AM Radio Receiver Project

UCLA - Summer 2022, Physics 4BL Lab 1B, Group 3
3 August 2022

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Abstract

FM and AM Radio waves are commonly used to send information across a wide range of frequencies. AM, or amplitude modulated waves have been used for over a century for broadcasting and various forms of wireless communication. The construction of an Amplitude Modulated wave is simple: the amplitude of a carrier signal is varied in proportion with the information wave and the combined signal is transmitted. These waveforms can be constructed anywhere between 540kHz-1700 kHz, a frequency range that makes it easy to build a circuit that can receive the radio wave and detect the information signal.

The main goal of our project was to build an AM radio receiver by constructing a circuit that can: wirelessly receive signals within the radio frequency range, and filter out the carrier wave to recover the information signal. The main circuit components included: an LC tank circuit with a resonant frequency tuned to 100kHz (the carrier wave frequency), an operational amplifier to increase the voltage of the received signal, and a diode detector circuit consisting of a diode that detects the information signal (we chose to use a “Concert A” with a frequency of 440Hz), and an RC circuit to filter out the carrier wave. The RC circuit would then be connected to a speaker, where the sound should only consist of the information signal we intended to receive. Three different circuits named Initial Circuit, Audio Detection Circuit, AM Radio Receiver Circuit were built and data was collected using an Analog Discovery 2 and an application called Waveforms.

Overall, the Initial Circuit and the AM Radio Receiver Circuit did not work properly due to a variety of reasons including the lack of an additional operational amplifier, poor choice of location to receive signals, and lack of proper material to build a good LC tank circuit. However, our Audio Detection circuit worked very well and we successfully detected and demodulated signals in the radio frequency range.

Introduction

Our project aims to build an AM radio receiver, a circuit that receives an amplitude modulated (AM) radio wave and demodulates the signal so that we can hear the information carried by the signal. To understand how to construct this circuit, we must first understand that AM radio waves are a special combination of two electromagnetic waves, a carrier wave and a message wave. AM stands for amplitude modulation, a process in which a carrier wave is generated with a varying amplitude proportional to the amplitude of an information signal according to the equation

$$y(t) = [1 + mcos(2\pi f_m t + \phi)]Asin(2\pi f_c t) \qquad (1)$$

where m is the modulation index, f_c is the carrier wave frequency, f_m is the message wave frequency, A is amplitude of the carrier wave, and ϕ is the phase shift. These two waveforms are combined into a singular waveform using a mixer in a transmitter (*Diode Detector: AM Envelope Demodulator » Electronics Notes*, n.d.), which can then be received by a circuit that can effectively filter out the carrier wave and return the information signal. This process is called demodulation, and there are a variety of different ways that one can build a circuit to successfully demodulate a wave. In general, a simple receiver circuit should consist of six components: an antenna, an LC tank circuit that receives the AM signal we want to hear, an amplifier that increases the voltage of the received signal, a diode that rectifies the signal, an RC circuit (also known as a high pass or low pass filter) that filters out the carrier wave, and a speaker to be able to hear the demodulated signal. It is worth mentioning that our circuit also utilized a high pass filter between the LC tank circuit and the non-inverting operational amplifier to filter out the 60Hz background noise that is usually present in common environments. To understand how these components all work together we must first understand how each of them work.

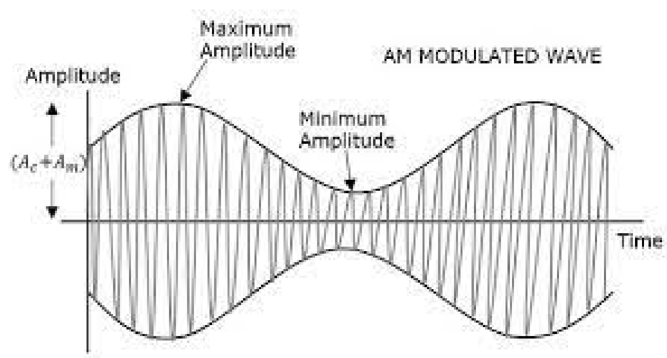


Figure 1: An example of an amplitude modulated signal. The high oscillation waveform is the carrier wave, and the wave enveloping that is the information wave. The amplitude of the carrier wave is varied in proportion to the information signal, and a mixer in a transmitter combines them together.

First, the LC tank circuit, which is composed of an inductor in series with a capacitor, detects the AM radio wave received by the antenna. LC circuits have a natural resonant frequency when the impedance, or total resistance, of the capacitor X_C and the inductor X_L are the same. The circuit can select the frequency we are looking for if a capacitance and inductance is calculated such that the resonant frequency of the circuit is the same as the frequency of the wave we are trying to receive. Resonance occurs when the imaginary components of the capacitor impedance and the inductor impedance equal to each other,

$$Im\{X_C\} = Im\{X_L\} \rightarrow \frac{1}{w_0 C} = w_0 L$$

solving for the angular frequency w_0, and finding the frequency of the wave

$$w_0 = \frac{1}{\sqrt{LC}}$$

$$w_0 = 2\pi f_0 \rightarrow f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

Where f_0 is the frequency of the AM wave we want to detect, L is the inductance, and C is the capacitance of our circuit. If we pick an inductance or capacitance and solve for the missing variable for the frequency we are looking for, we can construct an LC circuit with the same resonant frequency. It is important to note that the antenna will also pick up some noise interfering with the frequency we are looking for, so it is important for the LC circuit to be adjustable so that we can clearly hear the information signal. Thus, a variable capacitor is recommended to be used in LC circuits for AM receivers.

After the signal is received by the LC circuit, the signal is sent to an operational amplifier to increase the amplitude of the AM wave so that the diode detector and the speaker can detect the information wave. In other words, the voltage of the signal is increased sufficiently so that the other circuit components with a minimum operational voltage, like the diode and the speaker, can rectify the signal and replay the signal, respectively. AM receivers typically use a non-inverting amplifier circuit (Figure 2), whose output voltage is in phase with the input voltage since there is no motivation to invert the signal . The output voltage can be calculated by adjusting the resistors and using the following equation:

$$v_0 = \frac{R_s + R_f}{R_s} v_g \quad (3)$$

Where v_0 is the output voltage , v_g is the input voltage, and R_s and R_f are the values of the resistors.

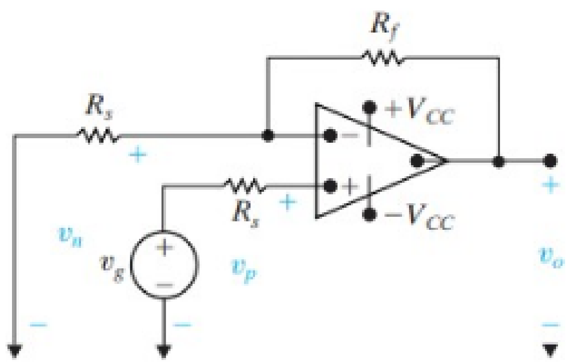


Figure 2: A schematic of the non-inverting amplifier circuit. The signal is read into the circuit, and a closed loop voltage gain is applied to the initial voltage fed into the circuit over the resistors

Next, the signal is sent to a diode detector, where the waveform is rectified by identifying the frequency of the envelope of the wave, also known as the information signal, and filtering out any waves with a higher frequency using a low pass filter. A diode detects the frequency of the information wave by enhancing half of the received signal. This is because current can only flow in one direction through the diode. The type of diode required to correctly detect what we want depends on the voltage of the signal we are trying to rectify because there has to be a minimum voltage flowing through the diode in order for it to work. Since AM signals are small compared to other radio signals, they are also quite low, so a diode with a turn on voltage around 0.2V (also called a Schotky diode) is recommended. After the diode detects the signal, a low pass filter, which consists of a capacitor and a resistor, filters out any waves with a frequency higher than the detected message signal. The circuit can select the frequency we want to filter out if the resistance and capacitance is calculated such that the cutoff frequency of the circuit is the same as the frequency of the wave we are trying to receive. This cutoff frequency is determined when the capacitive reactance and the resistance are equal to each other, and can be calculated using the formula derived from Figure 4,

$$w_c = \frac{\sqrt{2}}{RC}$$

$$w_c = 2\pi f_c \rightarrow f_c = \frac{\sqrt{2}}{2\pi RC} \qquad (4)$$

where f_c is the cutoff frequency, R is the resistance, and C is the capacitance. If we pick a resistance or capacitance and solve for the missing variable for the frequency of the information signal we want to hear, we can construct an RC circuit with the required cutoff frequency. It is worth mentioning that the high pass filter between the LC tank circuit and the non-inverting operational amplifier in our circuit also relies on the same principles to work. It is a circuit element tuned to a cutoff frequency such that any signals detected below that frequency (in our case 60Hz) are filtered out.

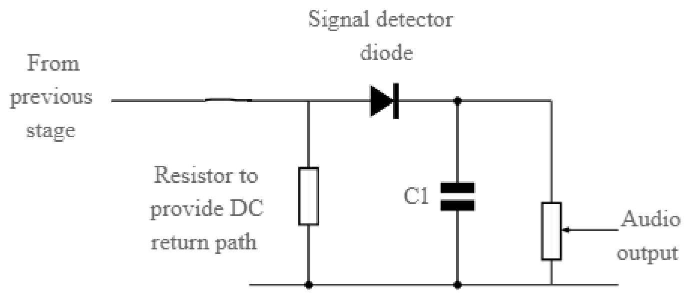
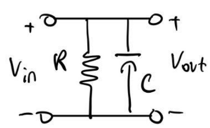


Figure 3: A schematic of the diode detector circuit. It is important to note that diodes also have a forward voltage, meaning that the diode will drop the voltage of the signal according to this value, and should be taken into consideration when choosing components like the speaker that the signal will be sent to after being rectified by the diode.



$$V_{in} = IX_R, \quad V_{out} = IX_C$$

$$V_{in} = IR, \quad V_{out} = I \cdot \frac{1}{i\omega C}$$

$$\Rightarrow I = \frac{V_{in}}{R} \longrightarrow V_{out} = V_{in} \cdot \frac{1}{i\omega RC}$$

The cut off frequency occurs at $\left| \frac{V_{out}}{V_{in}}(\omega) \right| = \frac{1}{\sqrt{2}}$ or 3dB

So, $\frac{1}{\omega RC} = \frac{1}{\sqrt{2}} \Rightarrow \omega_c = \frac{\sqrt{2}}{RC}$

since $\omega = 2\pi f$, $\boxed{f_c = \frac{\sqrt{2}}{2\pi RC}}$ is the cut off frequency

Figure 4: A derivation of the cutoff frequency formula over the RC circuit to filter out the carrier wave in the detector diode.

After the diode detector rectifies the signal the voltage leads across the low pass filter would be connected to a speaker which will play the signal that was demodulated by our circuit. We hypothesize that the signal we receive is the frequency of the information signal we expected to hear from the AM frequency signal detected by our circuit.

Materials

- Analog Discovery 2 (AD2)
- MCP6022 Operational Amplifier
- Waveforms Application
- Styrofoam
- 4.7nF, 157nF, 0.3pF, 220pF Capacitors
- 1N4148 Small Signal Fast Switching Diode
- Wired Headphones
- Audio jack
- 100Ω, 100kΩ, 1kΩ Resistors
- High Quality Polyurethane Enameled Copper Wire
- Computer

Methods

Initially, The circuit shown in Figure 6 which was based on the schematic shown in Figure 5 was built. The purpose of the antenna was to pick up various radio waves and transmit any signal via mutual inductance of the antenna and the inductor in the LC circuit. The LC “tank” circuit was made up of a 47μH inductor and a 0.3pF capacitor which resulted in a resonant frequency of about 1340kHz. The purpose of the LC tank circuit was to act as a tuner and only let Amplitude Modulated waves that are near its resonant frequency into the circuit while ignoring waves with a different frequency. Note that usually there would be a variable capacitor in the LC tank circuit in order to tune the overall circuit to a desired frequency. However, since there were limited resources, the LC tank circuit was tuned to a single resonant frequency which was chosen based on the proximity of local radio stations. 1340kHz was chosen as the resonant frequency because there was a local radio station called News Talk 1340 AM on that frequency. A 1N4148 Small Signal Fast Switching Diode was used to rectify the AM signal. The RC low pass filter was made up of a 100Ω resistor and a 4.7nF capacitor. Its purpose was to filter out the carrier wave so that the message wave could be sent to the speakers. However, after testing the circuit, it was concluded that the set up did not work for a variety of reasons (mentioned in the Conclusion section) and the data taken was discarded. The components that hindered the circuit were determined to be the inductor, the headphone jack to which the speaker - wired headphones- connects to.

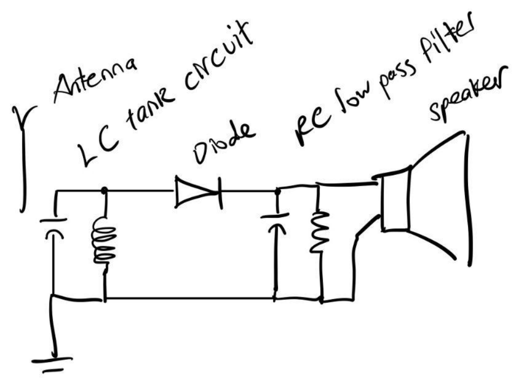


Figure 5: Schematic of the initial circuit that was implemented. The LC tank circuit and the Antenna act as a transformer. The LC tank circuit picks up the signal coming from the Antenna via mutual inductance. The diode rectifies the signal. The RC low pass filter filters the carrier wave. The speaker plays the resulting message signal.

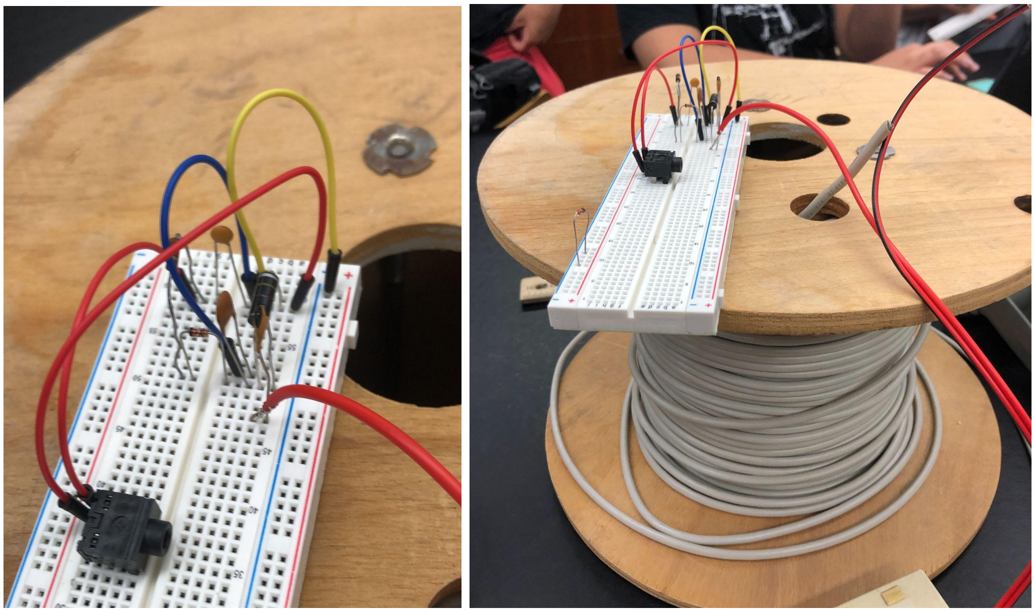


Figure 6: The figure on the left shows the circuit that was implemented based on the schematic given in Figure 5. The picture on the right shows the antenna that was used. Note that there were wired headphones connected to the audio jack on the bottom left of the picture on the left when the experiment was executed.

Once possible error sources were determined to hinder the initial circuit, the audio detection circuit shown in Figure 7 was built. The waveform generator built into the AD2 supplied an AM signal with 100kHz carrier wave and a 400Hz message wave at 60% modulation and 30mV amplitude. This signal was fed into the Operational Amplifier which was wired up in a non-inverting configuration. The resistors wired to the Op-Amp were chosen such that the gain was 101 - the amplitude of the signal was multiplied by a factor of 101 (theoretically). This amplification allowed the signal to pass through the diode and get rectified as opposed to the initial circuit where the voltage of the incoming signal was lower than the forward voltage of the diode. Then, the RC low pass filter had a resistance of 1kΩ and a capacitance of 4.7nF resulting in a cutoff frequency of 23.94kHz. This cutoff frequency was low enough to filter the carrier wave and high enough that the message signal was not filtered out. The +2 and -2 leads on the AD2 were connected to the audio detection circuit as shown in Figure 7 so that the output signal could be viewed on the AD2 oscilloscope.

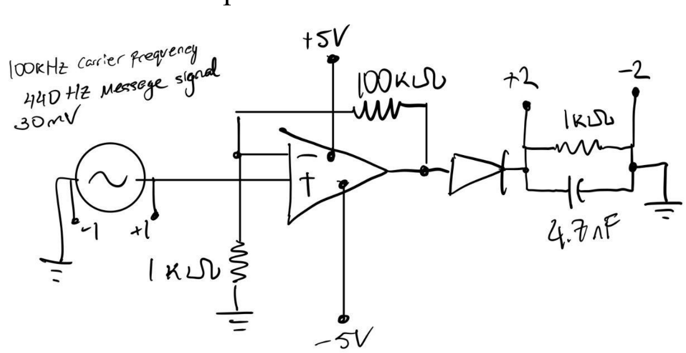


Figure 7: The schematic of the audio detection circuit that was implemented. The waveform generator supplies the Amplitude modulated signal at 60% modulation. The Operational Amplifier is in the non-inverting configuration and amplifies the AM signal by a factor of 100 (theoretically). Then, the diode rectifies the signal. The RC low pass filter filters the carrier wave. The +2, -2 and +1, -1 leads are the channel 2 and channel 1 leads on the Analog Discovery 2 (AD2) respectively. These leads allow us to measure the voltage drop across the resistor or the resultant message signal and lets us look at the overall AM signal on the AD2 oscilloscope.

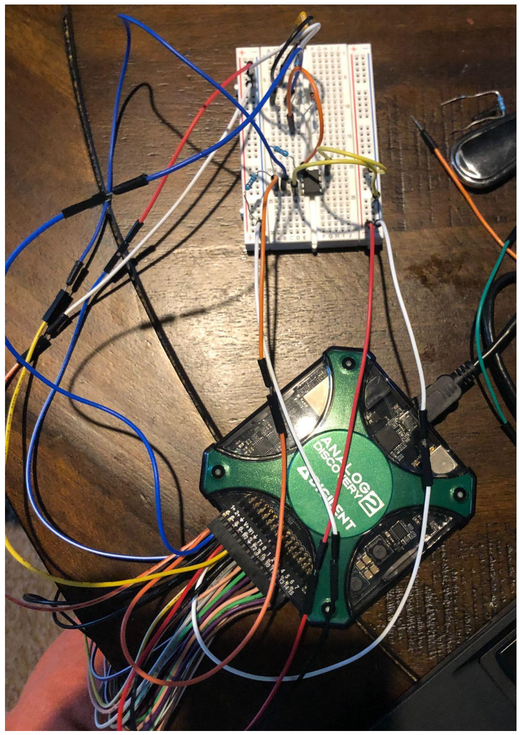


Figure 8: The circuit that was implemented based on the schematic given in Figure 7.

A picture of the circuit we implemented is shown in Figure 8. The Analog Discovery 2 was connected to a computer where the Waveforms application was used to configure the AD2 to the settings shown in Figure 9. The channel 1 and channel 2 ranges and the time “base” settings were adjusted so that the waveforms on the oscilloscope were readable/recognizable. Both channels were connected as in Figure 7 and the data logger was used to record the data in a .csv format. Then, the +1 lead was connected to the node at the output of the Op-Amp and channel 1 data was recorded using the data logger. These .csv files were uploaded to google drive where the data was processed in Google Collaboratory using python.

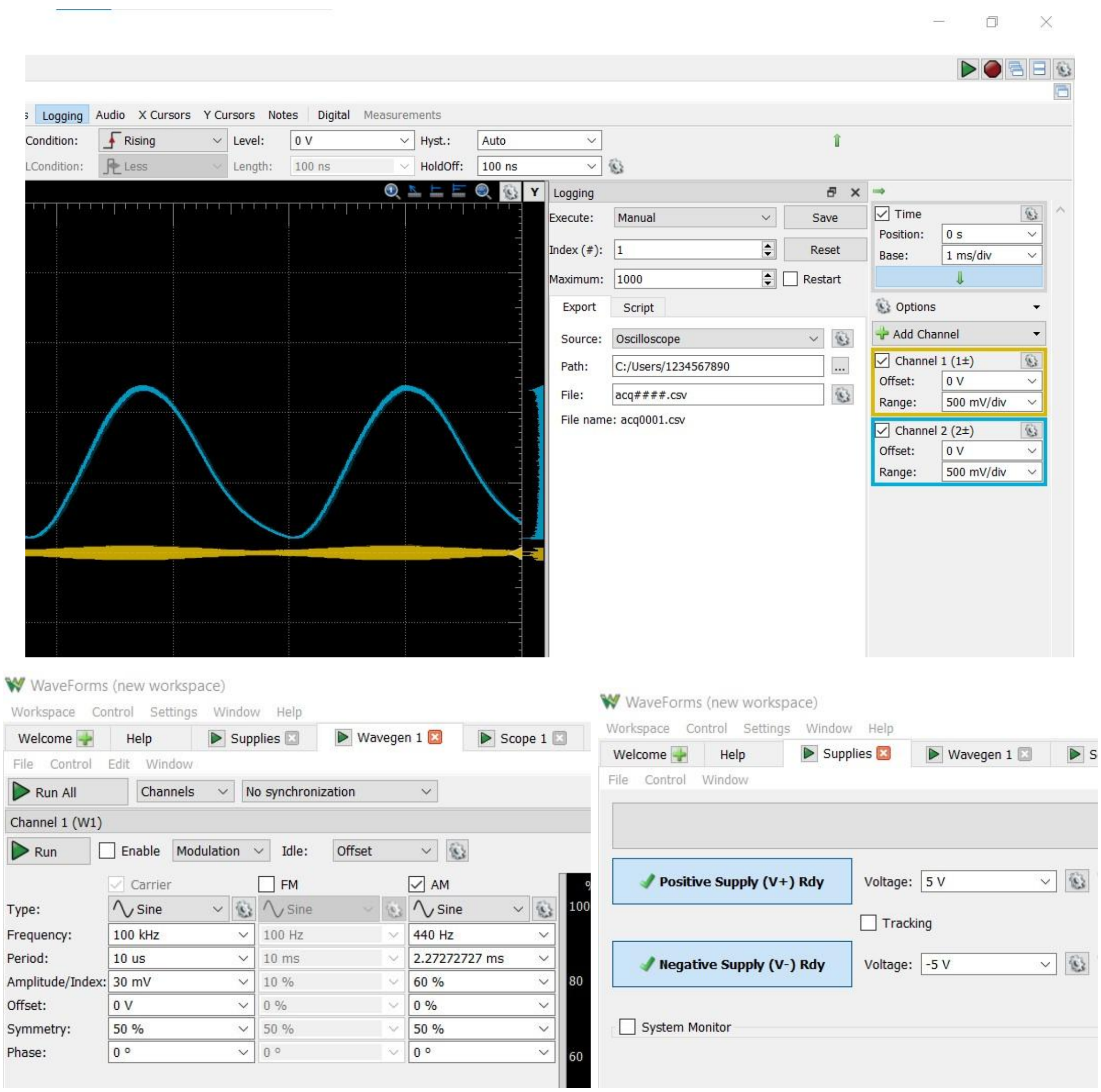


Figure 9: The settings used for the Analog Discovery 2 in the Waveforms application. Wavegen was used to create an Amplitude Modulated waveform. Supplies was used to power the operational amplifier. The Data logger was used to convert signals seen on the oscilloscope into .csv files

After the audio detection circuit was working and data was collected, the experimenters built the AM radio receiver circuit shown in Figure 11. A Styrofoam rectangle with a height of 6cm and an area of 8cm x 2cm was cut and about 50 turns of High Quality Polyurethane Enameled Copper Wire was wrapped around it to use it as an inductor in the LC tank circuit. The inductance of this component was measured to be 0.0162mH with an LCR meter. Various capacitors were put in a parallel connection in order to have an overall capacitance of 157nF in the LC tank circuit. This resulted in a resonant frequency of 99.975kHz ≈ 100kHz. An Antenna was made from the same copper wire and was about 20 meters in length (the coating on the side closer to the LC tank circuit was removed so that the copper was exposed) and was connected to the Wavegen on the AD2. The 200pF capacitor was used as a high pass capacitor in order to filter the ambient noise for a typical room which is usually about 60Hz. The rest of the circuit was exactly the same as the audio detection circuit and each component served the exact same purpose. Data was taken in exactly the same way described for the Audio detection circuit. However, after testing the circuit, it was concluded that the set up did not work for a variety of reasons (mentioned in the Conclusion section) and the data taken was discarded. The components that were determined to be causing errors were the LC tank circuit and the Antenna.

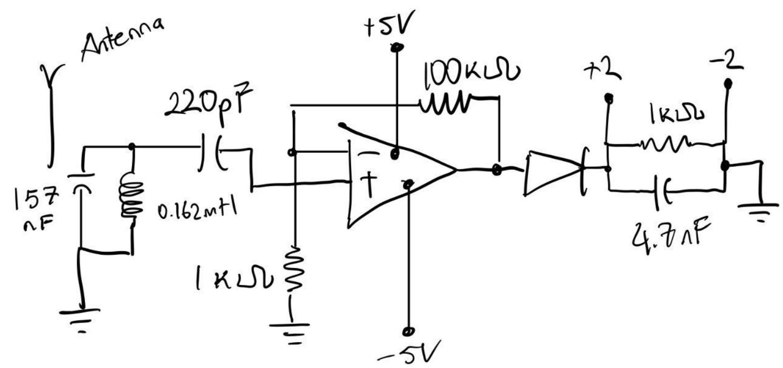


Figure 10: The schematic of the AM Radio Receiver circuit that was implemented in Figure 11. The LC tank circuit and the Antenna act as a transformer. The LC tank circuit picks up the signal coming from the Antenna via mutual inductance. The 220pF capacitor acts as a high pass filter - gets rid of 60Hz room noise. The Operational Amplifier is in the non-inverting configuration and amplifies the AM signal by a factor of 100 (theoretically). Then, the diode rectifies the signal. The RC low pass filter filters the carrier wave. The +2 and -2 leads are the channel 2 leads on the Analog Discovery 2 (AD2). These leads allow us to measure the voltage drop across the resistor or the resultant message signal on the AD2 oscilloscope.

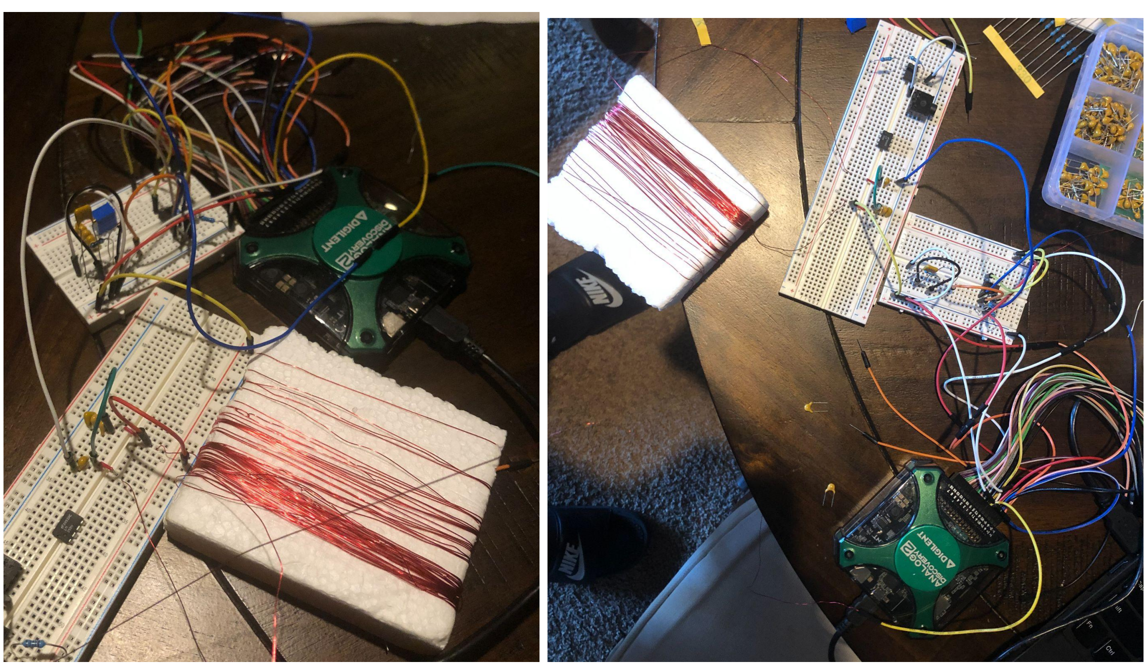


Figure 11: Both pictures show the AM Radio Receiver Circuit which is based on the schematic given in Figure 10. Note that a part of the Antenna is only visible in the lower right corner of the picture to the left.

Results & Analysis

Data was only taken for the Audio detection circuit since the Initial circuit and the AM Radio Receiver Circuit did not produce meaningful data. To measure a given signal, the -1/-2 lead was connected to ground and +1/+2 was connected to the node at which the signal of interest passes through.

Channel 1 and 2 were connected as in Figure 7. Data was taken using the data logger on the Waveforms app. The resulting csv file which included the Op-Amp Input signal and the Information/Message signal data was saved in google drive and analyzed using python in Google Collaboratory. Then Channel 1 was connected to the Op-Amp Output (the node in Figure 7 to which the diode, the 100kΩ resistor, and the Op-Amp output lead is connected to) and data was saved in google drive and analyzed using python in Google Collaboratory as previously done. Best fit curves using least squares was made for all the collected data using the numpy, matplotlib, and scipy libraries. Then, Channel 2 was connected to the output of the circuit again and the FFT (Fast Fourier Transform) capability in the Waveforms app was used to produce a Fourier Transform Graph (It is assumed that the reader knows about Fourier Series and Fourier Transform as Lab 2A and 2B focused on these topics).

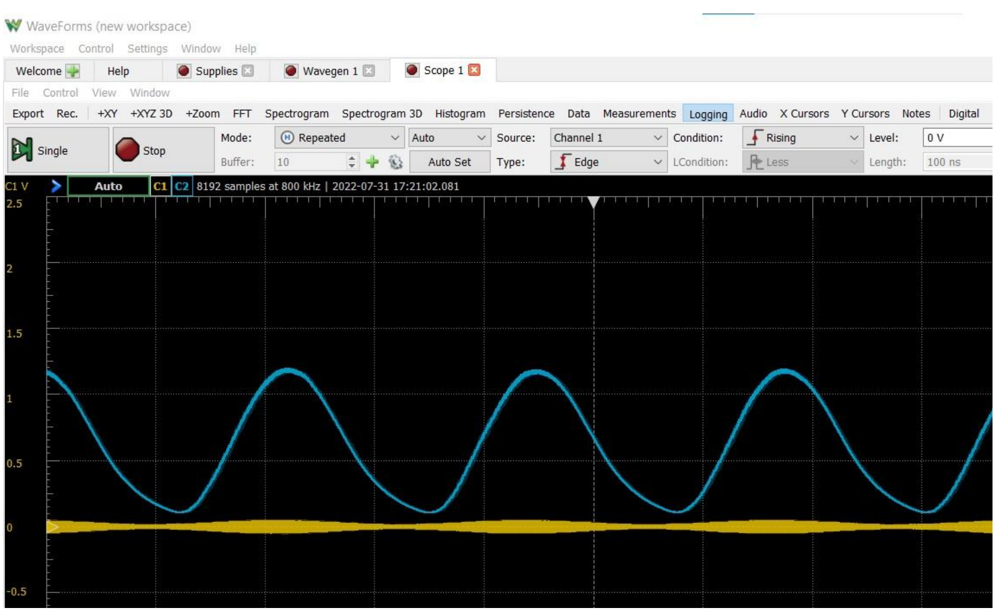


Figure 12: Window displaying the FFT option on the upper left corner next to +Zoom and Spectrogram 3D. The actual Fourier graph of the blue signal is given in Figure 18.

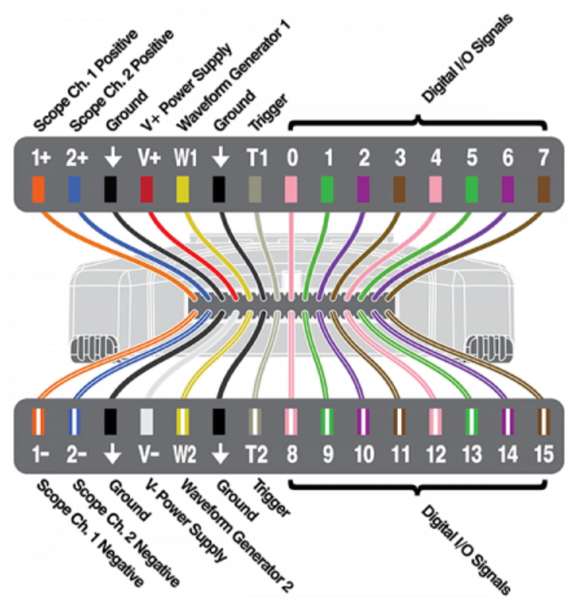


Figure 13: The Pinout of the Analog Discovery 2

Initially, the Op-Amp data we collected looked like the data displayed in Figure 14. Our data was very close together, which caused our best fits to be really inaccurate. So, we repeated our measurements this time taking data from a very small portion of the Op-Amp input and output signal - as opposed to a portion of data that contains multiple periods- such that our data is less cluttered.

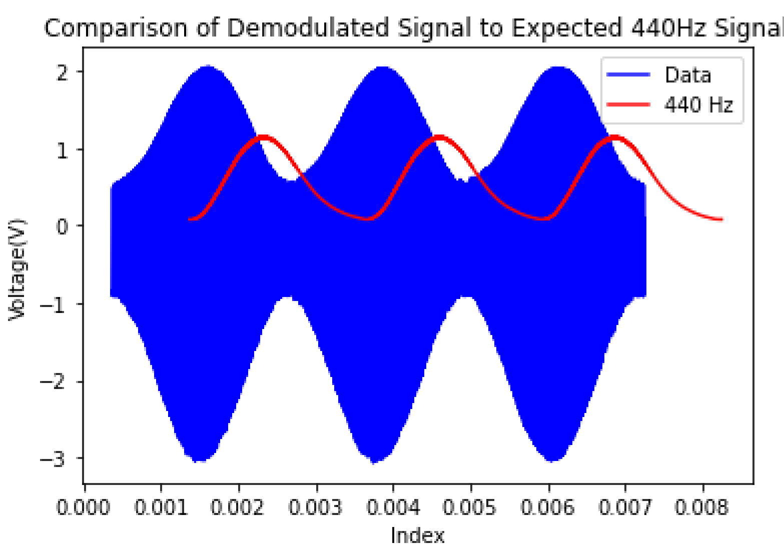


Figure 14: A graph displaying how cluttered our initial data was for the Op-Amp output. The Op-Amp input was cluttered in the same way.

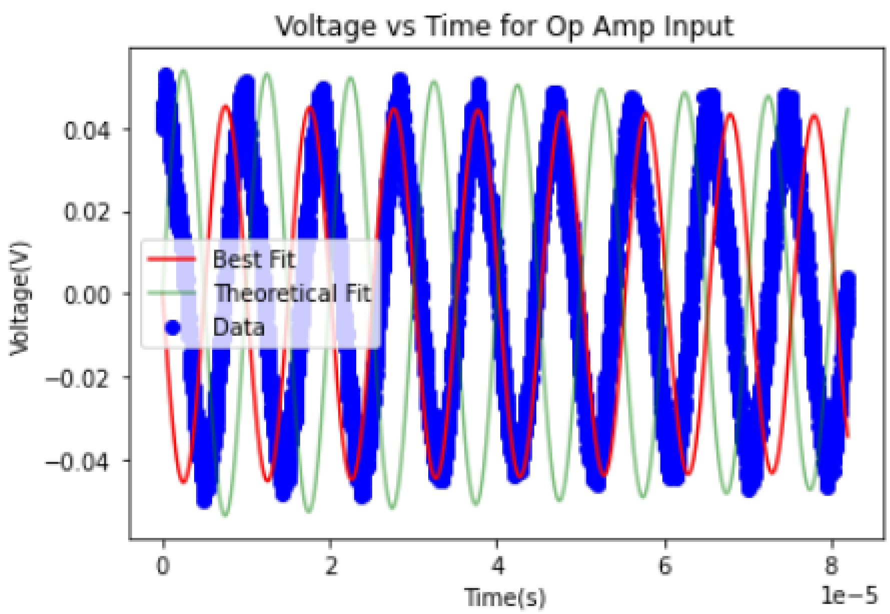


Figure 15: The Voltage vs Time graph for the Amplitude Modulated radio wave input to the Operational amplifier. The equation given by $y(t) = [1 + mcos(2\pi f_m t + \Phi)] * Asin(2\pi f_c t)$ was used to create a theoretical fit and a best fit. The Theoretical fit parameters were m=0.6, f_m= 440Hz, f_c=100kHz, $\Phi = \frac{\pi}{2}$ rad, A= 0.03000V and the best fit parameters were m=0.6, f_m= 155.15Hz, f_c=99.36kHz, Φ = 8.45 rad, A= 0.02718V. The best fit had significant inaccuracies because the peaks of the best fit and the data were not lined up properly. The data collected did not match predictions due to an unexpected phase difference in the data, however, if this phase difference was removed, the data would fit the theoretical fit as predicted.

Once the data we collected was spread out enough, as shown in Figure 15, a least squares best fit was performed on the Op-Amp input signal using Equation 1.Note that even though the data that was taken was less cluttered, the data points were still considerably close together. Consequently, when performing our best fit using least squares, we had to use our theoretical values for each parameter as guesses because not doing so would result in a much more inaccurate best fit. Theoretical fit parameters for the Op-Amp input signal were m=0.6, f_m= 440Hz, f_c=100kHz, $\Phi = \frac{\pi}{2}$, A= 0.03000V and the best fit parameters were m=0.6, f_m= 155.15Hz, f_c=99.36kHz, $\Phi = 8.45$, A= 0.02718V. The amplitude error was 9.4% which was very low as expected. The message signal frequency was significantly lower than the expected 440 Hz and had an error of 64.75%. The carrier signal was much more accurate with an error of 0.64%. The best fit had significant inaccuracies because the peaks of the best fit and the data were not lined up properly due to the data points being very close together. The data collected did not match the theoretical fit due to an unexpected phase difference in the data, however if this phase difference was removed, the theoretical fit would be more accurate as predicted. This unexpected phase difference was most likely due to the output impedance and the voltage swing of the Op-Amp that caused variation in our data (Our Op-Amp was operating near its limits specified by the manufacturer).

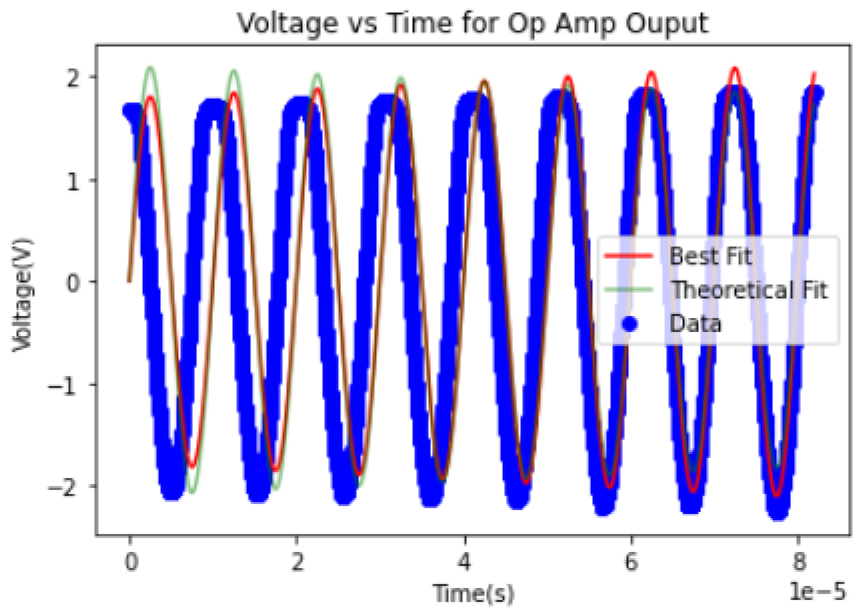


Figure 16: The Voltage vs Time graph for the Amplitude Modulated radio wave input to the Operational amplifier. The equation given by $y(t) = [1 + mcos(2\pi f_m t + \Phi)] * Asin(2\pi f_c t)$ was used to create a theoretical fit and a best fit. The Theoretical fit parameters were m=0.6, f_m= 440Hz, f_c=100kHz, $\Phi = \frac{\pi}{2}$ rad, A= 3.00V and the best fit parameters were m=0.6, f_m= 443.35Hz, f_c=100.01kHz, Φ = -2.31 rad, A= 2.01V. The best fit parameters were as predicted and thus our data was very accurate.

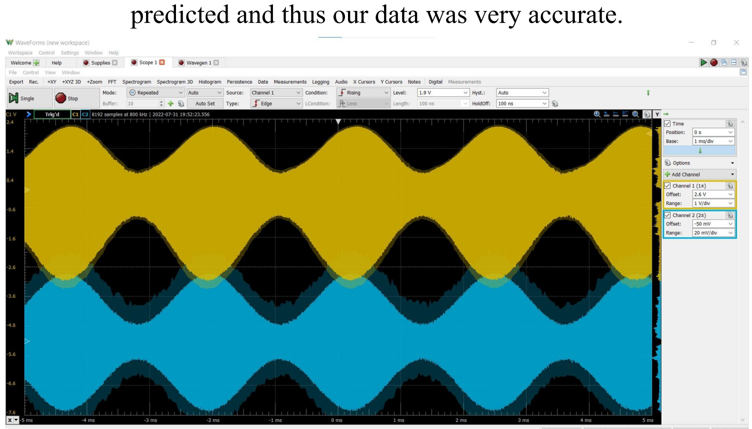


Figure 17: This figure shows a comparison between the op amp input wave (Blue) and the op amp output wave (Yellow). The op amp out shifts up due to the higher voltage drop in the wave.

Just as for the Op-Amp input data, the Op-Amp Output data was very cluttered so when performing our best fit using least squares, we had to use our theoretical values for each parameter as guesses because not doing so would result in a much more inaccurate best fit.

Theoretical fit parameters for the Op-Amp input signal were m=0.6, f_m= 440Hz, f_c=100kHz, $\Phi = \frac{\pi}{2}$, A= 3.00V and the best fit parameters were m=0.6, f_m= 443.35Hz, f_c=100.01kHz, Φ = -2.31 rad, A= 2.01V. The amplitude error was 33.00% which was unexpectedly high. Furthermore, the experimental gain was 74.11 with an error of 26.63% when compared to the theoretical gain of the 101. Again, we believe that this was due to the fact that the Op-Amp was operating at its limit and therefore could not amplify the signal as much as the value that was predicted. The message signal frequency was 443.25 Hz with an error of 0.76% and the carrier signal frequency was 100.01kHz with an error of 0.013%. Both parameters were very accurate as expected.

Error	Amplitude	f_m	f_c
Original AM signal	9.40%	64.75%	0.64%
Amplified AM signal	32.85%	0.76%	0.013%

Figure 18: A table summarizing the percent errors in the message signal frequency, carrier signal frequency and Amplitude.

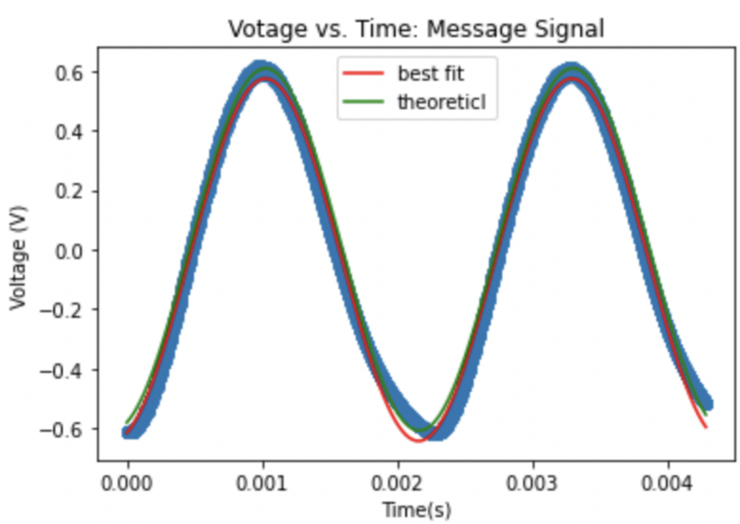


Figure 19: The Voltage vs Time graph for the message signal. The equation given by $y(t) = A * sin(2\pi f_m t + \Phi)$ was used to create a theoretical fit and a best fit. The Theoretical fit parameters were A = 0.61, f_m = 440Hz,Φ = -1.27 rad, and the best fit parameters were A = 0.61V, f_m = 439.999755672Hz or 440 Hz, Φ = -1.27rad. The best fit parameters were as predicted and thus our data was very accurate.

Theoretical fit parameters for the Circuit Output/Information/Message signal were A = 0.61V, f_m = 440Hz,Φ = -1.27 rad, and the best fit parameters were A = 0.61V, f_m = 439.999755672Hz or 440 Hz, Φ = -1.27 rad. We had zero percent error for our message frequency indicating that we successfully received our message signal. This shows that our circuit works properly. However, we should note that this amount of accuracy will most likely not translate to an experiment where an LC tank circuit and an Antenna is used unless noise is filtered really well. Overall, the best fit parameters were as predicted and thus our data was very accurate.

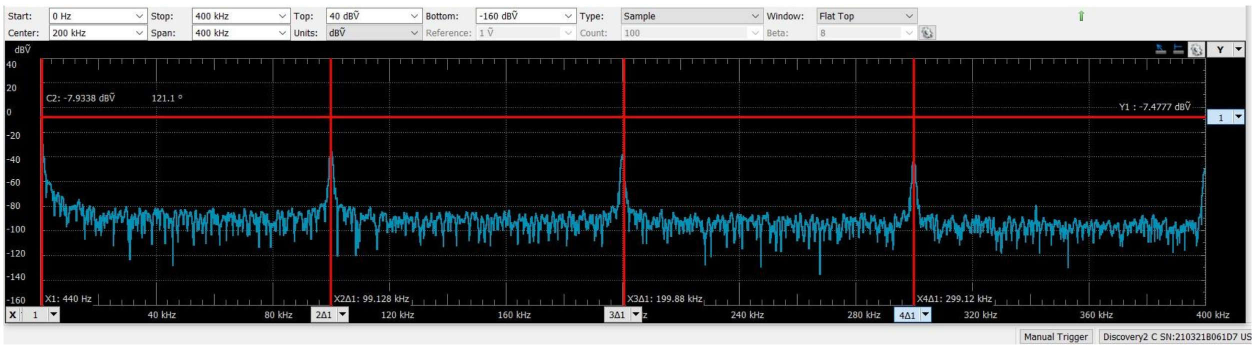


Figure 20: This figure represents a fourier transform of the messenger wave. The Fourier transform shows that it is 440 Hz.

To confirm that the messenger wave was the expected frequency, we plotted the messenger wave on a voltage vs time graph. We then performed a fourier transform on that signal to confirm if the message signal is 440 Hz. The horizontal red lines on figure 20 represents the maximum amplitude which is centered at 440 Hz. We observe peaks at different frequencies indicating that there were overtones in our message signal. Nevertheless. This confirms that the Op-Amp amplification allowed the diode to successfully demodulate the carrier signal and reproduce the messenger wave.

Conclusion

In attempting to build a circuit that could receive an AM radio wave and recover the information signal from the carrier wave, we were unsuccessful in receiving AM Radio waves with our antenna and LC tank circuit as shown from our Initial Circuit and AM Radio Receiver Circuit but were successful at recovering the information signal given the AM radio wave as shown with our Audio Detection Circuit.

We expect the Antenna to pick up surrounding radio waves and the LC tank circuit to pick up radio waves at its resonant frequency. However, there was only noise on the AD2 oscilloscope when we measured the signal that was picked up for the Initial Circuit. Although we initially picked up a recognizable AM signal with our AM Radio Receiver Circuit, similarly, the signal was soon invisible due to noise. This suggests that there were systematic error sources.

We highlight the Impedance of our LC tank circuit as one major source of error for the Initial Circuit. The AM signal that the Antenna picks up and transmits to the LC tank circuit will have very low amplitude/peak voltage which means that if thc circuit components that the signal passes through have a very high impedance, there will be little to no current reaching the diode, and hence no current reaching the speaker. Using $|Z_{eq}| = |\frac{Z_L Z_C}{Z_L + Z_C}| = |\frac{iwL * \frac{1}{iwC}}{iwL + \frac{1}{iwC}}| = |\frac{iwL}{1 - w^2 LC}|$ we calculate the impedance of our LC tank circuit to be $|Z_{eq}| = 396.11\Omega$. Comparing this to the impedance of our LC tank circuit in our AM Radio Receiver circuit which is $|Z_{eq}| = 11.26\Omega$, it is clear that this error source made our data immeasurable.

Another major source of error for the Initial circuit was the Inductor that was used. All inductors are self resonant so choosing an inductor that has a self resonant frequency sufficiently higher than the operating frequency of the LC tank circuit is very important. However, we choose to use an axial inductor which may have had a resonant frequency close to 1340kHz. This self resonance phenomena would make our data inaccurate and imprecise if we were able to get readings using our antenna.

For the AM Radio Receiver Circuit, a major source of error was the Antenna that was used. The Antenna was connected to the Wavegen lead of the AD2. However, due to the thinness of the wire, it was not connected properly. It was only when the experimenter put their hands on the connection - strengthening the antenna) or connected the antenna to the LC tank circuit that there was a brief valid reading on the output of the LC tank circuit. Otherwise, there was only static noise at the output. Furthermore, the Copper wire coating had to be removed first before the antenna was connected to the AD2 Wavegen. The experimenters did not have the best tools to remove the coating so the signal may not have been transmitted to the antenna in the first place. These factors were very significant in making the data immeasurable.

Another source of error were the locations where we tried to capture AM radio waves. We chose the 3rd floor of the Physics & Astronomy building to take data for the Initial circuit and chose an apartment room and its balcony to take data for the AM Receiver circuit. The higher up the antenna is located, the better chance there is to receive a clear signal from nearby radio stations. Our choice of locations could have hindered the signals that we wanted to receive and thus made our data immeasurable.

Another flaw of our Initial Circuit was that it did not have any Operational Amplifiers to amplify the signal that we received for the diode or the speaker.

For the Audio Detection circuit, an AM signal with 100 kHz carrier wave and a 400 Hz message wave at 60% modulation and a 30 mV amplitude was input to the circuit. The Op-Amp Input signal was determined to have 27.18mV amplitude, 155.12Hz message signal frequency, and 99.36 kHz carrier wave frequency. The error for the carrier frequency was 0.64% and that of the message frequency was 64.75% when compared to their theoretical values. The error for the message frequency was attributed to the fact that our best fit was inaccurate due to the nature of the data while the low error for the carrier frequency was as predicted. The Op-Amp output signal was determined to have 2014.27mV amplitude, 443.35Hz message signal frequency, and

100.01kHz carrier wave frequency. The error for the carrier frequency was 0.013% and that of the message frequency was 0.76% when compared to their theoretical values. The error for the carrier frequency and the message frequency was as predicted.

The experimental gain of the Op-Amp was calculated to be 74.11 and had an error of 26.63% when compared to its theoretical value of 101. This error can be attributed to the unit gain bandwidth of our Op-Amp. The unit gain bandwidth of our Op-Amp was 10 MHz which means that the maximum gain that our Op-Amp can produce with a 100kHz carrier frequency is $\frac{10MHz}{100kHz} = 100$. Because the Op-Amp was operating at its limits, there was a drop in performance which resulted in the decreased experimental gain.

The message signal was determined to have a frequency of 441.00Hz using a best fit which resulted in an error of 0.23%. This was the expected result which indicates our Audio Detection circuit works as expected. The small error can be attributed to the output impedance and voltage swing of the Op-Amp. Because the Op-Amp is not realistically ideal, it has an output impedance which causes the voltage of the output signal to be shifted downwards as in Figure 17. Also, the voltage swing of the Op-Amp (the uncertainty on the output voltage) also introduces imprecision to our data. Nevertheless, this error source is very insignificant.

Many improvements can be made to this lab experiment. One improvement would be to use Amplifiers with higher unit gain bandwidths in order to increase amplification of our signal. This would decrease error from the impedance and the voltage swing of the Op-Amp and make our data more accurate. A second Operational Amplifier and a good quality speaker could also be purchased so that the output signal can be heard and the speaker can be integrated to the Audio Detection circuit. Another improvement would be to use a thicker material for the Antenna so that it can pick up radio waves much better and so that the connections to the leads on the Analog Discovery 2 are strong. This would allow the circuit to properly pick up signals. The circuits can also be tested on very high buildings where AM radio waves are very strong so that the LC tank circuit and the Antenna can pick up stronger signals. A final improvement could be to use a completely different circuit layout such as the three transistor radio circuit which may end up being a better design than our circuit for this application.

Resources

Diode Detector: AM Envelope Demodulator » Electronics Notes. (n.d.). Electronics Notes. Retrieved August 1, 2022, from https://www.electronics-notes.com/articles/radio/modulation/am-diode-detector-demodulator.php

Serych, J. (n.d.). Amplitude modulation. Wikipedia. Retrieved August 1, 2022, from https://en.wikipedia.org/wiki/Amplitude_modulation

Appendix 1: Formulas

Amplitude Modulation Formula

$$y(t) = [1 + mcos(2\pi f_m t + \phi)]Asin(2\pi f_c t) \quad (1)$$

Resonant Frequency Formula for LC Circuit

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

Voltage output across a non-inverting operational amplifier

$$v_0 = \frac{R_s + R_f}{R_s} v_g \quad (3)$$

Cutoff frequency Formula for RC circuit

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

Appendix 2: Python Code

Least Squares Fit over Op Amp Input/Output:

```
from google.colab import drive
drive.mount('/content/drive')
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import least_squares
#the number of data points are really high so it was hard to do a least
squares fit
#trimming the data
data2 = np.loadtxt("/content/drive/MyDrive/Output (1).csv", delimiter =
",", skiprows = 1)
t2 = data2[:,0]
t2 = t2 - t2[0]
c2 = data2[:,1]
plt.scatter(t2,c2)

data = np.loadtxt("/content/drive/MyDrive/Input (1).csv", delimiter = ",",
skiprows = 1)
t1 = data[:,0]
c1 = data[:,1]
```

```
t1 = (t1 - t1[0])
#plt.scatter(t1,c1)
def modulation(t, parameters):
  m = 0.6
  A = parameters[0]
  fm = parameters[1]
  fc = parameters[2]
  phi = parameters[3]
  y = (1 + m * (np.cos((2*np.pi*fm*t)+phi))) * A * (np.sin(2*np.pi*fc*t))
  return y

def get_residuals_mod(parameters, data, t):
  residuals = np.abs(data - modulation(t, parameters))
  return -residuals
#least squares fit
gp = [0.08,440., 100000., np.pi/2]
c1 = c1 - np.average(c1) #DC offset removed from voltage swing across op
amp
res_lsq = least_squares(get_residuals_mod, gp, args = (c1,t1))
parameters = res_lsq['x']
print(parameters)
plt.plot(t1, 2.5*modulation(t1, parameters), color = "red", label = "Best
Fit")
plt.plot(t1, 2.5*modulation(t1, parameters), color = "red", label = "Best
Fit")
plt.scatter(t1,c1, color = "blue", label = "Data" )
plt.plot(t1, modulation(t1, [ 0.03*1.8,440, 100000, np.pi/2]), color =
"green", alpha = 0.5, label = "Theoretical Fit")
plt.xlabel("Time(s)")
plt.ylabel("Voltage(V)")
plt.title("Voltage vs Time for Op Amp Input")
plt.legend()

gp = [0.08*100,440., 100000., np.pi/2]
c2 = c2 - np.average(c2) #DC offset removed from voltage swing across op
amp
res_lsq = least_squares(get_residuals_mod, gp, args = (c2,t2))
parameters = res_lsq['x']
print(parameters)
```

```
plt.plot(t1, 1.5*modulation(t1, parameters), color = "red", label = "Best
Fit")
plt.scatter(t2,c2, color = "blue", label = "Data")
plt.plot(t2, modulation(t2, [ 0.03*70,440, 100000, np.pi/2]), color =
"green", alpha = 0.5, label = "Theoretical Fit")
plt.xlabel("Time(s)")
plt.ylabel("Voltage(V)")
plt.title("Voltage vs Time for Op Amp Ouput")
plt.legend()
```

Least Squares Fit over Message/Information Signal:

```
from google.colab import drive
drive.mount('/content/drive')
import numpy as np
import matplotlib.pyplot as plt
from scipy.fftpack import fft
data = np.loadtxt('/content/drive/MyDrive/4BL
Data/Project/440Hz_Excel.csv' , delimiter = ',', skiprows=1)
time = data[:,0]
voltage = data [:,1]
plt.plot ( voltage, "blue")
plt.xlabel('Time(s)')
plt.ylabel('Voltage (V)')
plt.title ('Voltage vs. Time: 440Hz')
plt.legend()

plt.vlines(1200,0, 1.5 )
plt.plot(voltage)
in_vtrim = voltage[1200:8000]
in_ttrim = time[1200:8000]
in_vtrim = in_vtrim - np.average(in_vtrim)
plt.plot(in_ttrim, in_vtrim)

def modulation(t, parameters):
 C = parameters[0]
 A = parameters[1]
 w = parameters[2]
 phi = parameters[3]
 y =  C + A*np.sin(w*t + phi)
```

```
 return y

def get_residuals_mod(parameters, data, t):
 residuals = np.abs(data - modulation(t, parameters))
 return -residuals

#least squares fit
from scipy.optimize import least_squares
guess_parameters_mod = [5,1, 1500., 1.]

in_ttrim = in_ttrim - in_ttrim[0]
res_lsq = least_squares(get_residuals_mod, guess_parameters_mod, args =
(in_vtrim,in_ttrim))

parameters_mod = res_lsq['x']
print(parameters_mod)
plt.plot(in_ttrim, modulation(in_ttrim, parameters_mod), color = "red",
label = "best fit")

plt.plot(in_ttrim, modulation(in_ttrim, [ 0, 6.08202956e-01,
2*np.pi*440,-1.26896998e+00]), color = "green", label = "theoreticl")
plt.xlabel('Time(s)')
plt.ylabel('Voltage (V)')
plt.title('Votage vs. Time: Message Signal')


plt.legend()

plt.scatter(in_ttrim,in_vtrim,  label= "Data")
#voltage vs time message signal
```