5 Amplitude Modulation

5.1 Summary
This laboratory exercise has two objectives. The first is to gain experience in actually programming the USRP to act as a transmitter or a receiver. The second is to investigate classical analog amplitude modulation and the envelope detector.

5.2 Background

5.2.1 Amplitude Modulation
Amplitude modulation (AM) is one of the oldest of the modulation methods. It is still in use today in a variety of systems, including, of course, AM broadcast radio. In digital form it is the most common method for transmitting data over optical fiber [1].

If \( m(t) \) is a baseband “message” signal with a peak value \( m_p \), and \( A_c \cos(2\pi f_c t) \) is a “carrier” signal at carrier frequency, \( f_c \), then we can write the AM signal \( g(t) \) as

\[
g(t) = A_c \left[ 1 + \mu \frac{m(t)}{m_p} \right] \cos(2\pi f_c t) \tag{18}
\]

where the parameter \( \mu \) is called the “modulation index” and takes values in the range \( 0 < \mu \leq 1 \) (0 to 100%) in normal operation. For the special case in which \( m(t) = m_p \cos(2\pi f_m t) \) where \( f_m \) is the frequency of the message, we can write equation (1) as

\[
g(t) = A_c \left[ 1 + \mu \cos(2\pi f_m t) \right] \cos(2\pi f_c t)
\]

\[
= A_c \left[ \cos(2\pi f_c t) + \frac{\mu}{2} \left[ \cos(2\pi [f_c - f_m] t) + \cos(2\pi [f_c + f_m] t) \right] \right] \tag{19}
\]

In the above expression the first term is the carrier, and the second and third terms are the lower and upper sidebands, respectively. Fig. 42 and Fig. 43 is a plot of a 20 kHz carrier modulated by a 1 kHz sinusoid at 100% and 50% modulation.

![AM 100% Modulation](image)

**Fig. 42: AM Signal: Modulation Index = 1**
When the AM signal arrives at the receiver, it has the form

\[ r(t) = A_r \left[ 1 + \mu \frac{m(t)}{m_p} \right] \cos(2\pi f_c t + \theta) \]  

(20)

where the angle \( \theta \) represents the difference in phase between the transmitter and receiver carrier oscillators. We will follow a common practice and offset the receiver's oscillator frequency \( f_0 \) from the transmitter's carrier frequency, \( f_c \). This provides the signal

\[ r_1(t) = A_r \left[ 1 + \mu \frac{m(t)}{m_p} \right] \cos(2\pi f_{IF} t + \theta) \]  

(21)

where the so-called “intermediate” frequency (IF) is given by \( f_{IF} = f_c - f_0 \). The signal \( r_1(t) \) can be passed through a bandpass filter to remove interference from unwanted signals on frequencies near \( f_c \). Usually the signal \( r_1(t) \) is amplified since \( A_r < A_c \) due to signal attenuation as it moves through the transmission medium.

Demodulation of the signal \( r_1(t) \) is most effectively carried out by an envelope detector. An envelope detector can be implemented as a rectifier followed by a lowpass filter. The envelope \( A(t) \) of \( r_1(t) \) is given by

\[ A(t) = A_r \left[ 1 + \mu \frac{m(t)}{m_p} \right] = A_r + \frac{\mu A_r}{m_p} m(t) \]  

(22)
5.3 Pre-Lab

5.3.1 Transmitter

The task is to add blocks as needed to produce an AM signal, and then to pass the AM signal into the while loop to the Write Tx Data block. A template for the transmitter has been provided in the file AM_Tx_Template.vi (Fig. 44). This template contains six interface controls, two waveform graphs to display your message signal and scaled amplitude modulated signal, and “message generator” controls set to produce a message signal consisting of three tones. The three tones are initially set to 1, 2, and 3 kHz, but these frequencies can be changed using the message generator front-panel controls.

\[ g_I(nT) = A_c \left[ 1 + \mu \frac{m(t)}{m_p} \right] \quad \text{(23)} \]

And

\[ g_Q(nT) = 0 \quad \text{(24)} \]
You will explore other modulation methods in subsequent lab projects that use both components.

The baseband signal is expressed as

\[ \bar{g}(nT) = g_I(nT) + j \ g_Q(nT) \]  \hspace{1cm} (25)

The signal transmitted by the USRP is

\[ g(nT) = A_c \ g_I(nT) \cos(2\pi f_c t) + A_c \ g_Q(nT) \cos(2\pi f_c t) \]  \hspace{1cm} (26)

These values are entered in the Tx Front Panel (Fig. 44) in the following fields

- \( f_c \) is the carrier frequency.
- Sampling interval \( T \) is the reciprocal of the “IQ rate.”

Note that the signal \( g(t) \) produced by the USRP is a continuous-time signal; the discrete-to-continuous conversion is done inside the USRP.

b) The message generator creates a signal that is the sum of a set of sinusoids of equal amplitude. You can choose the number of sinusoids to include in the set, you can choose their frequencies, and you can choose their common amplitude. The initial phase angles of the sinusoids are chosen at random, however, and will be different every time the VI runs. Get the data values of the generated signal by using the “Get Waveform Components” VI (Fig. 45) for amplitude modulation operations.

c) Set up a “MathScript Node” (Fig. 46) with data values of the generated signal \( \{m\} \), maximum value of the generated signal \( \{mp\} \), and modulation index \( \{mu\} \) as inputs. Use “Array Max and Min” VI (Fig. 47) to get the maximum value of the generated signal, and the “Modulation Index” control provided to set the modulation index \( \{mu\} \). Use equations (23), (24), and (25) to set up the text-based script to get the baseband signal \( \{b\} \).
d) There is one practical constraint imposed by the D/A converters in the USRP: The maximum magnitude of the transmitted signal $|g(nT)|$ needs to have a maximum scaled value of 1. Set up a text-based script by dividing the baseband signal $\{b\}$ by the maximum of its absolute value ($\text{max}(\text{abs}(b))$) to get the scaled baseband signal $\{A\}$.


e) The USRP is designed to transmit using a quadrature modulation approach. So in order to use the radio to transmit an AM signal, it is necessary to represent the signal as a complex sequence. The quadrature modulation then transmits the real and complex sequences using two orthogonal waveforms. The real part is sent using a cosine carrier and the complex part using a sine function as the carrier. Set up a text-based script to convert the scaled amplitude modulated signal from 1D double $\{A\}$ to 1D complex double form $\{G\}$. The 1D complex double form is attained by multiplying the 1D double form by $\{e^{(j*0)}\}$.

f) Set up both the forms of the scaled baseband signal as outputs of the MathScript Node. Plot the scaled baseband signal $\{A\}$ by using the “Baseband Signal” waveform graph provided, and input the complex form $\{G\}$ to the “niUSRP Write Tx Data” VI (Fig. 48) to be transmitted.
Fig. 48: niUSRP Write Tx Data VI

5.3.2 Receiver
A template for the receiver has been provided in the file AM_Rx_Template.vi (Fig. 49). This template contains the six interface controls and two waveform graphs to display the received amplitude modulated signal and the demodulated baseband output.

Rx Programming Notes:
a) Plot the received amplitude modulated signal from the “niUSRP Fetch Rx Data” VI (Fig. 50) using the “Rx AM Signal” waveform graph provided.

g) Save your transmitter in a file whose name includes the letters “AM_Tx” and your initials.

Note: Modulation with the carrier occurs after the baseband signal is sent to the buffer for transmission. To visualize the amplitude modulated signal, you may plot the waveform received at the receiver end.
b) Get the data values of the signal received from the “niUSRP Fetch Rx Data” VI (Fig. 50) by using a “Get waveform components” VI (Fig. 45) so as to perform filtering operations.

c) To remove unwanted interferences around carrier frequency, design a fifth order “Chebyshev” band-pass filter (Fig. 51) with a high cutoff frequency of 105 kHz, a low cutoff frequency of 95 kHz, pass-band ripple of 0.1 dB, and a sampling frequency equal to the “actual IQ rate” obtained from the niUSRP Configure Signal VI.

d) Extract the real part of the complex filtered signal from the output of the Chebyshev band-pass filter using the “Complex to Real/Imaginary” VI (Fig. 52). The real part is expressed as shown in equation (21).
e) Use “Absolute Value” VI to take the absolute value of the real part of the filtered signal for full-wave rectification.

![Absolute Value VI](image)

Fig. 53: Absolute Value VI

f) To filter out high frequencies to complete envelope detection, design a second order “Butterworth” low-pass filter (Fig. 54) with a low cutoff frequency of 5 kHz, and a sampling frequency the same as the “actual IQ rate” obtained from the niUSRP Configure Signal VI.

![Butterworth Filter VI](image)

Fig. 54: Butterworth Filter VI

g) Build a waveform from the data values of the output of the low-pass filter designed above by using a “Build Waveform” VI, setting the sampling time interval same as that of the received waveform. Plot the waveform obtained with the “Baseband Output” waveform graph provided.

h) Save your receiver in a file whose name includes the letters “AM_Rx” and your initials.
5.4 Lab Procedure

1. Run LabVIEW and open the transmitter and receiver VIs that you created in the pre-lab.
2. Connect the computer to the USRP using an Ethernet cable.
3. Open the NI-USRP Configuration Utility found in the National Instruments directory under programs files as shown in Fig. 2. Be sure to record the IP addresses since you will need them to configure your software.

![Select All Programs from menu](image1)

![Select the NI-USRP Configuration Utility from the National Instruments directory](image2)

![Select Find Devices and record the IP address of the radio or radios since you will need them to configure the software in the lab.](image3)

**Fig. 55: Finding the IP Address: Radio Connectivity Test**

If the IP address does not appear in the window then check your connections and ask the Teaching Assistant (TA) to verify that the LAN card has been configured correctly.

4. Connect a loopback cable between the TX 1 and RX 2 antenna connectors. Remember to connect the attenuator to the receiver end.

![Fig. 56: Broadcast Setup](image4)

5. Ensure that the transmitter VI is set up according to Table VI.
### Table VI – Transmitter Settings

<table>
<thead>
<tr>
<th>Field</th>
<th>Setting</th>
<th>Field</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Name</td>
<td>192.168.10.x</td>
<td>Message Length</td>
<td>200,000 samples</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>915.1 MHz</td>
<td>Modulation Index</td>
<td>1.0</td>
</tr>
<tr>
<td>IQ Rate</td>
<td>200 kHz</td>
<td>Start Frequency</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Gain</td>
<td>20 dB</td>
<td>Delta Frequency</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Active Antenna</td>
<td>TX1</td>
<td>Number of Tones</td>
<td>3</td>
</tr>
</tbody>
</table>

#### Important set-up notes:
- Make sure the global set-up configuration has been performed before interfacing with the USRPs.
- Make sure the Tx and Rx VIs are always set to the same carrier frequency whenever you pair them up to communicate.
- Transmission should start only after receiving workstations are ready to receive.
- Verify that device name fields in both Tx and Rx VIs are set to the IP address of the URSP in use.
- Make sure to connect the provided attenuator between the receiver USRP’s Rx input and the antenna/loopback-cable. The attenuator is used to decrease the power level of the transmitted signal in order to avoid a high power signal at the receiver’s end, due to Rx and Tx inputs’ proximity to each other.

6. Run the transmitter VI. LED “A” will illuminate on the USRP if the radio is transmitting. Use zoom operations to check the message and scaled baseband waveforms on the transmitter VI front panel.
7. Stop the transmission by using the large “STOP” button on the front panel.
   Note: Using the “STOP” button on front panel rather than stopping from the “Abort Execution” button on the menu bar ensures that the USRP is stopped cleanly.
8. Ensure that the receiver VI is set up according to Table VII.

### Table VII – Receiver Settings

<table>
<thead>
<tr>
<th>Field</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Name:</td>
<td>192.168.10.x</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>915 MHz</td>
</tr>
<tr>
<td>IQ Rate:</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Gain:</td>
<td>0 dB</td>
</tr>
<tr>
<td>Active Antenna:</td>
<td>RX2</td>
</tr>
<tr>
<td>Number of Samples</td>
<td>200,000 samples</td>
</tr>
</tbody>
</table>

9. Run the receiver VI. LED “C” will illuminate on the USRP if the radio is receiving data.
10. Next, run the transmitter.
11. Use zooming operations from the graph palette to zoom into the “Rx AM Signal” and “Baseband Output” waveforms on the receiver front panel. The demodulated AM waveform “Baseband Output” should be identical to the “Baseband Signal” waveform, except for scaling (receiver output has a DC offset) and marginal noise.
5.4.1 Worksheet: The Effect of Varying the Modulation Index

1. Set the transmitter to use one of the three tones. Please note that using more than one tone will make it very hard to make the observations.
2. Set the Start Frequency to 1 kHz.
3. Set the transmitter VI modulation index to the first value in Table VIII.
4. Start the transmitter VI.
5. Observe the demodulated signal i.e. “Baseband Output” waveform on the receiver VI. Note the peak to peak voltage in Table VIII.
6. Stop the receiver VI. Update the modulation index to the next value in Table VIII and repeat steps 4 through 6 until the table is complete.

Table VIII – Modulation Index Observations

<table>
<thead>
<tr>
<th>Modulation Index</th>
<th>Amplitude (Peak to Peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

![Baseband Output](image.png)

\[ V_{\text{peak-to-peak}} = \mu = 0.1 \]
5.4.2  Worksheet: The Effect of Varying the Receiver Gain.

Warning: Too much receiver gain will overload the receiver A/D converters.

1. Set the transmitter to use one of the 3 tones. Please note that using more than one tone will make it very hard to make the observations.
2. Set the transmitter VI gain to 20 dB.
3. Set the receiver VI gain to the first value in Table IX.
4. Run the receiver VI, and then the transmitter VI.
5. Observe the demodulated signal i.e. “Baseband Output” waveform. Note the peak to peak voltage in Table IX.
6. Stop the receiver VI. Update the receiver gain to the next value in Table IX and Repeat steps 4 through 6 until the table is complete.

<table>
<thead>
<tr>
<th>Receiver Gain (dB)</th>
<th>Voltage (Peak-to-Peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
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</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Table IX – Receiver Gain Observations

Baseband Output

$V_{\text{peak-to-peak}}$

Tx Gain = 20dB
Rx Gain = 10dB

5.5 Lab Write-up

Performance Checklist
Amplitude Modulation

Short Answer Questions
1. What is the relation between the message bandwidth and the IF and baseband filter bandwidths?

2. What is the effect of varying the modulation index?

3. What is the effect of varying the transmitter and receiver gain?

Performance Measures

<table>
<thead>
<tr>
<th>Task</th>
<th>Standards</th>
<th>Sat/Unsat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware Setup</td>
<td>Working setup for all with Loopback-cable.</td>
<td></td>
</tr>
<tr>
<td>Running VIs</td>
<td>Successful transmission and reception of tones.</td>
<td></td>
</tr>
<tr>
<td>Data Collection</td>
<td>Collect data to answer Short Answer Questions.</td>
<td></td>
</tr>
</tbody>
</table>

Discussion
Did all configurations perform as expected?
Did you have any difficulties completing the lab?
Did your TA provide enough guidance?
Do you have any recommendations to improve the lab?
5.6 References