University of Pennsylvania

Department of Electrical and Systems Engineering

ESE206: Electrical Circuits and Systems II – Lab

Amplitude Modulated Radio Frequency Transmission System

Mini-Project

Part 2: Receiver and Demodulator

Introduction

This mini-project is the continuation of the AM Radio Transmission System lab you did earlier. In this lab you will build the receiver section (part 2), shown in Fig. 1 below. The goal of the circuit of part 2 is to recover the modulation signal $v_m(t)$ that contains the information of interest (e.g. the voice or music transmitted over the radio waves).

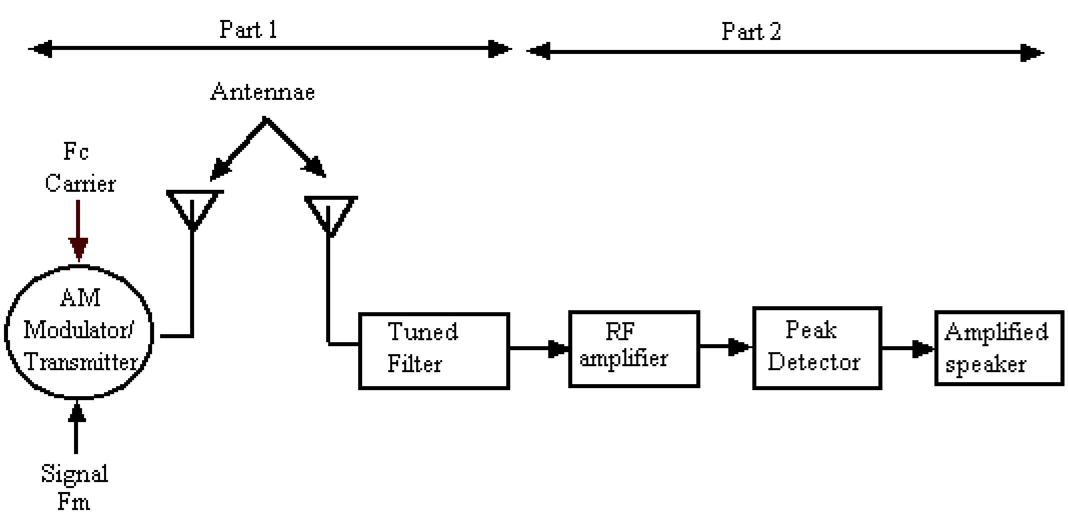


Figure 1: Elements of a basic AM Radio Transmission System

You will learn how to demodulate an AM signal, using a peak detector (or envelope detector), and how to amplify this signal using an audio amplifier. Once you have built these elements you will put the modulator (built during part 1) and the demodulator together and test out the overall system of Fig. 1.

This lab is more ambitious than any of the previous labs. It makes use of your knowledge gained during the previous labs. In order the finish on time, you will need to prepare the pre-lab carefully and review part 1 ("AM Transmitter/Receiver" of this mini-project).

Distortion

Signals undergo distortion as a result of non-linearity in the circuits. A good system should introduce as little distortion as possible. When you did part 1 of this lab, you noticed that the modulated signal could get distorted when the modulator is not adjusted properly. Further distortions will be introduced during the demodulation process. In this lab you will learn how to specify the amount of distortion of a signal. However, first lets introduce some basic concepts about distortion.

We will consider a pure sinusoidal signal. When no distortion occurs the spectrum of this signal should be a component at the frequency of the sinusoid (called the fundamental frequency f_0), shown in Fig. 2a. As a result of non-linearities that are introduced at several stages of the processing chain, the signal won't be a pure sinusoid anymore. This results in a spectrum that has components besides the fundamental frequency f_0. These frequency components are usually at multiples of the fundamental frequency and are called harmonics. For instance the components at $2f_0$, $4f_0$, etc. are called the "even" harmonics while the ones at $3f_0$, $5f_0$, etc. are called "odd" harmonics. Fig. 2b shows the spectrum of a distorted sinusoid. The larger harmonics the spectrum has the larger the distortion of the pure sinusoid will be.

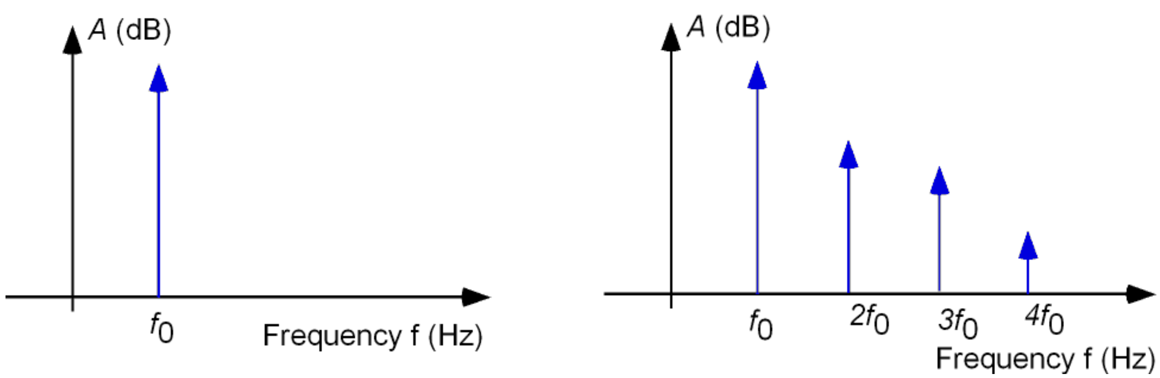


Figure 2: Spectrum of (a) a pure sinusoid and (b) a distorted sinusoid.

Total Harmonic Distortion (THD)

The distortion is usually expressed by the quantity, called "total harmonic distortion" or *THD*. This is defined as the ratio of the power in the harmonics over the power of the signal. The power is related to the square of the amplitude of the frequency components. This allows us to write the *THD* (%) as,

$$THD = \sqrt{\frac{V(2f_0)^2 + V(3f_0)^2 + V(4f_0)^2 + V(5f_0)^2 + ...}{V(f_0)^2}} \quad (1)$$

Since the *THD* is obtained by taking a ratio, it does not matter whether the amplitude is expressed in *RMS* or as a peak amplitude. As can be seen in Fig. 2, the magnitude of the frequency components in the spectrum is usually given in dB. In order to find the magnitude (in V) of each component one has to convert from dB into voltage. This can be easily done through the definition of dB:

$$A = 20.\log_{10}(V) \text{ (in dB)} \quad (2)$$

$$or \ \ V = 10^{A/20} \text{ (in Volt)} \quad (3)$$

As can be seen from Eq. (1) the *THD* is given by the ratio of the harmonics over the fundamental component. This implies that the *difference* in dB between the fundamental and the harmonics determines the amount of distortion. One can give the fundamental component a reference level of e.g. 0 dB. An example is shown in the figure below.

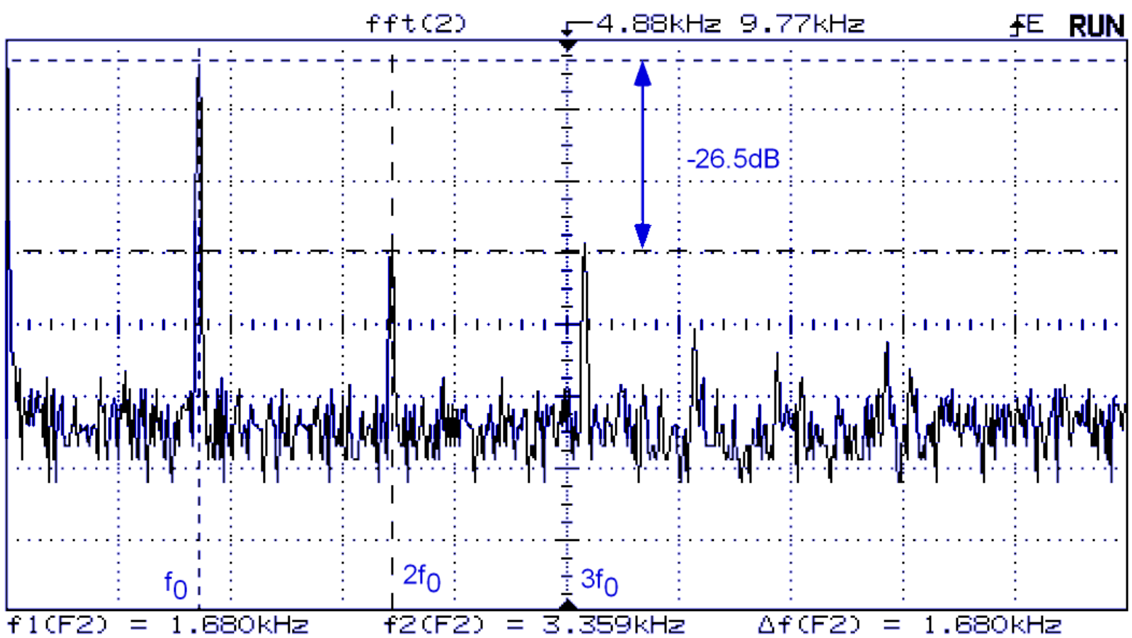


Figure 3: Spectrum of a distorted sinusoid with fundamental frequency f_0=1.68kHz.

The fundamental frequency is f_0=1.68kHz. The two most pronounced harmonics are the 2nd and the 3rd ones which are each about 26.5dB below that of the fundamental component. Using the expressions (1) and (3) one finds that the *THD* of 6.7%. This is a pretty bad *THD*. For high quality audio systems the *THD* is typically 0.01% and for digital audio systems is may be as low as 0.002% over the audio frequency range from 20 to 20 kHz.

Receiver with peak detector and audio amplifier

The details of the receiver circuits are shown in Fig. 4. The first section consists of an antenna and a LC tuned filter followed by a wide-bandwidth amplifier (LF 356 with a gain-bandwidth product of 5 MHz) . The tuned circuit selects the carrier frequency. The next section is a simple peak detector that is used to demodulate the AM signal. It consists of a diode followed by a capacitor in parallel with a resistor (see section3.5.4 "Rectifier with a Filter Capacitor or Peak Detector" in the textbook by Sedra-Smith, 5^{th} ed.). This circuit, also called an envelope detector, extracts the modulating signal. The final stage is an audio amplifier. We have implemented this with an operational amplifier that has a gain of 10. Notice that a coupling capacitor C_c (also called a DC blocking capacitor) has been added after the peak detector. This is done to block the DC component in the rectified signal. This DC component does not carry information and can saturate the audio amplifier. Also, the speaker is connected through a coupling capacitor C_3 to the output of the amplifier. The audio amplifier is usually a power amplifier that is capable to deliver sufficient power to the speakers. For the purpose of this lab, we are using the 741 as an audio amplifier. This is done since we are not interested in providing a lot of power to the speaker in contrast to a conventional audio amplifier that is designed for large power delivery. When you measure your circuit you will notice that you won't be able to deliver a large signal to the speaker since the op-amp won't be able to deliver the necessary current (but for our purpose that is ok).

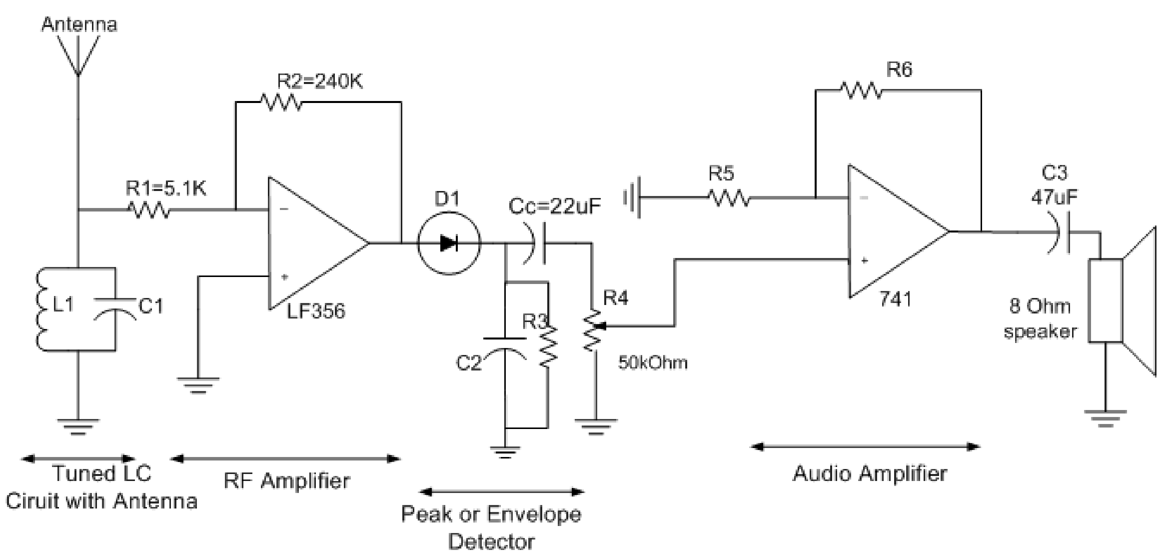


Figure 4: Receiver circuit consisting of an amplifier stage, a peak-detector and an audio amplifier.

The peak detector, shown in Fig. 5 can be considered as a half-wave rectifier with a low-pass filter (*RC* circuit). The value of the *RC* circuit determines the peak-to-peak value of ripple V_r of the rectified signal, according to the following expression,

$$V_r \approx V_p (1 - e^{-1/f_c R_3 C_2}) \qquad (4)$$

in which V_p is the peak value of the incoming, signal and f_c the frequency of the signal. When using the circuit to demodulate an AM signal, the *RC* time constant is chosen such that,

$$2\pi f_C > 1/R_3C_2 > 2\pi f_m \qquad (5)$$

in which f_c and f_m is the carrier and modulating frequency, respectively. The first condition determines the ripple of the signal while the second inequality assures that the modulating signal with frequency f_m passes through the peak detector (notice that the R_3-C_2 circuit forms a low pass filter. To keep the ripple small, you want to make sure that the you select the R_3C_2 such that $2\pi f_C >> 1/R_3C_2$ without violating the second condition ($1/R_3C_2 > 2\pi f_m$). This condition assures that the modulating signal will pass without being attenuated by the parallel R_3C_2 circuit.

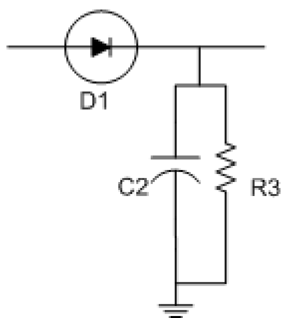


Figure 5: Envelope or peak detector

We will use as the carrier signal a sinusoid with a frequency f_c of about 100 kHz and as the modulation signal a sinusoid with frequency f_m of about 5000 Hz.

Pre-lab assignment

1. Read the introduction of part 1 on "AM Radio Frequency Transmission System"
2. Consider the following spectrum of a distorted sinusoid. Calculate the *THD* (in %) of this signal. Show how you got your result.

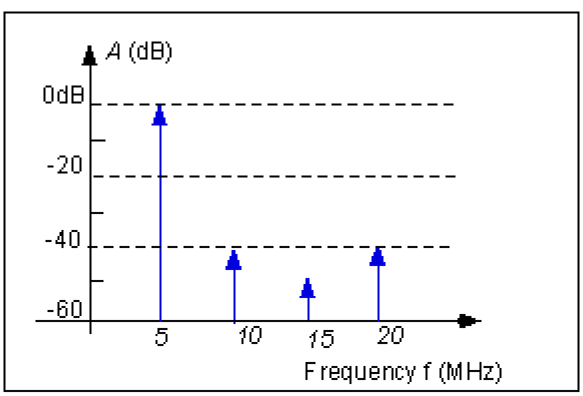
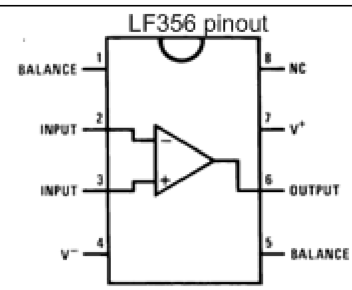


Figure 6: Spectrum of a distorted sinusoidal signal of 5 kHz.

3. Read the section on peak detectors in your textbook section 3.5.4 (Microelectronics by Sedra and Smith).
4. The LF356 amplifier has a gain bandwidth product of 5 MHz. What is the bandwidth of the inverting RF amplifier configuration shown in Fig. 4?
5. Design of a peak detector:
    a. Find the value of C_2 and R_3 of the peak detector (Fig. 5), using expression (5). Use a value of R_3 in the range of 2-10 kOhm and select a capacitor according to expression (5).
    b. For the selected values of R_3 and C_2 calculate the corresponding ripple V_r/V_p (see expression (4). Assume a frequency f_c of 100 kHz.
6. Design the audio amplifier, shown in Fig. 4 such that it has a gain of 11. Use resistor values in the range of 1 to10 kOhm.
7. Coupling capacitor C_3:
    a. What is the role of the coupling capacitor?
    b. This capacitor forms a high pass filter. What is the lowest frequency that can be passed un-attenuated, assuming that the speaker has a resistance of 8 Ohm?

In-lab assignment

1 – OpAmp 741
1 – LF356 Op-Amp
1 – Diode 4148
1 – Inductor
1 – Capacitors: 47 uF and others (TBD)
2 – Capacitors: 0.1 uF as decoupling caps
1 – Resistors: 5.1k, 240 kOhm and others (TBD)
1 – Potentiometer of 50 kOhm



Note: You will be using the modulator circuit that you constructed during the first part of this mini-project (Fig. 7 part 1).

Procedure:

1. Check that you still have the modulator circuit of the first part of this mini-project, shown below. You should add a decoupling capacitor between the two power supply pins (7 and 4) of the op-amp and the ground. Connect all ground wires to a single point on your protoboard to reduce the noise.

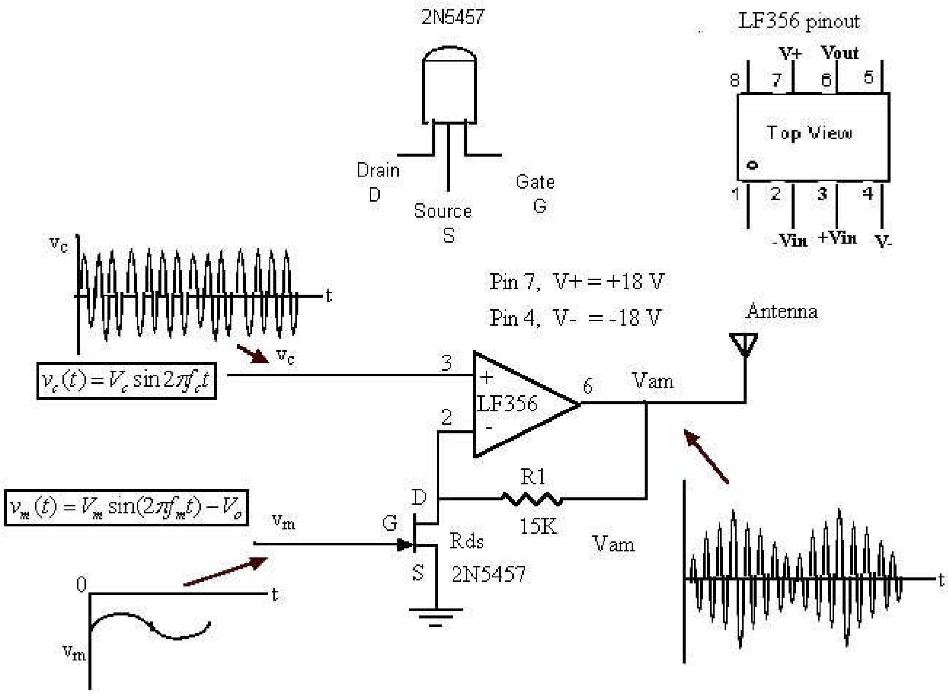


Figure 7: AM Modulator/transmitter circuit (built during part 1 of the project).

2. Next you will construct the receiver and demodulator circuit of Fig. 4. **Construct this circuit in a corner of the protoboard as far from the modulator circuit as possible to reduce interference**. Start with the tuned LC circuit that you designed earlier in part 1 of the project.

3. Construct the amplifier using the LF356 as shown in Fig. 4. The pins of the amplifier are given in the parts list (Fig. 7). Use a voltage of +12V, and –12V for the power supply. Place 0.1 uF decoupling caps between the power supply pins (4 and 7) and ground. Check that the amplifier functions properly. You can apply a small input voltage and measure the output voltage. Notice that the amplification is about 50. *Do not saturate the amplifier*.

4. Construct the peak detector. Use for the resistor R3 a 50 kOhm potentiometer, so that you can adjust the resistor value to optimize the rectified and filtered signal. Be careful to use short connections and use a single point to which you connect all the grounds of your instruments and circuit. When finished, you should ensure that the receiver works properly. You can apply a small AM modulated sinusoidal signal at the input of the operational amplifier and verify the operation. To generate the AM signal, use the HP Function generator and select an AM signal (carrier frequency of 100 kHz, modulation frequency of 5000 Hz and modulation depth of 50%). Display the AM signal and the output of the peak detector on the oscilloscope. Take a snapshot of the waveforms.

[For use of the function generator see:
http://www.ese.upenn.edu/rca/instruments/HPfuncgen/WaveFormGen/WaveFormGen.html#b.%20Example%202:%20Advanced]

5. Construct the audio amplifier. When finished check the operation and verify that it amplification is 11. Display the output on the oscilloscope and take a snapshot.

6. When all the circuits work properly (RF amplifier, peak detector and the audio amplifier) you can connect these together.

7. Verify that the modulator/transmitter circuit that you built in a previous lab still works properly. For the carrier signal $v_c(t)$ use the same frequency as the one you used in part 1 of the previous lab (this should be around 100 kHz - see your lab notebook or report). Use the HP 33120 function generator for the carrier signal. For the modulation signal $v_m(t)$ use a sinusoid of 5000 Hz with an offset voltage of –1V. Use the Krohn-Hite 1200A function generator for this signal. As you did in the previous lab, observe the output signal v_{am} while you adjust the amplitude V_m and the offset voltage V_o of the modulation signal in order to produce a maximum linear output of about 2 Vp-p for v_{am}.

8. Connect a 1 to 2-ft long wire as antenna to the transmitter and receiver circuits (Fig. 1). Place the antennas parallel to each other, at a close distance (if necessary twist the two wires to get better coupling). Since the transmission and reception efficiency at these relatively low frequencies is low, we suggest that you couple the output of the transmitter to the input of the receiver through a 15 pF capacitor. This will increase the received signal considerably.

Display the output signal of the audio amplifier together with the transmitted AM signal $v_{am}(t)$ on the oscilloscope. Verify that the output signal corresponds to the modulation signal. When the output of the audio amplifier is a scaled version of the modulation signal, your circuit works properly. Record the amplitude of the waveforms. Take also a snapshot of the waveforms.

9. Connect the output of the audio amplifier to the input of a speaker, using a 47 μF coupling capacitor C_3. Listen to the output signal. Change the frequency of the modulation signal from 5000 to about 1000 Hz, you should hear the different tone being transmitted. Since the output amplifier is a regular op-amp (uA 741) the output current is limited to about 20mA. This will also limit the maximum amplitude you can put over the speaker. Adjust (reduce) the volume-control potentiometer R4 susch that the output signal is relatively distortion free.

10. When the received output signal looks undistorted (sinusoidal), display the spectrum of the output signal using the FFT function of the oscilloscope. If needed adjust the amplitude, the off-set voltage of the modulating frequency, or the value of the potentiometer R_4 until the output looks undistorted. Observe the fundamental and the harmonics in the spectrum. Take a snapshot of the spectrum and write down the horizontal and vertical scales.

To use the FFT function on the oscilloscope, see also
http://www.seas.upenn.edu/~ese206/labs/FFTScopeTutorialPart2.pdf

Report:

Under the experimental results include:

a. RF amplifier and peak detector.
    i. Circuit with component values.
    ii. Measured output characteristic for an AM input signal.
b. Audio amplifier:
    i. The circuit
    ii. Output signal for an AM input signal
    iii. Spectrum of the output signal, corresponding to the time domain signal shown in ii. above.
c. Calculation of the power delivered by the audio amplifier to the 8 Ohm resistor (speaker) for the signal shown in ii above.
d. Calculation and value of the *THD* of the output signal.

Modified and Updated by Jan Van der Spiegel
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