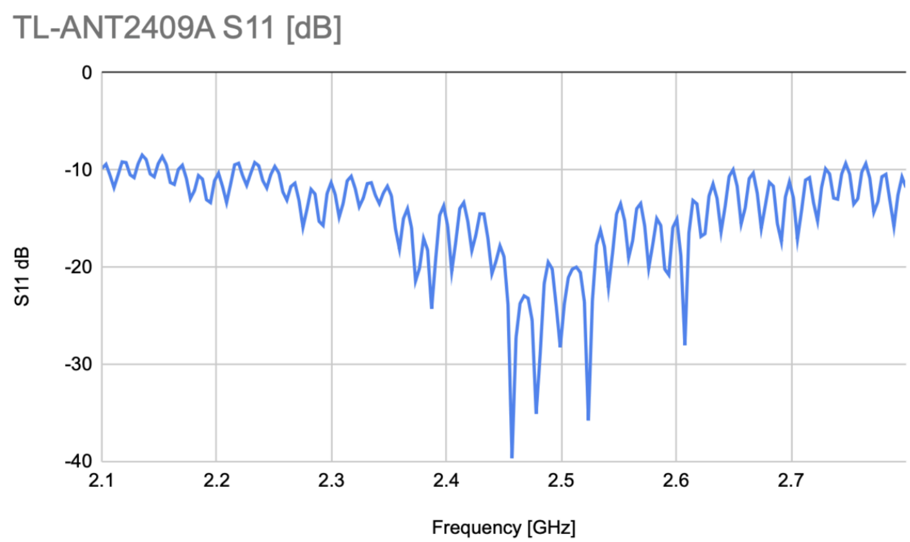


Figure 8: S11 of the TL-ANT2409A receive antenna

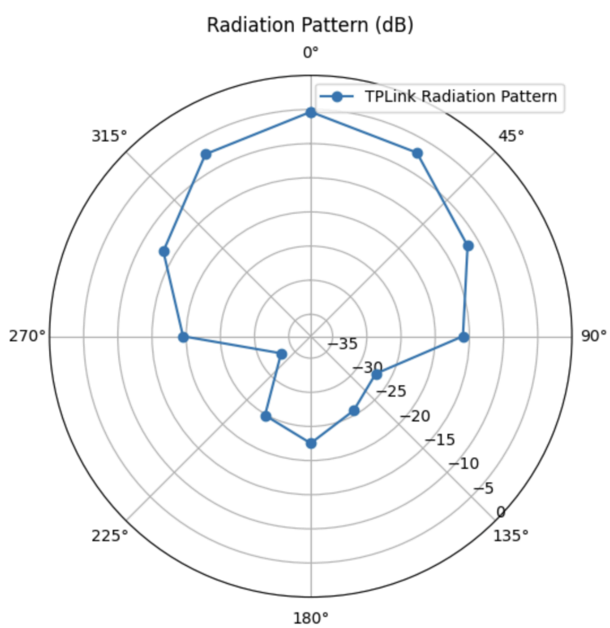


Figure 9: In-lab radiation pattern

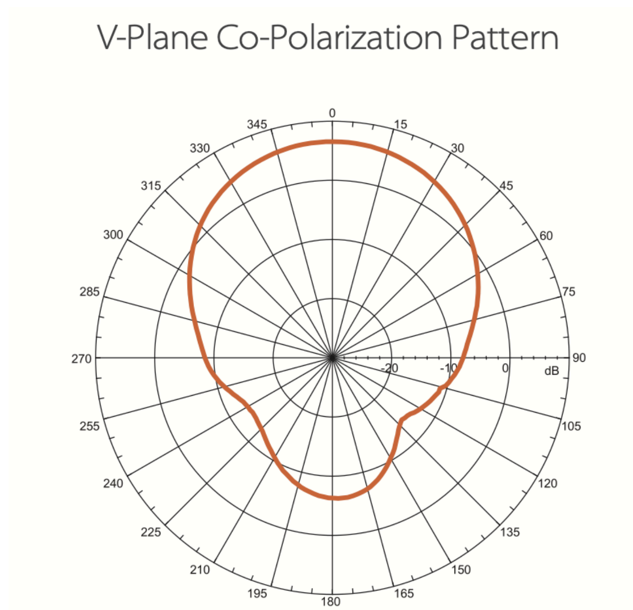


Figure 10: Radiation pattern from the datasheet

5. Receiver information

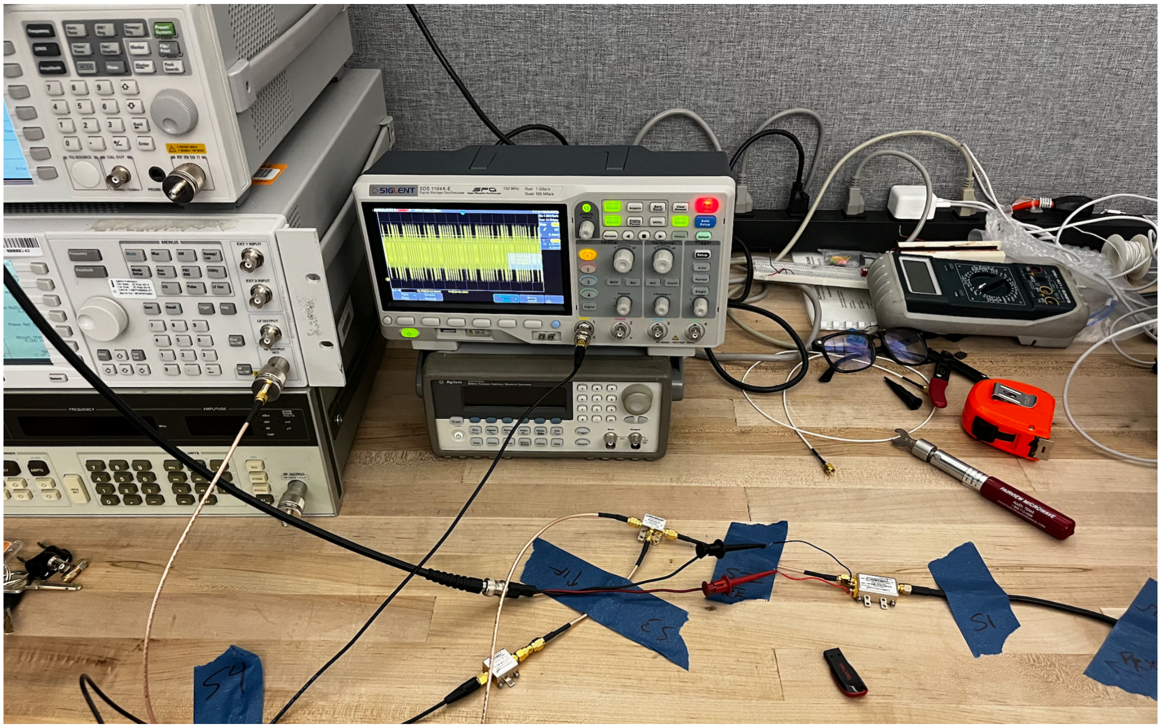


Figure 11: Picture of the receiver with LNA, mixer, LPF, and ADC the antenna is off-screen

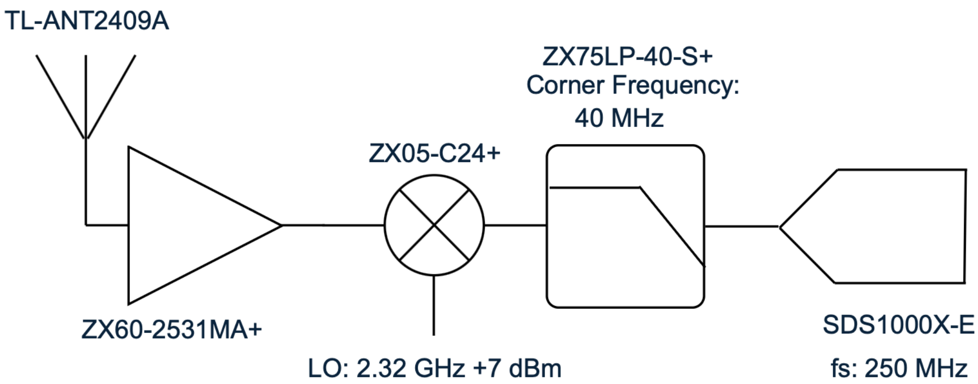


Figure 12: Schematic of receiver Recieve Antenna, LNA, mixer, LPF, and ADC

6. Receiver Stages

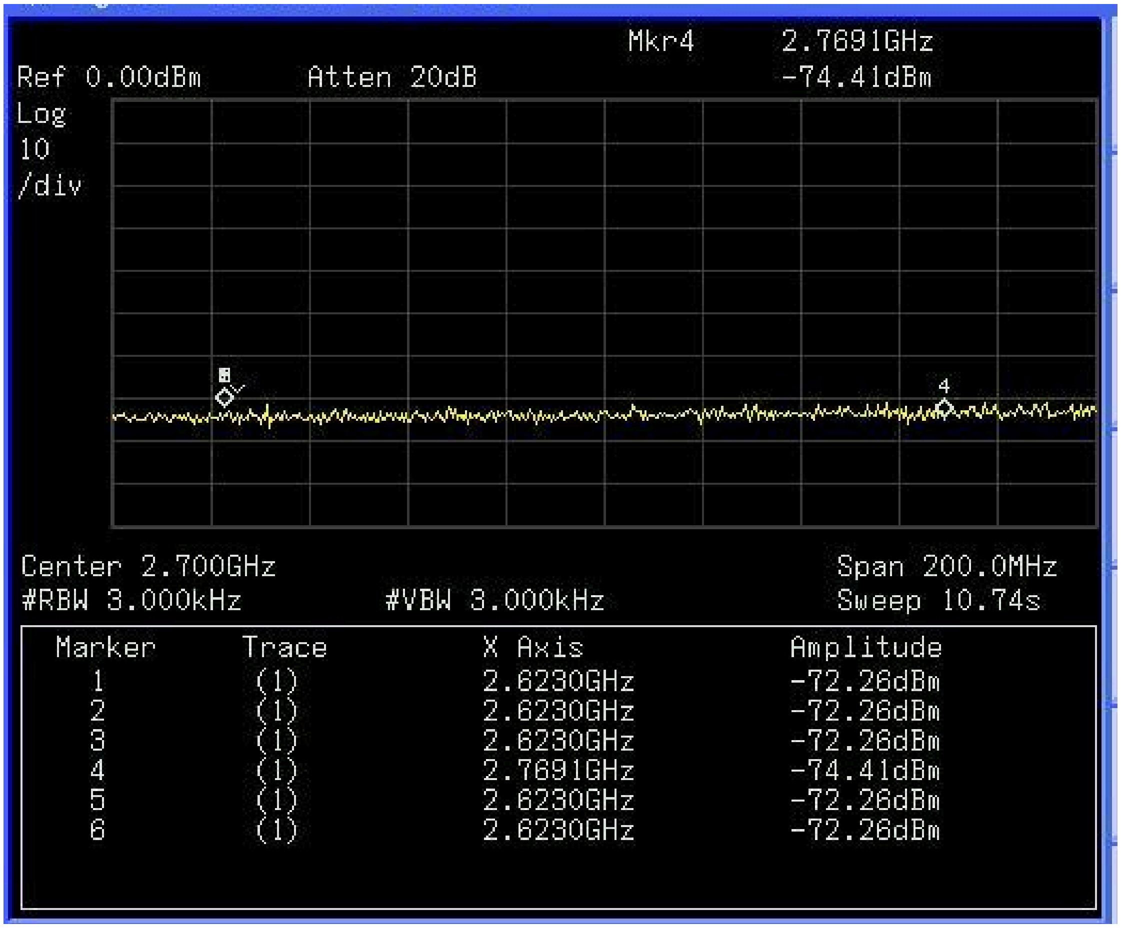


Figure 13: Spectrum directly off antenna under 3m test condition

Discussion:

There were no observed peaks at 3 [m] when the receive antenna was plugged directly into the VNA. This is because the signal is not strong enough to make it past the noise floor which is measured at -72.26 dBm with this configuration of RBW and VBW. The RBW and VBW are considerably narrow compared to the span of the VNA. Therefore we will be capturing very little of the total noise power and lowering the noise floor as a result.

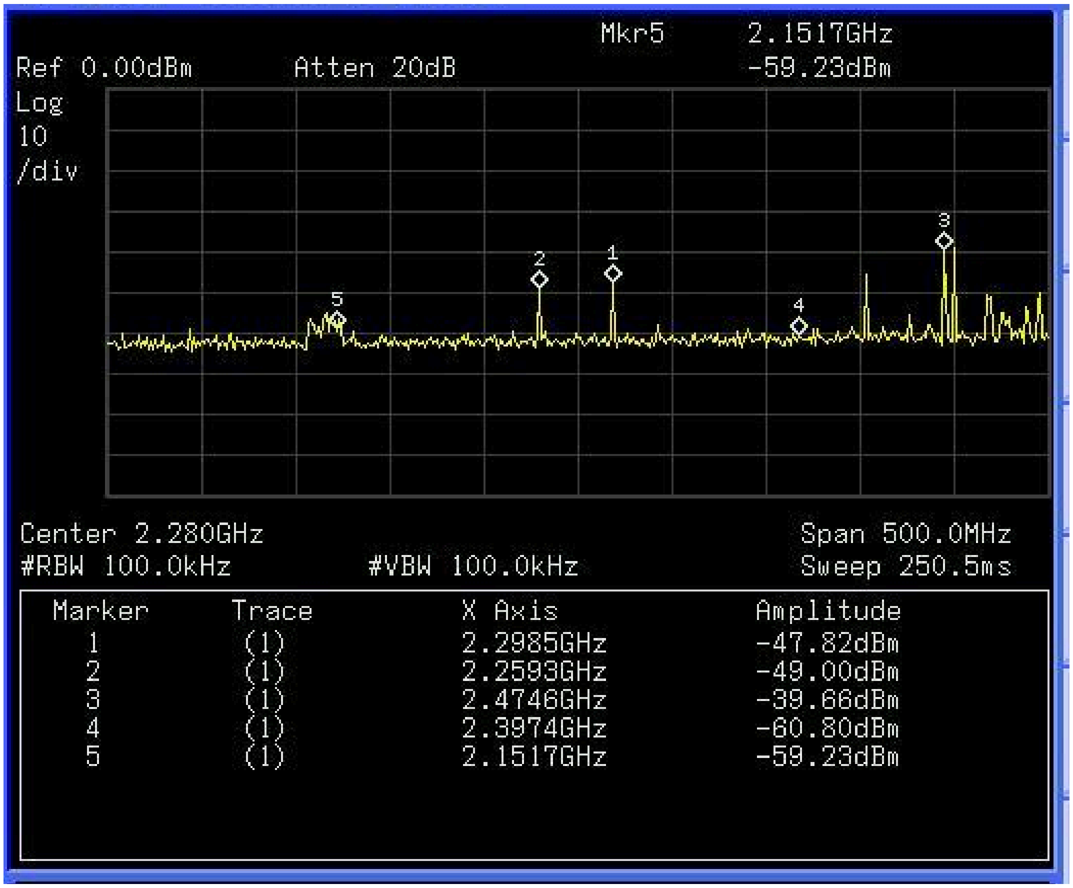


Figure 14: Spectrum for amplifier stage under 3m test condition

Discussion:

Adding the amplifier stage to the output of the receive antenna yielded more interesting results than without. At markers 1 (2.2985 [GHz]) and 2 (2.2593 [GHz]) we can see the two frequencies that the transmit antenna has been encoded to write a message. At markers 3 and 4 there are highly unpredictable peaks between 2.3974 [GHz] and above. This is most likely sourced from WIFI information transfer which carries a sophisticated protocol that could not be decoded with the present setup hence the chaotic perception. Marker 5 (2.151 [GHz]) carries a “lump” of interfering signal that has no discernible source. One thing we noticed in our data collection process is that this mysterious blocker became most prominent once we were outside of the lab room in the hallway. The noise floor is higher in this stage compared to the previous spectrum because the RBW is much larger.

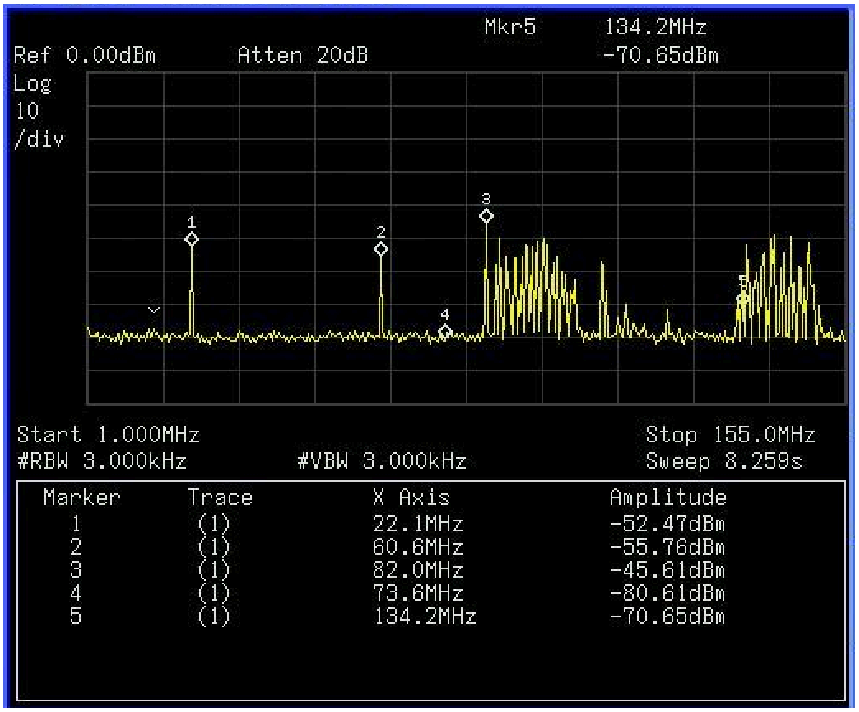


Figure 15: Spectrum for amplifier and mixer stage under 3m test condition

Discussion:

Adding the mixer stage to the output of the amplifier stage from before required us to shift the center frequency and span downwards to the downconverted signal. We downconverted with an LO of 2.32 [GHz] meaning all frequencies present before would be convolved with the frequency domain representation of the LO signal. This had the effect of shifting the signal that was previously 2.2985 [GHz] down to marker 1 or 22.1 [MHz] and the signal that was previously 2.2593 [GHz] down to marker 2 or 60.6 [MHz]. Markers 3 and 5 correspond to either the mysterious blocker discovered in the prior spectrum or wifi. Both of these signals were far from the LO frequency so they were shifted further to the right where they will later be filtered out. The noise floor measured at marker 4 is -80.61 dBm which is a result of the Low Noise Amplification done in the previous stage and the considerable low RBW.

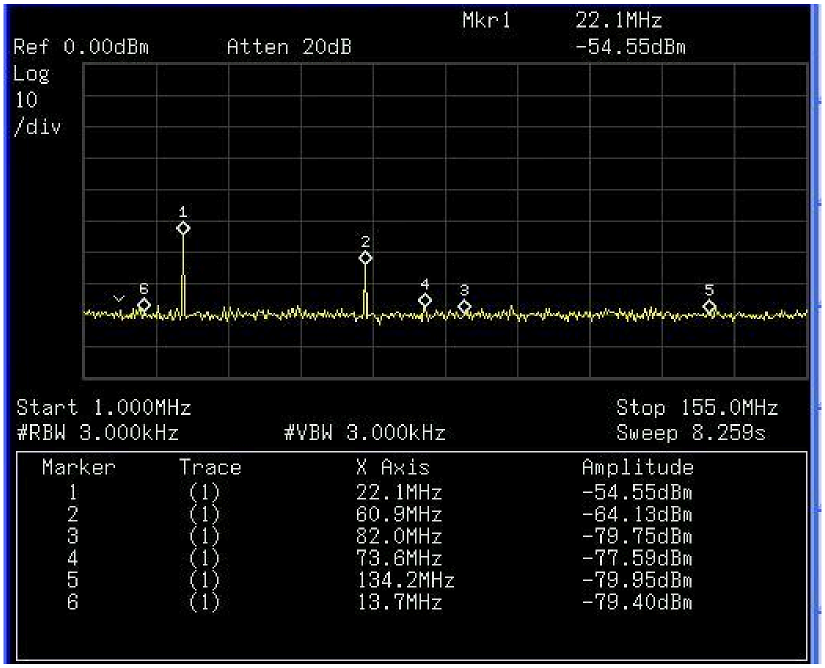


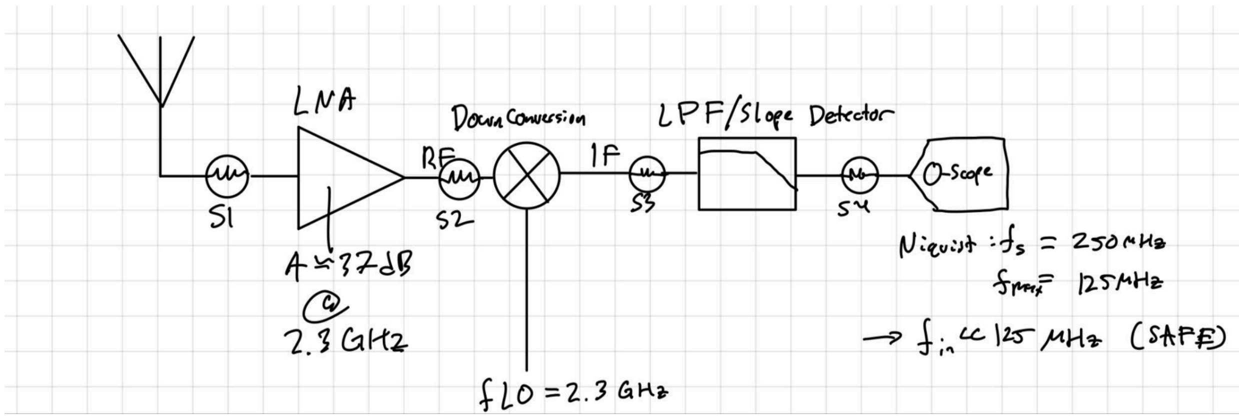
Figure 16: Spectrum for full receiver (amplifier, mixer, and filter) stage under 3m test condition

Discussion:

The final stage of the receiver was the LPF which served as a slope detector to decode the secret message but also as a method to filter out the large amount of extra signals due to WIFI and the mystery blocker. As expected the signals that were previously at marker 5 have completely been attenuated to below the noise floor. Thankfully the two encoded frequencies are still available to us in Markers 1 and 2. The noise floor at this stage is approximately -79.95 which is effectively the same as before.

7. Theoretical Levels

To find the Signal power we followed the power from the receiver through the system until it reached S4 or the ADC. To find the Noise level we used the relationship between DANL and Tsys using the BW of the system derived in lab 6. The DANL was assumed to be 90.1 which is the typical noise floor for the WIFI antenna which our TP link is. The BW was set by the LPF which had a pass band of DC - 40 MHz.



$\boxed{\text{Signal-Power}} = L_{LPF} \cdot S3$

$S_3 = G_{mix} S_2$

$S_2 = A_{amp} S_1$

$S_1 = P_{Rx}$

$\boxed{\text{Noise Level}}$

$DANL = k \cdot T_{sys} \cdot BW$

$BW = 40\ MHz$

k = boltzman constant

$DANL = -90.1\ dBm$

$$T_{sys} = 10^{-3} \cdot 10^{\frac{-90.1}{10}} \cdot \frac{1}{k \cdot 40 \times 10^{6}}$$

https://docs.google.com/spreadsheets/d/1147ZWIwtQ2b-p4KLiIQAYR0BwHkvn_7Ra2BexIPfxqI/edit?usp=sharing

8. IIP3

Pout vs. Pin plot showing fundamental power and IM3 power at the output of your receiver in the receiver characterization test configuration. Extrapolate measured lines to indicate a measured IP3. Include a point showing your theoretical IP3. Include a calculation below (with references to datasheets where appropriate) to explain how you calculated your theoretical IP3.

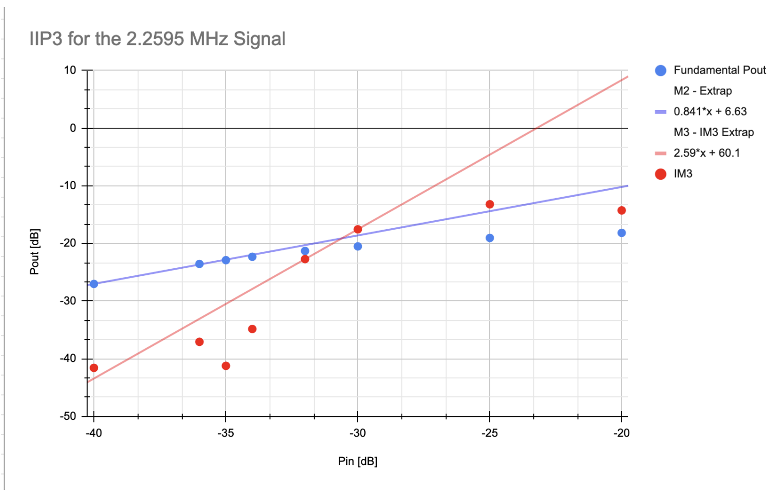
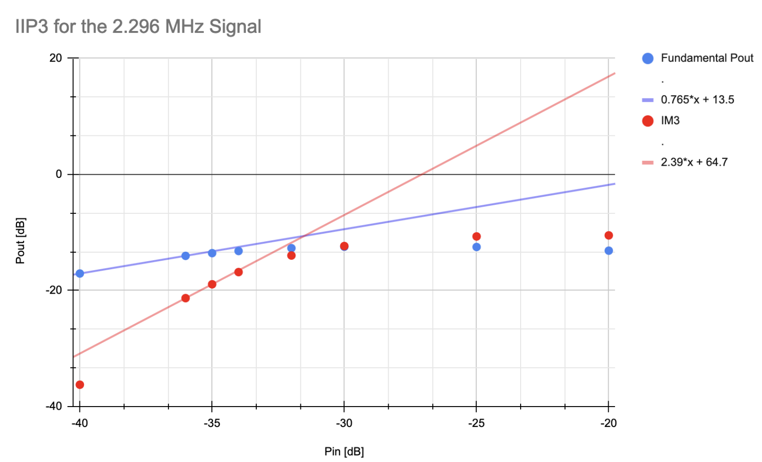
	

Figure 17: Fundamental and IM3 data extrapolated to find IIP3 for the 2.2595 [GHz] signal	Figure 18: Fundamental and IM3 data extrapolated to find IIP3 for the 2.296 [GHz] signal

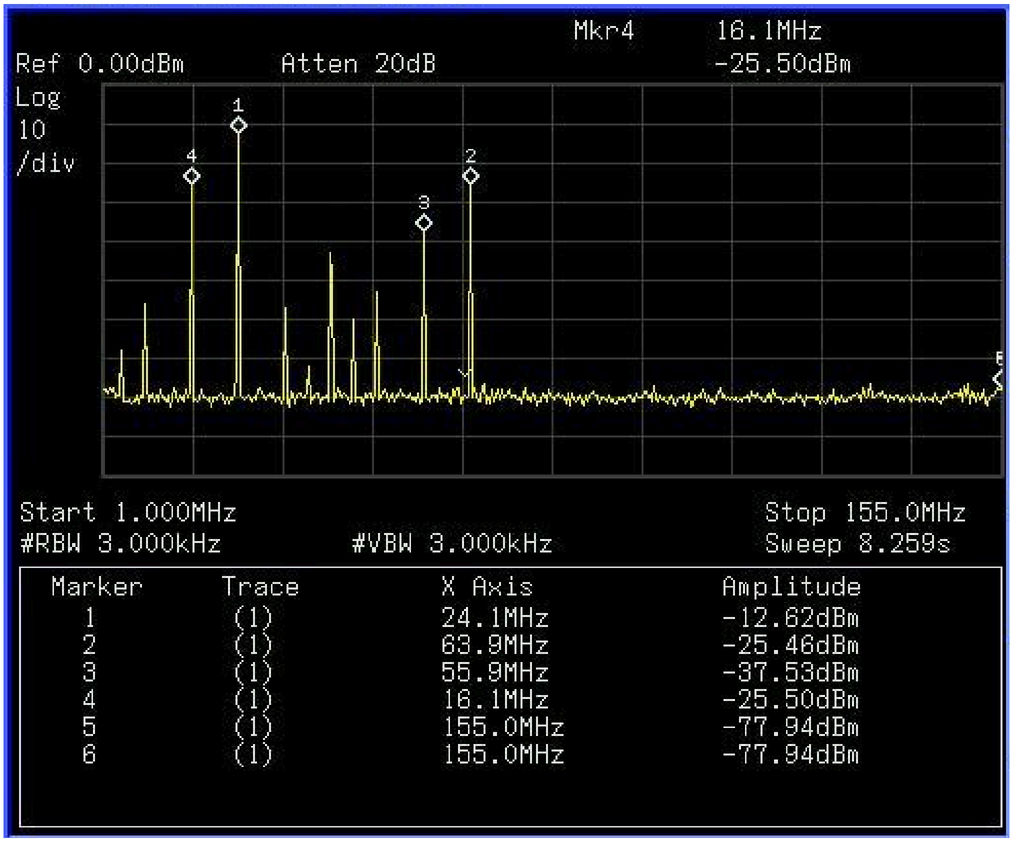


Figure 19: Spectrum of the intermodulation products of the receiver.

To measure this value we hooked up the receiver to two tones that were near the tones that the transmit antenna was transmitting (2.2595, 2.2965). After the downconverting, the signals appeared in the VNA as seen in Figure 19. Markers 1 and 2 correspond to the fundamental frequencies that we are attempting to model off of the transmitter's encoded frequencies. Markers 3 and 4 correspond to the intermodulation products of each of these signals. The difference between the fundamental and the intermodulation product is the IM3.

The IP3 was extrapolated to be ~-30.5 dB in this narrow frequency range. This is 50 dB off from the analytical IP3. Looking at the plot of Pout, we were never able to capture slopes of 1 and 3 for each of the Pout and IM3 plots. To do this we would have needed to take more data points below -40 dBm. Perhaps with a more accurate linear equation for both Pout and IM3, we could have a more accurate IP3 measurement.

To calculate the analytical IP3 we took the data from the datasheet for the amplifier used and created a linear regression therefore allowing us to find an estimated IP3 at each frequency.