Communication Systems Laboratory
Lab 1: Modulation and Demodulation

Report Due: 11:59 pm, Sep. 16, 2025

The goals of this lab are to understand (a) IQ modulation from baseband to radio frequency and (b) the optimal demodulation process.

For the submission, please use the MATLAB live script (.mlx).

[Part 1] IQ modulation from baseband to RF (51 points)

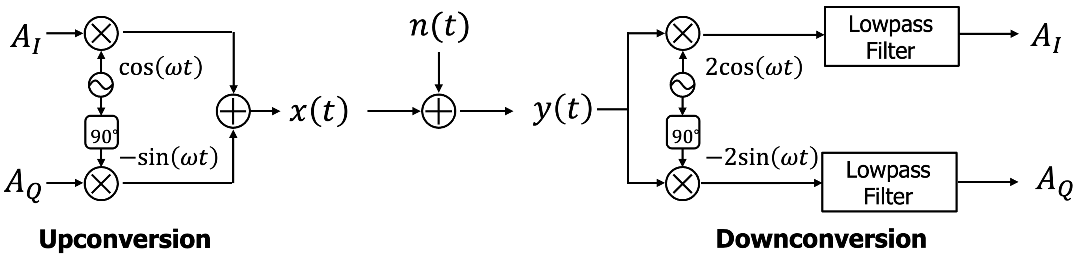

Fig. 1

In this lab, we examine the journey of signals from baseband to radio frequency and then back to baseband, as illustrated in Fig. 1. To this end, a series of symbols to be transmitted, together with their up-sampled version, is provided in Lab1_TXSig.mat file. The symbols to be transmitted are stored in the variable Sym_TX, with the real part representing A_I and the imaginary part representing A_Q. There are 32 symbols in total, modulated using 16-QAM with an average power of 1. These 32 symbols are transmitted with a symbol rate of 5 Hz (i.e., transmit 5 symbols per second). To emulate the signal in the analog domain, the up-sampled signal in the baseband is also provided and stored in the variable Sig_BB_TX_Upsamp, with a sampling rate of 1000 Hz. The variable tSamp is the sampling times for Sig_BB_TX_Upsamp. The imaginary part of the signal is plotted in Fig. 2 for reference.

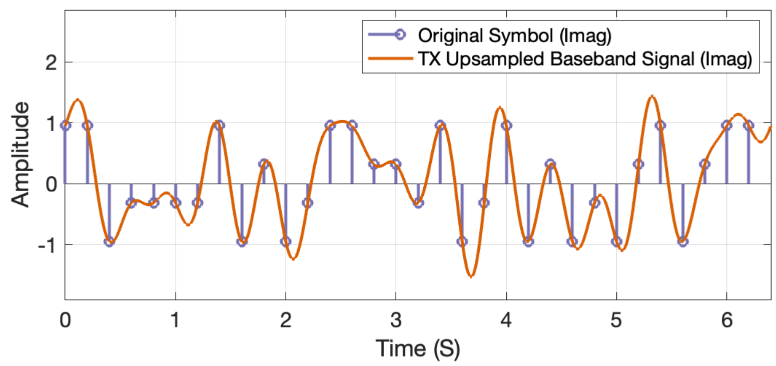

Fig. 2

Upconversion and downconversion without noise: Using the provided baseband signal (Sig_BB_TX_Upsamp), upconvert the signal to 50 Hz and then downconvert it back to the baseband, as illustrated in Fig. 1. Here, the noise $n(t)$ is assumed to be 0 (noiseless).

(1) For the 32 transmitted symbols, plot the constellation diagram to show they are modulated in 16-QAM.

(2) Perform FFT to Sym_TX and Sig_BB_TX_Upsamp and plot the magnitude of the two frequency spectrums on the same figure with 0 Hz in the center, i.e., the range of the frequency in the x-axis should be from -500 Hz to 500 Hz (hint: fftshift). Please provide a clear legend and label the x-axis with the correct frequency unit.
Note: The goal here is to see that the two frequency spectrums are identical. A normalization factor of 500 between the two spectrums is expected.

(3) Following (2), replot by zooming in on the frequency range from -5 Hz to 5 Hz, showing that the two have the same spectrum. Also, what is the bandwidth of the transmitted signal?

(4) After upconverting the baseband signal to a carrier frequency of 50 Hz, perform FFT to the upconverted signal. Plot the frequency spectrums of both the baseband and upconverted signals on the same figure. As before, have the 0 Hz in the center, provide a clear legend, and label the x-axis with the correct frequency in Hz. What frequencies does the upconverted signal center around?

(5) Plot the time domain signal of Sig_BB_TX_Upsamp and its upconverted version, both the real and imaginary parts. Please zoom in on the first 8 symbols and make sure your figure clearly shows the oscillation in the upconverted signal. There should be four curves: baseband real, baseband imaginary, upconverted real, and upconverted imaginary, on the same plot or arranged side by side for comparison. Please make sure the four curves are clearly labeled, and the x-axis is labeled with the correct time in seconds.
Note: The goal of this plot is to see that the upconverted signal for over-the-air transmission is purely real, although the baseband signal has both real and imaginary parts.

(6) For the downconversion process, what is the minimum cutoff frequency for the lowpass filter that preserves the signal?

(7) Continue with the downconversion process. For the downconversion process, plot the frequency spectrum before and after the lowpass filter, with the x-axis ranging from -125 to 125 Hz.

(8) Plot the frequency spectrum of the downconverted and low-passed signal against the frequency spectrum of Sig_BB_TX_Upsamp on the same plot, showing that the two are identical. Please zoom in on the x-axis ranging from -5 to 5 Hz.

(9) Plot the downconverted and low-passed signal in the time domain and compare it with Sig_BB_TX_Upsamp to show they are identical. There should be four curves: TX baseband real, TX baseband imaginary, RX baseband real, and RX baseband imaginary. Please label the x-axis with the correct time in seconds.

(10) Downsample the received baseband signal to 32 received symbols. Plot the constellation diagram of the 32 received symbols. The goal is to confirm that the transmitted constellation is preserved at the receiver in this noiseless wireless transmission simulation with upconversion and downconversion operations.

Additive noise: Previously, the channel is assumed to be noiseless. Now, we consider the noise to be AWGN, $n \sim \mathcal{N}(0, \sigma^2)$. In the following, you will learn how to choose the noise power to correctly simulate transmissions of a targeted SNR, and see how the AWGN noise impacts the received constellation.

(11) Calculate the power of the provided signals, Sym_TX and Sig_BB_TX_Upsamp. What are the values? Why is the power not exactly 1? If all constellation points are used with the same

probability, show that the expected power is 1.

(12) Given the average signal power to be 1, what should the noise power be if we want to emulate an SNR of 20 dB?

(13) Assume the AWGN has a power of σ^2. What is the noise power after downconversion and lowpass filtering? (Hint: The downconversion process has a coefficient of 2, and the lowpass filter discards noise in high frequencies, so that the noise power after downconversion and lowpass filtering is no longer σ^2. These factors must be accounted for when choosing σ^2 to correctly simulate a target SNR.)

(14) Following (12) and (13), to emulate an SNR of 20 dB for the transmitted symbols, what should the value of σ be?

(15) Implement the AWGN with the σ selected in (14). Plot the frequency spectrum of the generated AWGN.

(16) Perform downconversion, lowpass filtering, and downsampling as before to get the received symbols. Plot the constellation diagram of the received symbols. Please also plot the constellation diagram without noise for reference to see how the noise impacts the received constellation.

(17) From (16), calculate the noise for each received symbol. What is the empirical noise power of the received symbols? Combined with the empirical signal power you obtain in (11), what is the empirical SNR for this specific noise realization (in dB)? (Hint: the empirical SNR you obtain should be around 20 dB.)

[Part 2] Demodulation (39 points)

In Part 1, we see that the additive Gaussian noise results in complex normal noise in the symbol space. Thus, in Part 2, we omit the upconversion and downconversion and emulate AWGN transmission directly in the symbol space. That is,

$$Y = X + N,$$

where X and Y are complex symbols, with the real part representing A_I and the imaginary part representing A_Q; the noise N follows the complex normal distribution.

In this lab, you will write your own script to simulate AWGN transmission. The process includes:

a) Generate random bits
b) Modulate the bits with the desired modulation scheme with unit average power
c) Generate noise with appropriate power
d) Add the noise to the modulated symbol
e) Demodulate the noisy symbol
f) Compare the transmitted and received bits to calculate the BER

Note: You are allowed to use MATLAB built-in functions like qammod, qamdemod with proper symOrder specified.

Gray code vs Natural code: In this part, you will compare the BER based on Gray mapping vs. binary mapping.

(1) Simulate 16-QAM transmission with Gray coding for an SNR of 10 dB based on 10^6 uniformly random bits. The transmitted 16-QAM constellation should be scaled so that its expected power is 1 (hint: UnitAveragePower = true). Plot the TX constellation marked with Gray mapping and provide the variance value you specify to simulate an SNR of 10 dB.

(2) Following (1), what are the (a) empirical signal power, (b) empirical noise power, and (c) the empirical SNR in dB from the 10^6 random bits you generated?

(3) Following (1), what is the bit error rate?

(4) Similar to (1), simulate 16-QAM transmission with natural coding (i.e., binary coding) for an SNR of 10 dB based on 10^6 uniformly random bits. Plot the constellation marked with binary mapping.

(5) Following (5), what is the bit error rate of the 16-QAM transmission with natural coding?

(6) Comparing the BER you obtained in (3) and (5), what is the reason for the difference?

Optimal decoding with MAP: In the previous simulation, bits are uniformly generated. Here, we simulate a scenario where bit 0 has a prior probability of 0.1 while bit 1 has a prior probability of 0.9. For simplicity, use BPSK for modulation.

(7) Explain the strategy you employ to generate bit 0 with a probability of 0.1 and bit 1 with a probability of 0.9. Using your method, what is the percentage of bit 0 of the 10^6 generated bits in your simulation?

(8) Simulate the BPSK transmission for SNR = 5 dB. Considering that the expected power of the transmission constellation is 1, what variance value should you specify to simulate an SNR of 10 dB? Note that the noise still follows a complex normal distribution.

(9) Using the noise variance you obtained in (9), simulate the BPSK transmission. Plot the received constellation to see the unbalanced constellation, and verify that the empirical SNR is close to 5dB with the 10^6 generated bits you generated.

(10) Using the ML rule, what is the BER?

(11) Based on the MAP rule, what is the decision boundary? Please include your derivation in the answer.

(12) Demodulate the received symbols using the decision boundary you derived in (11). Using the MAP rule, what is the BER?

(13) Comparing the BER you obtained in (10) and (12), what is the reason for the difference?

Grading:

- 3 points for each problem. 90 points in total for 30 questions.
- 10 points for homework submission.