UNIVERSITY OF BATH
Department of Electronic &
Electrical Engineering

EXPERIMENT CP-SRP

Second Year Laboratory

Modulation Waveforms

1 Introduction

Communication systems use modulation to translate baseband signals up to a carrier frequency, and demodulation to translate the signal back down to baseband. This exercise looks at this from a simulation point of view in MatLab, bringing out some detail that is harder to identify in an experimental scheme.

2 Objectives

1. To examine simple Amplitude Modulation (AM) waveforms and their characterisation parameters.
2. To examine the demodulation of an AM signal using the envelope follower and the synchronous detection schemes, and look at how poor synchronisation causes problems.
3. To look at multi-tone modulation signals that are generated with mutual orthogonality - the Orthogonal Frequency Division Multiplex (OFDM) modulation scheme.

3 Preparation

1. Read this script to find out what you need to do in the Laboratory session, and to find the formulas needed for the following questions.
2. For a sinusoidal signal with a peak to peak voltage of 8 V determine the voltage amplitude of the sine wave and the time average power when this voltage is applied across a resistance of $R = 50\ \Omega$.
3. A single tone message is modulated onto a constant carrier using a mixer with a conversion loss $C_L = 1.0$ to produce DSBAM. The waveform produced has a maximum signal voltage of 4 V and a minimum of 1 V when applied to a 50 Ω impedance. Find the modulation index, the carrier power, the mean power, the PEP and the PAPR.
4. Determine the magnitude, M, and phase, ϕ, of the complex number $3 - j\,4 \;=\; M\,\angle\phi \;=\; Me^{j\,\phi}$. Further determine the real, x, and imaginary, y, parts of the complex number $x \,+\, j\,y \;=\; 1.4142\,\angle - 3\pi/4$.
5. Copy the files from the Moodle site for Communications Principles to a folder on your H-drive.

4 Simple Amplitude Modulation (AM) Waveforms

4.1 Single frequency modulation AM signal theory

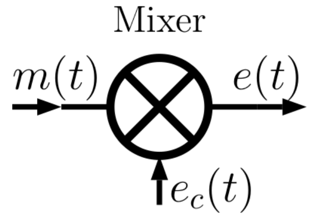


Figure 1: Mixer with message and carrier inputs.

The AM signal is created by multiplying a carrier signal:

$$e_c(t) \;=\; A_c \cos\left(\omega_c t \;+\; \theta_c\right)$$

with a single frequency modulation signal

$$m(t) \;=\; E_0 \;+\; E_m \,\cos\left(\omega_m t \;+\; \theta_m\right)$$

The complete signal is:

$$e(t) \;=\; \frac{A_c}{C_L}\left[E_0 \;+\; E_m \cos\left(\omega_m t + \theta_m\right)\right] \cos\left(\omega_c t \;+\; \theta_c\right)$$

where C_L is the conversion loss of the mixer. the conversion loss of the mixer models power loss which can occur in real mixers. Extracting the E_0 term the total signal becomes:

$$\begin{aligned} e(t) &= \frac{A_c}{C_L}\, E_0 \left[1 \;+\; \frac{E_m}{E_0} \cos\left(\omega_m t + \theta_m\right)\right] \cos\left(\omega_c t \;+\; \theta_c\right) \\ &= \frac{A_c}{C_L}\, E_0 \left[1 \;+\; m\; \cos\left(\omega_m t + \theta_m\right)\right] \cos\left(\omega_c t \;+\; \theta_c\right) \end{aligned} \tag{1}$$

where $m = \frac{E_m}{E_0}$ is called the modulation index. The maximum and minimum of the signal are:

$$E_{max} \;=\; \frac{A_c}{C_L}\, E_0(1 \;+\; m) \qquad\qquad E_{min} \;=\; \frac{A_c}{C_L}\, E_0(1 \;-\; m)$$

from which the modulation index can be found:

$$m \;=\; \frac{E_{max} \;-\; E_{min}}{E_{max} \;+\; E_{min}} \tag{2}$$

Expanding equation (1) using the half-angle trigonometric relation for the multiple of two cosines gives:

$$\begin{aligned} e(t) \;=\; & \frac{A_c}{C_L}\, E_0 \cos\left(\omega_c t \;+\; \theta_c\right) \\ & + \frac{A_c\, m\, E_0}{C_L\; 2} \cos\left[(\omega_c - \omega_m)t + (\theta_c - \theta_m)\right] \;+\; \frac{A_c\, m\, E_0}{C_L\; 2} \cos\left[(\omega_c + \omega_m)t + (\theta_c + \theta_m)\right] \end{aligned} \tag{3}$$

which is the sum of three contributions at different frequencies:

Carrier : at ω_c with amplitude $\frac{A_c}{C_L}\, E_0$.

Lower side band : at $\omega_c - \omega_m$ with amplitude $\frac{A_c\, m\, E_0}{C_L\; 2}$.

Upper side band : at $\omega_c + \omega_m$ with amplitude $\frac{A_c\, m\, E_0}{C_L\; 2}$.

This is a Double Side Band Amplitude Modulated (DSBAM) signal.

4.2 Power calculations

The time average power is related to rms voltage by the resistance it is measured across as $P = V_{rms}^2/R$. For a single frequency sinewave signal $V_{rms} = V_{peak}/\sqrt{2}$.

Mean Power: This is the sum of the mean powers in all of the frequency components in the waveform. It is an average value. It is often most easily identified by looking at the frequency spectrum of a signal.

Single frequency modulation case: In the case of the single modulation frequency the mean power is the sum of the carrier power, P_{Carr}, and the upper and lower side band mean powers, P_{USB}, P_{LSB}:

$$\begin{aligned} P_{mean} &= P_{Carr} + P_{USB} + P_{LSB} = \left(\frac{A_c}{C_L}\right)^2 \left[\frac{E_R^2 + \left(\frac{m}{2}E_R\right)^2 + \left(\frac{m}{2}E_R\right)^2}{R}\right] \\ &= \frac{(A_c\,E_R)^2}{C_L^2\,R}\left[1 + 2\left(\frac{m}{2}\right)^2\right] = P_0\left[1 + \frac{m^2}{2}\right] \end{aligned} \tag{4}$$

where m is the modulation index and P_0 is the carrier power when $E_m = 0$. Note that $E_R = E_0/\sqrt{2}$ is the rms voltage for a single frequency sinewave.

Peak Envelope Power (PEP): This is the power at the point where the Envelope is maximum. It is expressed as an average value which can easily be determined from the rms of the peak voltage in the time waveform.

Single frequency modulation case: For a single frequency modulation the peak amplitude is the sum of the carrier, upper side band and lower side band components. The PEP is then

$$PEP = \left(\frac{A_c}{C_L}\right)^2 \left[\frac{\left(E_R + \frac{m}{2}E_R + \frac{m}{2}E_R\right)^2}{R}\right] = \frac{(A_c\,E_R)^2}{C_L^2\,R}\,[1 + m]^2 = P_0\,[1 + m]^2$$

Peak to Average Power Ratio (PAPR): The PAPR is simply:

$$PAPR = \frac{PEP}{P_{mean}} \tag{5}$$

Single frequency modulation case: In the case of the single frequency modulation the PAPR is

$$PAPR = \frac{(1 + m)^2}{\left(1 + \frac{m^2}{2}\right)} \tag{6}$$

4.3 Modulation tests

In the following all voltages may be assumed to be measured across a resistance of $50\ \Omega$, and in these simulations $C_L = 1$ is used.

The MatLab file AM_2.m includes three modulation tones. These allow observation of modulation waveforms that are approximately a square wave and a 'triangle' wave. Running AM_2.m produces time domain pictures of the waveforms as you would see on an oscilloscope and frequency domain pictures as you would see on a spectrum analyser.

Square wave: Using the values given in the adjacent table and determine the PEP and the PAPR in this case of an approximation to square wave modulation.

Note the powers in the side bands and the carrier, the proportion of power in the sidebands and whether cross over distortion is apparent.

Table 1: Parameters for an approximation to a square wave.

Component	Amplitude (volts)	Frequency (Hz)	Phase (rads)
Carrier	2.4	600	0.0
Modulation DC	1.0	0.0	0
Modulation 1	0.333	45.0	$\pi/2$
Modulation 2	1.0	15.0	$\pi/2$
Modulation 3	0.2	75.0	$\pi/2$

Triangular wave: Using the values given in the adjacent table and determine the PEP and the PAPR in this case of an approximation to triangular wave modulation.

Note the powers in the side bands and the carrier, the proportion of power in the sidebands and whether cross over distortion is apparent.

Table 2: Parameters for an approximation to a triangular wave.

Component	Amplitude (volts)	Frequency (Hz)	Phase (rads)
Carrier	2.4	600	0.0
Modulation DC	1.0	0.0	0
Modulation 1	0.333	45.0	0.0
Modulation 2	1.0	15.0	0.0
Modulation 3	0.2	75.0	0.0

4.4 Demodulation/detection

There are two basic method of demodulating or detecting AM signals:

Rectification and filtering: Rectifying the signal and filtering produces an 'envelope follower'. The output tracks the magnitude of the input, and provided the carrier signal is large enough the output, $o_R(t)$, is a scaled version of the original modulation signal, $m(t)$. If the carrier is too small there is overmodulation and the detected output is a distorted version of the original modulation signal.

Synchronous Detection: The amplitude modulated signal is multiplied by another version of the carrier and filtered. The multiplication produces components around twice the carrier frequency and the original modulation signal. The low pass filter removes the components around twice the carrier frequency, so the output, $o_S(t)$, is a scaled version of the original modulation signal, $m(t)$.

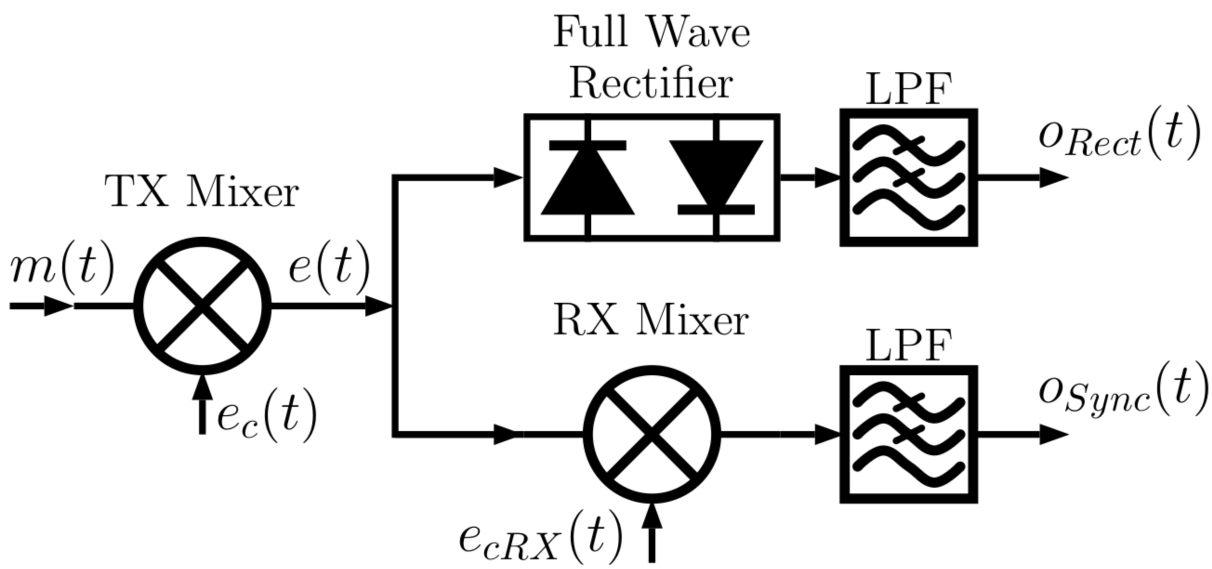


Figure 2: Formation of an AM signal and demodulation through rectification or synchronous detection.

4.4.1 AM detection

The MatLab file AM_RX_1.m adds in the rectification of the AM signal and low pass filtering to produce $o_R(t)$ and the multiplication by the receiver carrier and low pass filtering to produce $o_S(t)$.

Using the adjacent data observe the waveforms a signal spectra, and describe how well the two outputs match the input modulation.

Table 3: Parameters for an approximation to a square wave.

Component	Amplitude (volts)	Frequency (Hz)	Phase (rads)
Carrier	2.4	600	0.0
Modulation DC	1.0	0.0	0
Modulation 1	0.333	45.0	$\pi/2$
Modulation 2	1.0	15.0	$\pi/2$
Modulation 3	0.2	75.0	$\pi/2$
RXCarrier	2.0	600	0.0

Change the signal parameters to those shown in the adjacent table and again describe how well the two outputs match the input modulation.

Table 4: Parameters for an approximation to a triangular wave.

Component	Amplitude (volts)	Frequency (Hz)	Phase (rads)
Carrier	2.4	600	0.0
Modulation DC	1.0	0.0	0
Modulation 1	0.333	45.0	0.0
Modulation 2	1.0	15.0	0.0
Modulation 3	0.2	75.0	0.0
RXCarrier	2.0	600	0.0

4.4.2 Phase offset in the receiver carrier

Progressively change the phase of the receiver carrier in steps of $\pi/4$ rads and explain why the outputs change.

4.4.3 Frequency offset in the receiver carrier

The carrier oscillators in physically separated transmitters and receivers may not be at exactly the same frequency.

To observe the effect of the transmitter and receiver carrier not being synchronised change the signal parameters to those shown in the adjacent table.

Describe how well the outputs match the input modulation.

Table 5: Parameters for an approximation to a triangular wave with a receiver carrier.

Component	Amplitude (volts)	Frequency (Hz)	Phase (rads)
Carrier	2.4	600	0.0
Modulation DC	1.0	0.0	0
Modulation 1	0.333	45.0	$\pi/2$
Modulation 2	1.0	15.0	$\pi/2$
Modulation 3	0.2	75.0	$\pi/2$
RXCarrier	2.0	**605**	0.0

5 Orthogonal Frequency Division Multiplex (OFDM)

Here the signal spectrum is defined by the parameters passed to an Inverse Fast Fourier Transform (IFFT) calculation and the output of the IFFT describes the signal voltage as a function of time. The data that is produced by the IFFT calculation is sent out through Digital to Analog Converters (DACs) to produce the baseband OFDM symbols. In the simulation used here the mixers are perfect multipliers, and so no band pass filters (BPFs) need to be simulated.

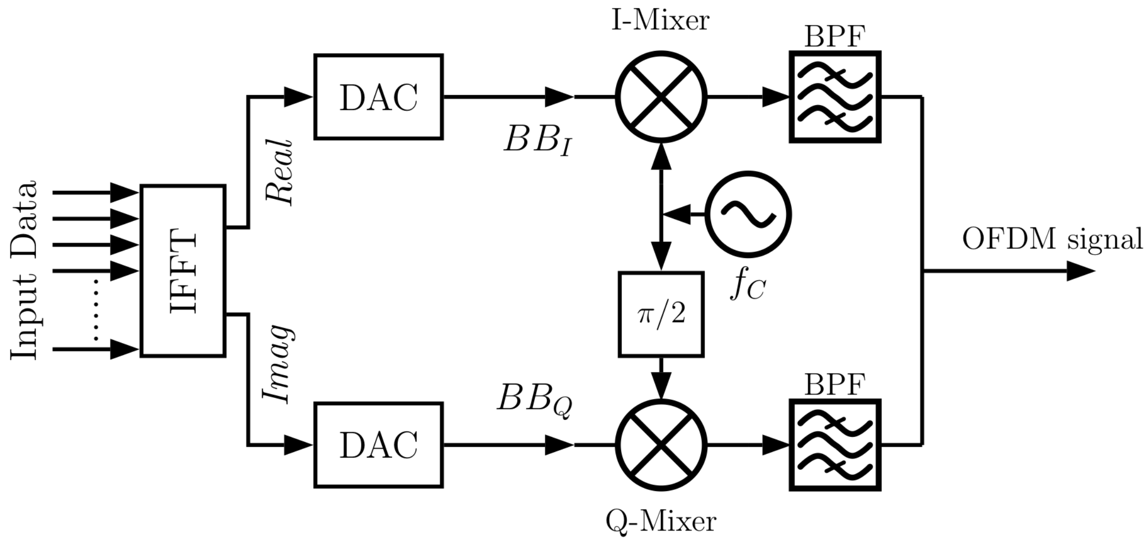


Figure 3: OFDM signal generation scheme.

The OFDM scheme is simulated in two parts. The first part looks at the formation of the baseband signal and the second part looks at the transmitted signal where the baseband is I/Q modulated onto a carrier.

In these simulations the MATLAB IFFT is used. The DC term is at array index 1, and higher frequency terms need to be repeated at the negative frequencies towards the top end of the data array for the IFFT calculations. The IFFT calculations use N data points.

5.1 OFDM baseband signal

The MatLab file OFDM_TX1.m provides simulation of the formation of the OFDM signal. In the first instance the formation of OFDM symbols to represent single characters is examined.

In the following calculations the IFFT evaluations need frequency components to be repeated at the negative frequencies towards the top end of the data array.

To represent the character ’S’ the RTF-8 binary sequence is 01010011. The first two bits determine the DC component. The others bits govern the fundamental and the second and third harmonics.

In the MATLAB file the signal_spectrum array should be set to zero apart from the terms in the adjacent table and the carrier amplitude $E_c = 12$ V.

Table 6: Non-zero array values for OFDM symbol representation of ’S’.

Component	Real (volts)	Imag	Bits
Signal_spectrum(1)	0.0	1.0	01
Signal_spectrum(11)	0.0	1.0	01
Signal_spectrum(21)	0.0	0.0	00
Signal_spectrum(31)	1.0	1.0	11
Signal_spectrum(N+2-11)	0.0	1.0	01
Signal_spectrum(N+2-21)	0.0	0.0	00
Signal_spectrum(N+2-31)	1.0	1.0	11

Using these values observe the frequency spectrum of the baseband signals, their time waveforms and their PEP and PAPR.

Voltages of 1.0 and 0.0 do not need to be used to represent the digital bits 1 and 0.

Set the signal_spectrum array to zero apart from the terms in the adjacent table and the carrier amplitude $E_c = 1$ V.

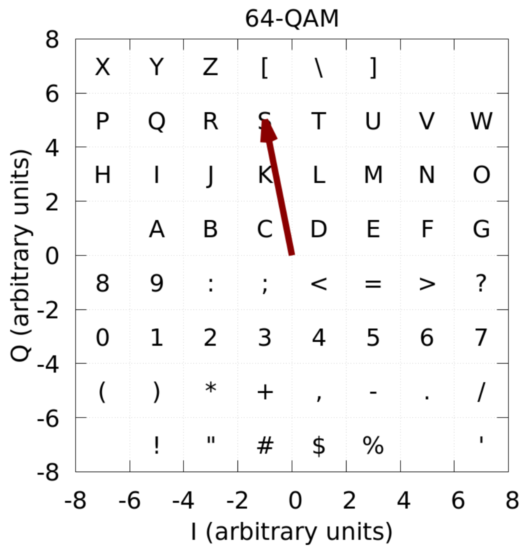
Observe the OFDM waveform and determine the PAPR in this case.

Table 7: Non-zero array values for alternate OFDM symbol representation of ’S’.

Component	Real (volts)	Imag	Bits
Signal_spectrum(1)	0.0	2.5	01
Signal_spectrum(11)	0.0	2.5	01
Signal_spectrum(21)	0.0	0.0	00
Signal_spectrum(31)	2.5	2.5	11
Signal_spectrum(N+2-11)	0.0	2.5	01
Signal_spectrum(N+2-21)	0.0	0.0	00
Signal_spectrum(N+2-31)	2.5	2.5	11

5.1.1 64-QAM on OFDM

In 64-QAM each state represent 8 bits or a character when using UTF-8 coding.



Using this 64-QAM coding, assume that the arbitrary units shown are voltages, and also assume that the carrier amplitude $E_c = 12$ V.

Set the OFDM signal_spectrum array to represent each of the five letters in the sequence "X+Y<3".

Determine the PAPR in each of these five individual letters and when all five letters are transmitted together.

6 Report

Your report should include the results obtained, observations made and relevant graphs. In particular you should consider the power handling characteristics needed for the AM and OFDM schemes, how successful the detection schemes for AM signals are, and which would be more suitable for receiving OFDM signals. The report should be three to five pages in length

The report can be submitted electronically through Moodle as a .pdf file by 17:00 on Thursday 29th February 2024.