

University of Pennsylvania

Department of Electrical and Systems Engineering

ESE206: Electrical Circuits and Systems II – Lab

Amplitude Modulated Radio Frequency Transmission System

Mini-Project

Receiver and Demodulator

Goals

1. Getting familiar with Amplitude Modulated signals
2. Learn how to demodulate an AM signal
3. Build a demodulator using a peak detector
4. Learning to characterize distortion (Total Harmonic Distortion) using Fast Fourier Transform (FFT)

Introduction

An Amplitude Modulated Radio Frequency Transmission system consists of a modulator in which a sinusoidal high frequency carrier waveform $\cos(2\pi f_c t)$ is amplitude modulated (AM) by a lower frequency signal $v_m(t)$, containing the information to be transmitted. In case of an AM radio transmission, the signal $v_m(t)$ is the voice or music while the carrier frequency f_c is the frequency at which one tunes the radio, e.g. 1060 kHz. The expression of the AM signal is then be written as,

$$v_{am}(t) = [(A + v_m(t))] \cos(2\pi f_c t) \quad (1)$$

in which A is large enough so that $[(A + v_m(t))]$ never becomes negative. Let us assume that the modulating signal is a sinusoidal signal of frequency f_m . In that case the AM signal can be expressed as,

$$v_{am}(t) = [(A + V_m \cos(2\pi f_m t))] \cos(2\pi f_c t) = A[1 + m \cos(2\pi f_m t)] \cos(2\pi f_c t) \quad (2)$$

In this expression m is called the "modulation index" that is always less or equal to 1. An example of a modulated signal $v_{am}(t)$ is shown in Fig. 1 below. Notice that the envelope of the high frequency signal corresponds to the modulating signal $v_m(t)$.

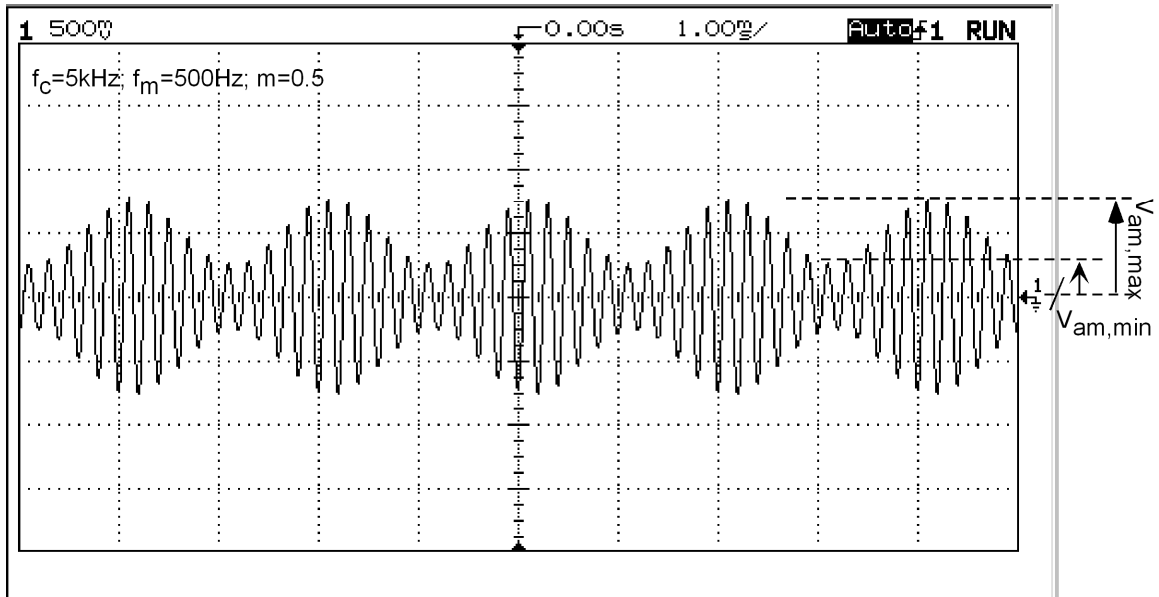


Figure 1: Am Modulated Signal $v_{am}(t)$ with ($f_m=500$ Hz, $f_c=5$ kHz and $m=0.5$)

In case of radio signals, the AM signal is transmitted over the air, using an antenna. At the receiver end, an antenna picks up the AM signal and demodulate it in order to recover the original signal $v_{am}(t)$ that contains the information of interest. In this mini-project you will build the receiver section (part 2), shown in Fig. 2 below.

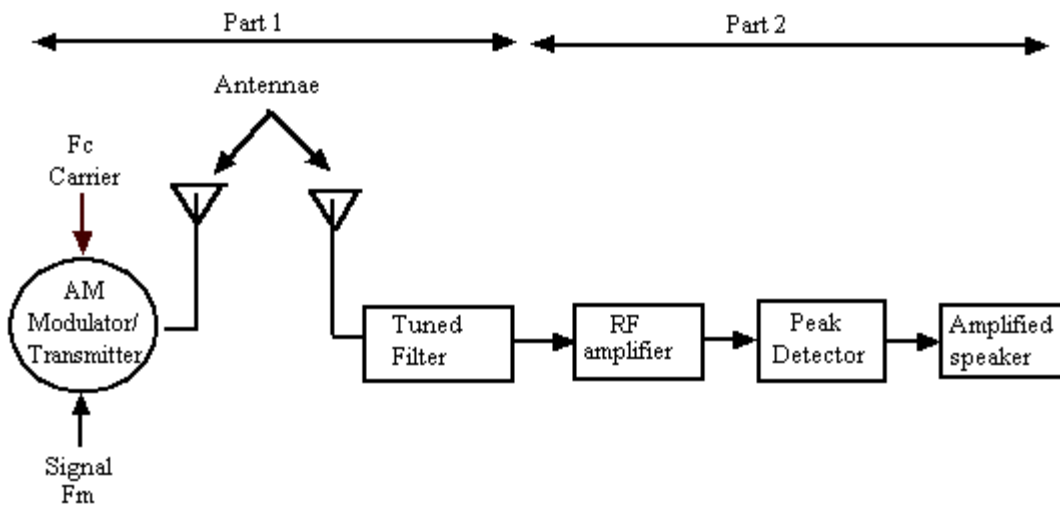


Figure 2: Elements of a basic AM Radio Transmission System

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 test them out by using a AM signal.

This lab is more ambitious than any of the previous labs. It makes use of your knowledge gained during the previous labs. In order to finish on time, you will need to prepare the pre-lab carefully.

Distortion

Signals undergo distortion as a result of non-linearity in the circuits. A good system should introduce as little distortion as possible. Distortion is introduced during the modulation and transmission of the signal. 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 let's 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. 3a. 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. 3b shows the spectrum of a distorted sinusoid. The larger harmonics the spectrum has the larger the distortion of the pure sinusoid will be.

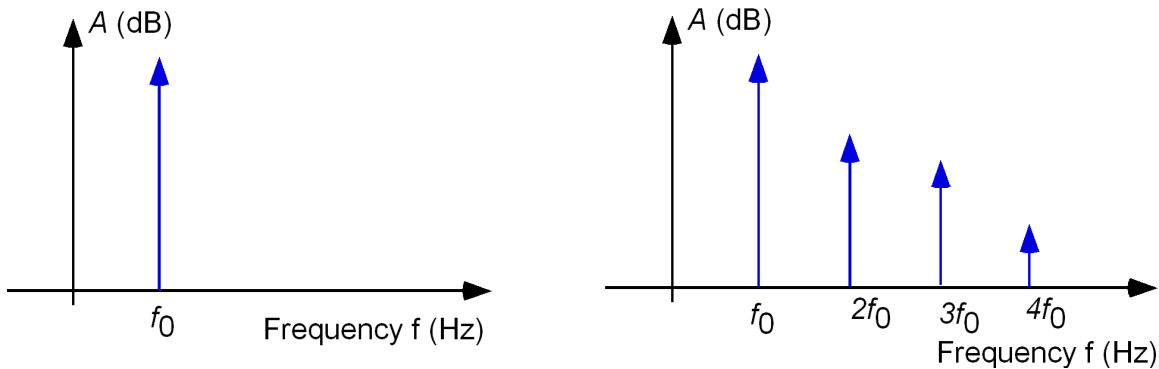


Figure 3: Spectrum of (a) a pure sinusoid and (b) a distorted sinusoid.

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,

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

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. 4, 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:

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

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

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.

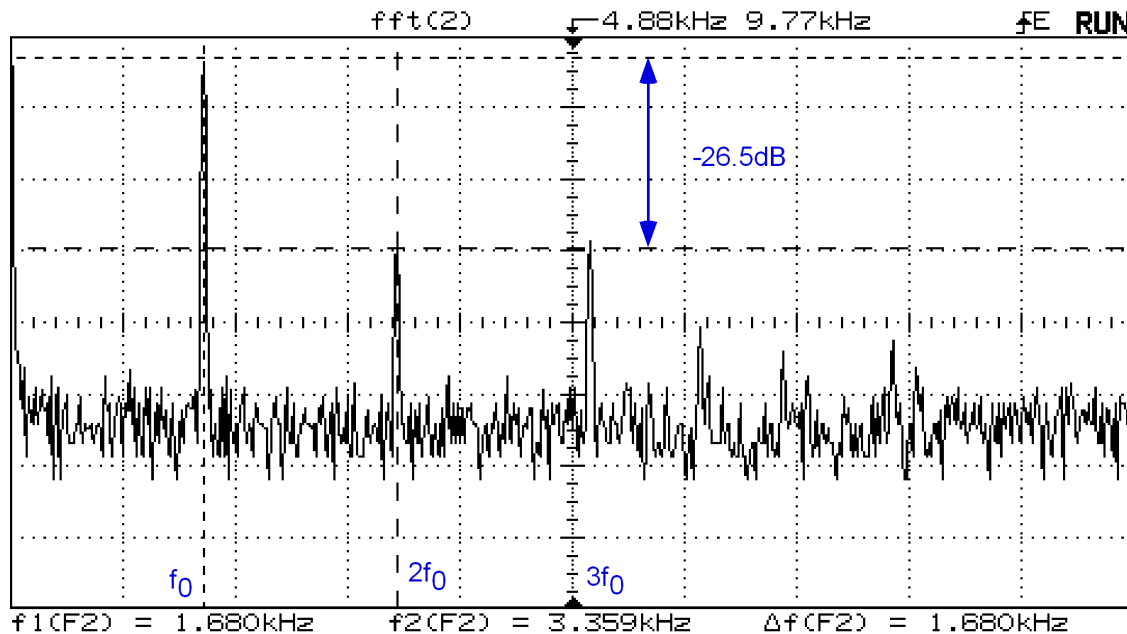


Figure 4: Spectrum of a distorted sinusoid with fundamental frequency $f_0=1.68\text{kHz}$.

The fundamental frequency (or 1st harmonics) is $f_0=1.68\text{kHz}$. 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. 5. 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 section 3.5.4 “Rectifier with a Filter Capacitor or Peak Detector” in the textbook by Sedra-Smith, 5th 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).

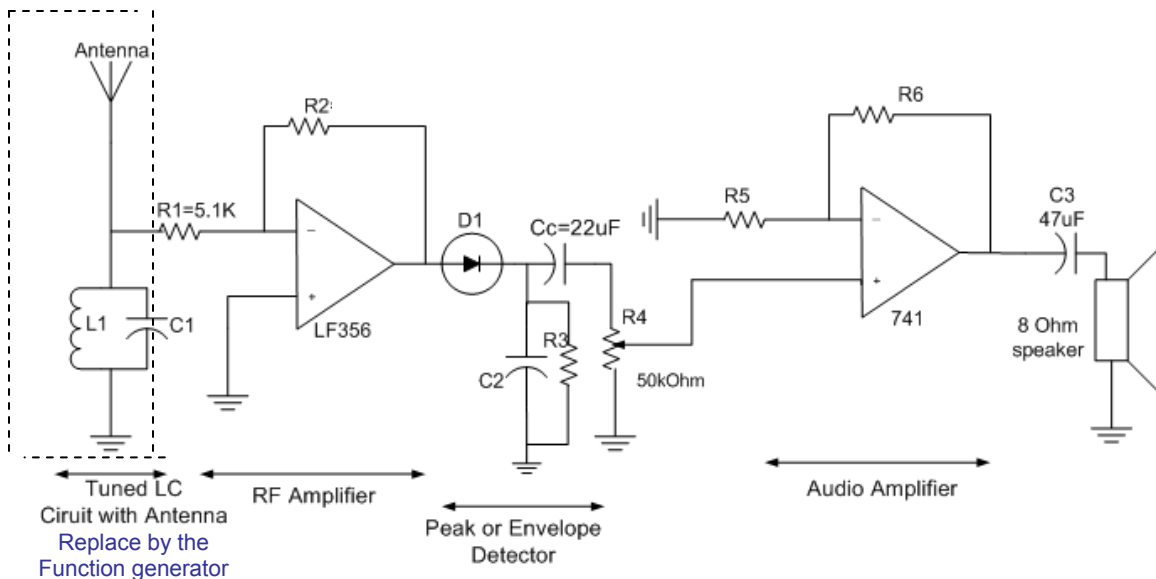


Figure 5: Receiver circuit consisting of an amplifier stage, a peak-detector and an audio amplifier.

The peak detector, shown in Fig. 6 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,

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

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,

$$2\pi f_c > 1/R_3 C_2 > 2\pi f_m \quad (5)$$

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 $2\pi f_c \gg 1/R_3C_2$ 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.

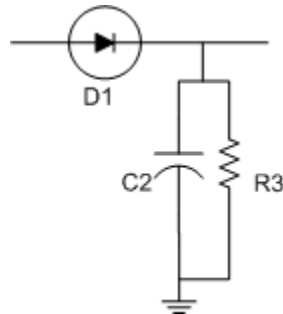


Figure 6: Envelope or peak detector

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. Consider the following spectrum of a distorted sinusoid. Calculate the *THD* (in %) of this signal. Show how you got your result.

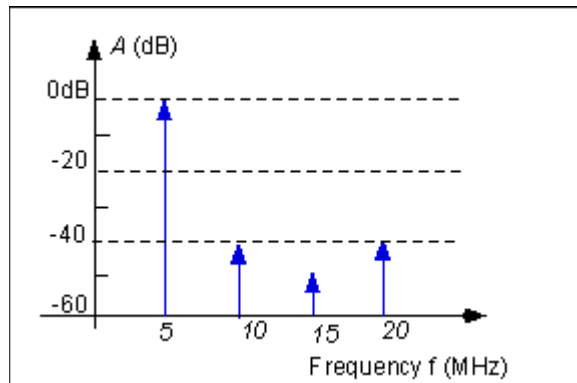


Figure 7: Spectrum of a distorted sinusoidal signal of 5 kHz.

2. Read the section on peak detectors in your textbook section 3.5.4 (Microelectronics by Sedra and Smith).
3. The LF356 amplifier has a gain bandwidth product of 5 MHz. What is the bandwidth of the inverting RF amplifier configuration shown in Fig. 5?
4. 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.
5. Design the audio amplifier, shown in Fig. 4 such that it has a gain of 11. Use resistor values in the range of 1 to 10 kOhm.
6. 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

<ul style="list-style-type: none"> 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 	<p style="text-align: center;">LF356 pinout</p>
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Procedure:

1. Construct the amplifier using the LF356 as shown in Fig. 5. The pins of the amplifier are given above. 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 **10**. *Do not saturate the amplifier.*
2. Construct the peak detector. Use for the resistor R_3 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.es.eupenn.edu/rca/instruments/HPfuncgen/WaveFormGen/WaveFormGen.html#b.%20Example%202:%20Advanced>]

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

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

5. Use as the transmitter the output of the function generator. Use an AM output with carrier frequency of 100kHz and modulation frequency of 5kHz. Select an output value of about 1V.

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. Make sure that the amplifier does not saturate. If needed adjust the values of the resistor R2 in Fig. 5 (i.e. adjust the amplification). Record the amplitude of the waveforms. Take also a snapshot of the waveforms.

6. Connect the output of the audio amplifier to the input of a speaker, using a 47 μ F 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 such that the output signal is relatively distortion free.

7. 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 R4 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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