National University of Singapore
Department of Electrical & Computer Engineering
CG2023 Signals & Systems

Mini-Project: Single Tone Amplitude Modulation and Demodulation

Please read this manual carefully before attending the laboratory session. You will work in teams of 3 students and submit a group report within 1 week from your last scheduled laboratory session.

1. Introduction

In communications, the message signals are usually lowpass in nature with their spectral energy concentrated in the low frequency region. If several such signals are transmitted in a common channel, their spectra will overlap, which results in mutual interference. Such signals are also not suitable for radio communication. To resolve these problems, the message signal is embedded in a high-frequency single-tone carrier wave to produce a new signal, which is then transmitted. This process is called **modulation** and the new signal is called the modulated carrier signal. In radio communication, the carrier frequency is chosen to lie within the radio band Interference-free multiple transmissions over a common channel can then be achieved with proper choice of carrier frequencies to avoid spectral overlap of the modulated carrier signals. At the receiver, a process called **demodulation** (or detection) is used to extract the original message signal from the received modulated carrier signal.

Suppose the carrier wave, $c(t)$, is the sinusoid $c(t) = A_c \sin(2\pi f_c t + \varphi)$. The carrier wave has 3 parameters, A_c, f_c and φ_c, which are, respectively, called the amplitude, frequency and phase of the sinusoid. The message signal, $m(t)$, can alter any of these 3 parameters to produce a corresponding modulated carrier signal for transmission. Consequently, there are at least 3 modulation schemes. This project focuses on **Amplitude Modulation** (AM) where $m(t)$ is used to alter the amplitude of $c(t)$. The block diagram of an AM transmission system is shown in Figure 1.

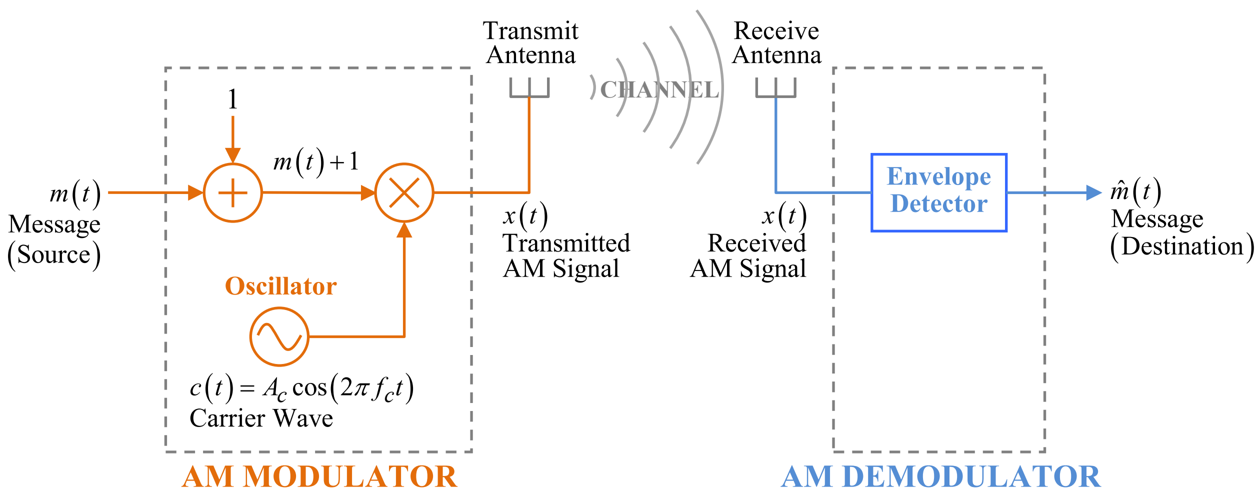

Figure 1: AM transmission system

2. Objectives

In the mini-project, your team will design and implement the AM modulator and AM demodulator blocks shown in Figure 1. Besides providing exposure to one of the popular modulation techniques, another objective of this exercise is to reinforce circuit design/implementation skills and confidence in using emerging portable electronical engineering instrument -- Analog Discovery 2 (AD 2).

The task may be sub-divided into the modulation and demodulation stages as follows.

- ***Modulation:***

  Build a circuit that generates the AM signal $x(t)=\left[m(t)+1\right]c(t)$ where $m(t)$ is an audible single-tone message signal and $c(t)$ is a sinusoidal carrier wave.

- ***Demodulation (or Detection)***

  Build a circuit on the breadboard provided to recover the message signal, $m(t)$, by demodulating the AM signal. The demodulation process comprises of two stages:
  - Envelope detection
  - Low pass filtering

  Refer to the reference material post in LumiNUS CG2023 course web for further information about envelope detection and the method for designing a low pass filter.

3. Equipment

- Analog Discovery 2 (the portable device) and Waveforms (the software). They work together to provide the functions of two signal generators, two oscilloscope channels, a spectrum analyser, a network analyser, a dual power supply of ±5V, etc.
- AD835, analogue multiplier that implements W = XY + Z operation
- 1N914 diode for the envelope detection circuit
- LM324 general purpose operational amplifier (Op-Amp)
- Resistors, capacitors and an 8 Ohm speaker

Datasheets for AD835 and LM324 have been posted in LumiNUS Project folder.

4. Modulation

The amplitude modulation process will be performed using the AD835 multiplier. The integrated circuit generates a signal that is the linear product of its X and Y voltage inputs with a −3 dB output bandwidth of 250 MHz. The linear product of X and Y may also be summed with a third input voltage, Z to produce the signal XY + Z. Figure 2 shows the schematic diagram and the pin configuration of the chip. Note that ±5 V supplies, via the VP and VN pins, need to be provided for the circuit to operate.

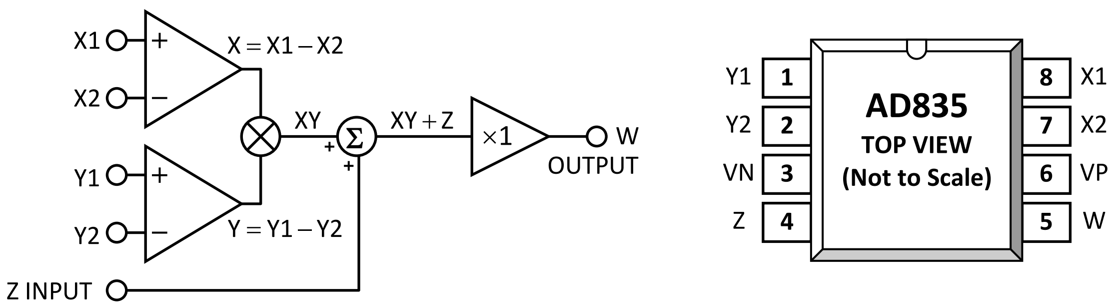

Figure 2: Schematic diagram and pin configuration of the AD835 chip

Using the signal generators to provide the input signals to the AD835 multiplier, generate the AM signal $x(t)=[m(t)+1]\cdot c(t)$ where $m(t)=A_m\cos(2\pi f_m t)$ is the message signal and $c(t)=A_c\cos(2\pi f_c t)$ is the carrier wave. The frequency of the message signal should be in the audible range $(\text{i.e. } f_m \in [400, 4K] \text{ Hz})$, while the frequency of the carrier wave should be at least 10 times of f_m. The amplitude of $m(t)$ should not exceed unity $(\text{i.e. } A_m \le 1)$ so that the envelope of $x(t)$ is positive at all times $(\text{i.e. } A_c[m(t)+1] \ge 0)$, thus allowing $x(t)$ to be demodulated using an envelope detector.

Observe and compare the message signal, carrier wave and the AM signal using the oscilloscope. The oscilloscope is also able to generate the amplitude spectrum of the signals. Generate plots of signals and spectra for your report.

Notes:

- The portable device Analog Discovery 2 (AD2) will be used in this project. It works together with the software named Waveforms running on computer. They provide all needed lab equipment functions in this project. These functions include two signal generators, two oscilloscope channels, a spectrum analyzer, a network analyzer, a dual power supply of ±5V. Refer to Figure 3 below on the connection of AD 2 and the pinout diagram for different functions.

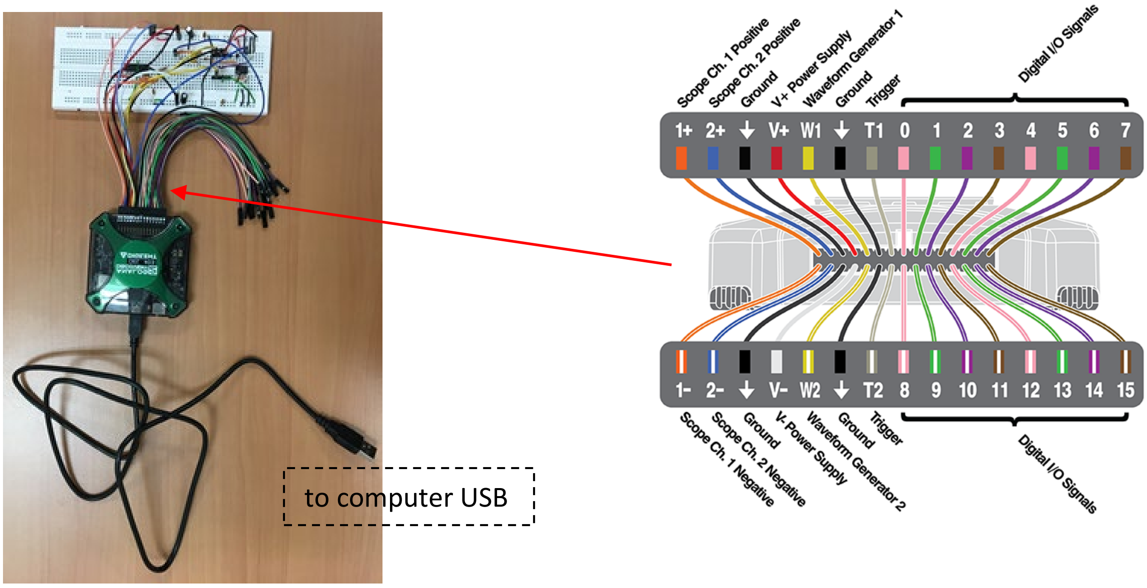

Figure 3: AD 2 connections and pinout diagram

- Please refer to the provided videos in the module LumiNUS Multimedia folder Project channel on how to use AD2 functions or refer to the link https://reference.digilentinc.com/reference/instrumentation/guides/start.

- Vpp (peak-to-peak) value given by the signal generator indicates the total voltage swing of the output signal. For example, it is twice the amplitude of a sinusoid.

5. Demodulation

5.1 Envelope Detector

By setting $A_m \le 1$, the shape of the AM signal "envelope" follows the shape of the message signal. It is thus possible to recover the message by detecting the "envelope" of the AM signal. The envelope detection circuit, shown in Figure 4, comprises of a diode and a RC circuit. The diode rectifies the AM signal, and would produce a half-wave rectified signal that only have positive values if the capacitor is absent.

When a capacitor is connected in parallel to the resistor, the capacitor will charge up when its voltage is lower than that of the AM signal (diode in conduction mode). Conversely, the capacitor will discharge through the resistor when its voltage is higher than that of the AM signal (diode in cut-off mode). Hence, the voltage $\hat{m}(t)$ across the capacitor would approximately follow the envelope of the AM signal $x(t)$, as shown in Figure 4.

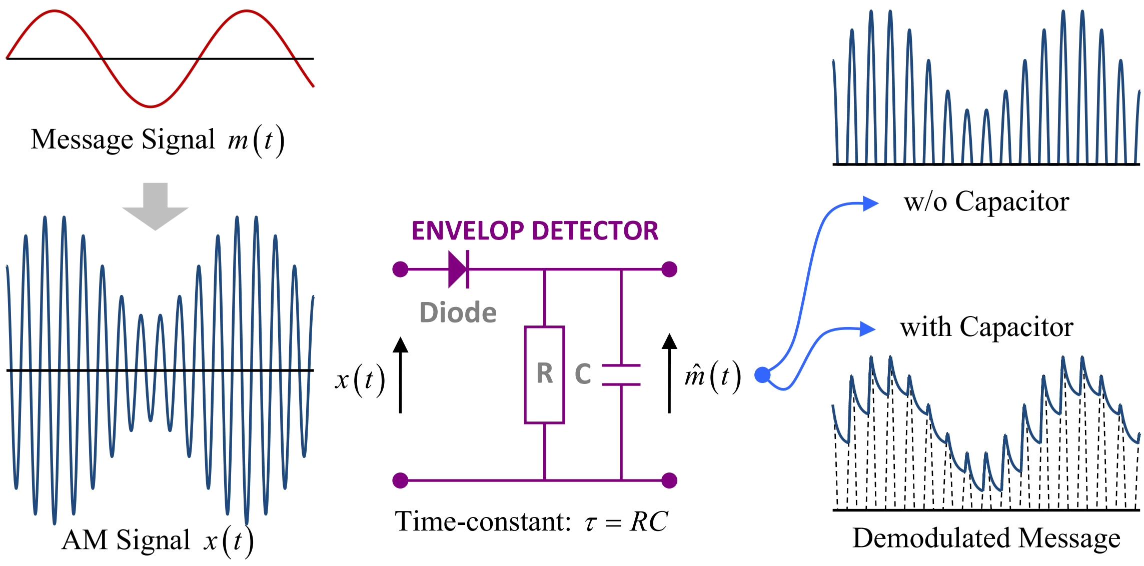

Figure 4 : Envelope detector

The RC time-constant has to be as small as possible in order to detect all the peaks in the rectified modulated signal. On the other hand, the RC time-constant needs to be as large as possible to minimize ripple. In practice, these two conflicting requirements translate to the following condition :

$$\frac{1}{f_m} >> \underbrace{\tau = RC}_{\text{time constant}} >> \frac{1}{f_c}.$$

This constraint can be closely met only if $f_c >> f_m$, and this is the reason for the recommendation that f_c should be at least 10 times of f_m.

Implement the envelope detector and use the oscilloscope to observe the half-wave rectified signal and the voltage across the capacitor. Is the output of the envelope detector “smooth”?

Using the speaker, listen to both the message signal and the output of the envelope detector. What are the differences?

You should aim to complete this section mid-way through the first project session.

5.2 Low pass filter

The last stage of the project is to design and implement a second order active Butterworth lowpass filter to remove the high frequency ripples found in the envelope detector output. The Butterworth filter will be based on the Sallen-Key topology shown in Figure 5.

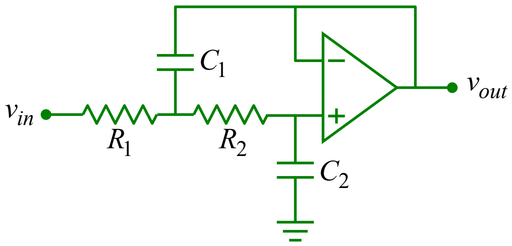

Figure 5: 2nd-order Butterworth lowpass filter based on the Sallen-Key

The transfer function of the second order filter circuit is given by

$$\tilde{G}(s) = \frac{1}{C_1 C_2 R_1 R_2 s^2 + C_2 (R_1 + R_2) s + 1} = \frac{\omega_o^2}{s^2 + 2\zeta\omega_o s + \omega_o^2}$$

where

$$\omega_o^2 = \frac{1}{C_1 C_2 R_1 R_2} \quad \cdots\cdots\cdots \quad \text{Cutoff Frequency}$$

$$\zeta = \frac{C_2 (R_1 + R_2)}{2\sqrt{C_1 C_2 R_1 R_2}} \quad \cdots\cdots\cdots \quad \text{Damping Ratio}$$

The filter can be realized via the following 3 design equations that yields an underdamped second order system, $\tilde{G}(s)$, that has a damping ratio of $\zeta = 1/\sqrt{2}$:

$$R_1 = R_2 = R \quad \cdots\cdots\cdots \quad (1)$$

$$C_1 = 2C_2 = 2C \quad \cdots\cdots\cdots \quad (2)$$

$$\omega_o = 2\pi f_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} = \frac{1}{RC\sqrt{2}} \quad \cdots\cdots\cdots \quad (3)$$

Design the cut-off frequency of the filter by examining the amplitude spectrum of the signal $\hat{x}(t)$ generated by the envelope detector. Compute the resistor and capacitor values using the 3 design equations above. The design can be verified via http://www.pronine.ca/actlpf.htm.

Implement the filter using the LM324 general purpose operational amplifier (Op-Amp), whose pin configuration is shown in Figure 6. Use the AD 2 network analyzer function to obtain the Bode diagram of your filter.

Lastly, show the GA your demodulated signal and generate a printout for your report.

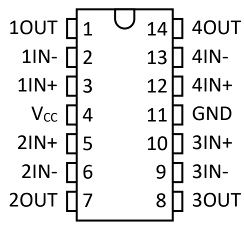

Figure 6: Pin configuration of the LM324

You should aim to complete this section mid-way through the second project session.

6. REPORT

Your report should contain a record of the following:

- Plots of the waveform and spectrum of each of the message signal $m(t)$, carrier wave $c(t)$, and AM signal $x(t)$ using the AD 2 oscilloscope and spectrum analyzer function.
- The RC value that you have chosen for the envelope detector.
- The cut-off frequency and the values of R_1, R_2, C_1 and C_2 of the 2nd-order Butterworth lowpass filter.
- Plots of the waveform and spectrum of the envelope detector output $\hat{m}(t)$: i) without the smoothing capacitor; ii) with the smoothing capacitor, using the AD 2 oscilloscope and spectrum analyzer functions.
- The Bode diagrams for your 2nd-order Butterworth lowpass.
- An explanation of how the ratio A_m/A_c impact the difficulty of choosing the RC time constant in the envelope detector, taking into consideration that $0 < A_m \leq 1$.
- An explanation of how the ratio f_m/f_c impact the difficulty of choosing the RC time constant in the envelope detector.
- A conclusion.

7. Weightage of Assessment Sub-Tasks

Circuit Implementation	:	30%	Assessed during the last project session (demonstration session).
Demonstration + Q&A	:	30%	
Report	:	40%	Submit your group report online before 11:59 pm the next day of demonstration.