ECSE 308, Winter 2024
Introduction to Communication Systems and Networks
Laboratory L3 – Report

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INSTRUCTIONS:

- **Student(s) need to upload one report per team on *myCourses* before the due date.**
- **Upload a single, clearly readable pdf file, including this cover page plus answers.**
- **DUE DATE: Monday Feb. 19, 5pm.**

REPORT:

Part	Question	Mark
1	1	/8
	2	/8
	3	/8
	4	/8
2	5	/8
	6	/8
	7	/8
	8	/8
	9	/8
	10	/8
		/80

GRADE:

	Student 1	Student 2
Participation	/20	/20
Report	/80	/80
TOTAL	/100	/100

McGill University
Montreal, Canada

Digital Transmission Techniques

Abstract— **The lab is designed to introduce students to the fundamental concepts and techniques of digital communication systems and networks. It focuses on baseband digital transmission and basic digital modulation schemes including ASK, PSK, FSK, and QAM. Through a series of hands-on experiments using MATLAB and Simulink, students gain practical experience in signal generation, modulation, noise addition, demodulation, and the analysis of signal-to-noise ratio and bit error rates. This lab provides step-by-step instructions to build and analyze each communication system, offering students a thorough understanding of the theoretical principles in a practical context.**

Keywords—Signal, ADC, DAC, BFSK, BASK, BPSK, 4QAM, Simulink

INTRODUCTION

In the field of digital communications, modulation techniques play a critical role in the transmission of data over various mediums. This lab provided a comprehensive exploration of the fundamental digital modulation schemes, namely Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), Frequency Shift Keying (FSK), and Quadrature Amplitude Modulation (QAM). Through a series of structured experiments using MATLAB and Simulink, this lab aimed to solidify theoretical knowledge by enabling hands-on experience in simulating and analyzing the performance of these modulation techniques under different conditions.

The primary objectives were to understand the principles behind each modulation scheme, the process of signal generation and demodulation, and the effect of noise on the communication system. We also aimed to study the signal-to-noise ratio (SNR) and bit error rate (BER) as key performance indicators. The lab's structured approach allowed for the incremental construction and enhancement of the communication system, beginning with baseband transmission and progressing to more complex forms of modulation.

This report summarizes the procedures followed, observations made, and insights gained during the laboratory sessions. Through these exercises, we were able to observe the practical implications of theoretical concepts and gain a deeper appreciation for the complexities involved in digital communication systems.

Part 1: Baseband Digital Transmission

A. ADC/DAC System

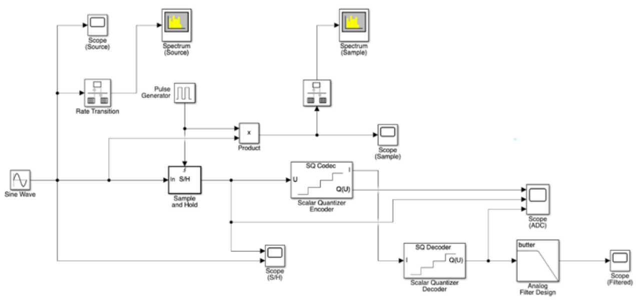

Figure 1: ADC/DAC System

Q1. Compare the outputs on Scope (ADC) and Scope(S/H). Explain how the Scalar Quantizer Encoder converts the analog input to the digital output.

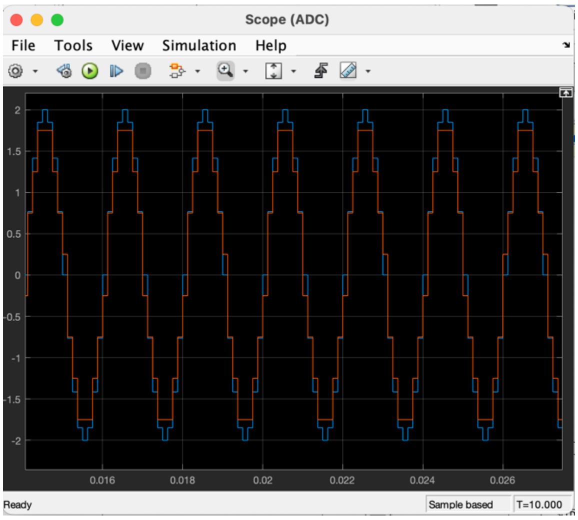

Figure 2: Output on Scope (ADC)

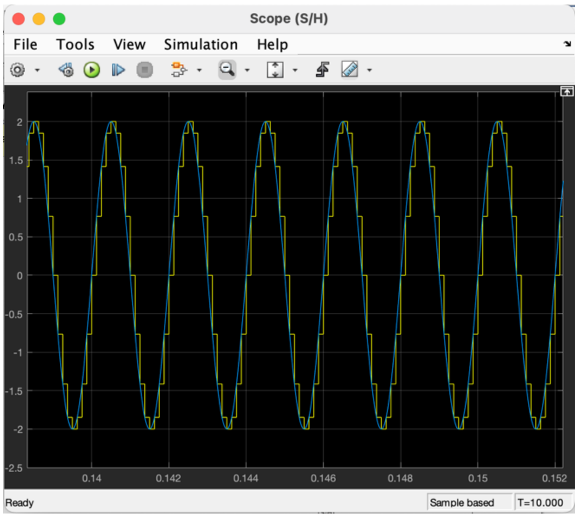

Figure 3: Output on Scope (S/H)

Upon examining the outputs on Scope (ADC) and Scope (S/H), we note that the Scope (ADC) display showcases two digital outputs which are the result of the analog-to-digital conversion process. The Scope (S/H) display shows one digital and one analog output. This analog output represents the sampled and held version of the original continuous signal, while the digital output reflects the discretized, quantized version of the same signal.

The Scalar Quantizer Encoder facilitates this conversion by taking the 'held' analog samples and assigning them digital values based on a predefined scale of quantization levels. This process involves mapping each sampled amplitude to the nearest quantization level, which is then encoded as a binary number. The result of this quantization is a step-like waveform, where each step signifies a quantized representation of the analog input. This is observable in the Scope (ADC) output where the waveform changes abruptly at each quantization step, indicating the digital representation of the continuous analog signal captured in the Scope (S/H) output. The Scalar Quantizer Encoder, therefore, is critical in digitizing the analog signal, enabling it to be processed by digital systems, stored, or transmitted over digital communication channels.

Q2. Compare the outputs on Spectrum (Source) and Spectrum (Sample). Comment on the effect on the spectrum of the source signal when multiplying with a pulse train. Explain why the output of the analog lowpass filter is the recovered source signal.

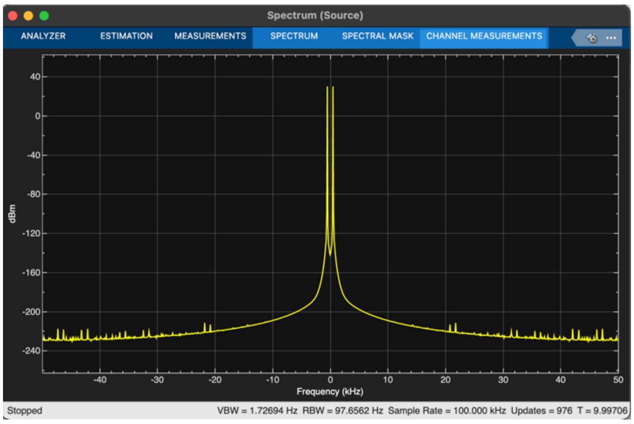

Figure 4: Output on Spectrum (Source)

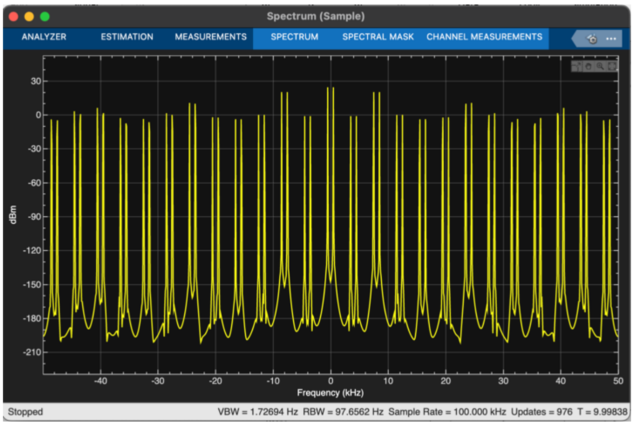

Figure 5: Output on Spectrum (Sample)

In Figure 4, we see a single, concentrated peak which represents the frequency component of the original source signal. When this source signal is multiplied by a pulse train (as seen in Figure 5), the spectrum displays a series of equidistant spikes. This pattern occurs due to the convolution in the frequency domain caused by the multiplication in the time domain, which is a fundamental property of Fourier transforms. Each spike in the spectrum represents a harmonic of the pulse train's fundamental frequency, and the spacing between the spikes corresponds to the pulse train's frequency. This multiplication spreads the energy of the original signal across multiple frequencies, creating a frequency comb in the spectral domain.

The use of an analog lowpass filter allows the recovery of the original source signal because it removes the high-frequency components that were introduced by the pulse train. The lowpass filter preserves the baseband, where the original signal's spectrum is located, and attenuates the higher frequency spikes, effectively eliminating the harmonics introduced by the sampling process. The output of the lowpass filter, therefore, closely resembles the original source signal, as it contains the primary frequency component that was present before the multiplication with the pulse train.

Q3. Observe the output on Scope (ADC). Comment on the number of quantization levels and quantization bits utilized. Repeat for the following parameter setup: Scalar Quantizer Encoder Boundary points: [-2:2] | Codebook values: [-1.5:1:1.5]; Scala Quantizer Decoder Codebook values: [-1.5:1:1.5]. Comment on the performance difference.

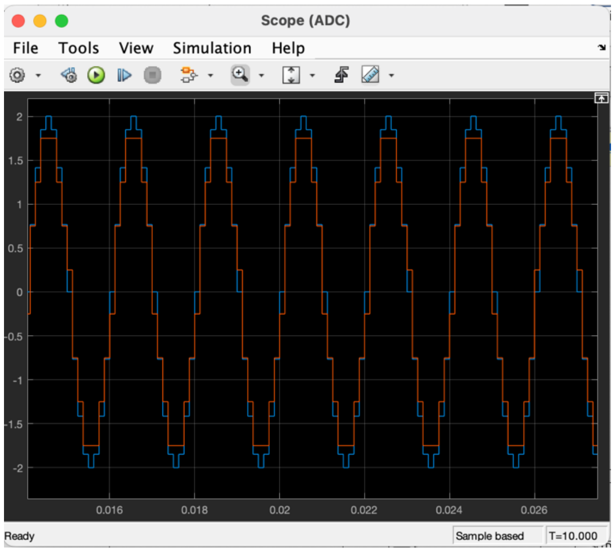

Figure 6: Output on Scope (ADC)

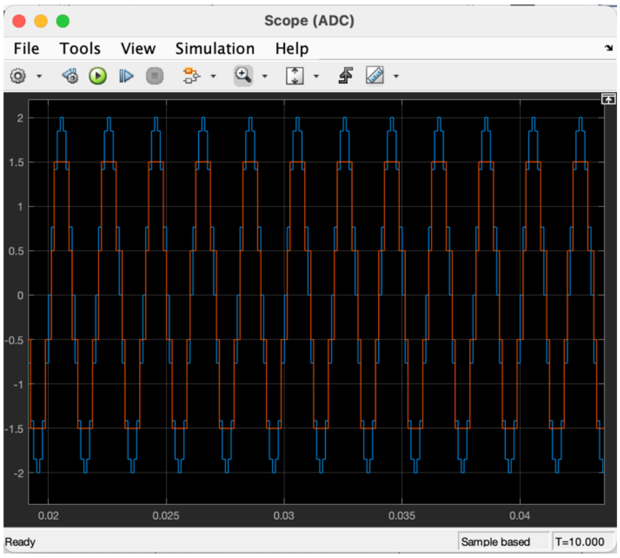

Figure 7: Output on Scope (ADC) after Value Changed

The Scalar Quantizer Encoder settings before changing values indicate that the quantization is performed within a bounded range of -2 to 2 with boundary points set at intervals of 0.5. This configuration results in a total of 9 quantization levels, which are represented by the codebook values [-1.75:0.5:1.75]. Each quantization level corresponds to a specific range of input signal values and is encoded as one of the codebook values.

For an encoder with 9 levels, the number of bits needed to represent each level would be $\log_2(9) \approx 3.17$ bits. Since we cannot have a fraction of a bit, this would be rounded up to 4 bits per sample to encode the quantization levels. With 4 bits, there are 16 possible combinations, which is more than enough to represent the 9 levels from the encoder settings.

In Figure 6, the ADC output exhibits more significant fluctuations between the quantization levels, suggesting a higher level of quantization noise or a less stable input signal. In contrast, Figure 7 shows a more stable and consistent quantization level with less fluctuation, indicating an improved performance. The consistent level heights in Figure 7 suggest less noise or interference, and possibly a higher Signal-to-Noise Ratio (SNR), resulting in a clearer and more accurate digital output from the ADC.

B. Baseband Transmission over AWGN Channel

Q4. Plot the BER - versus - Eb/No curve with Eb/No (dB)= 0, 2, 4, 6, 8, 10. (Change Eb/No and observe the BER, then plot BER - versus - Eb/No using Excel, Matlab, Python, …)

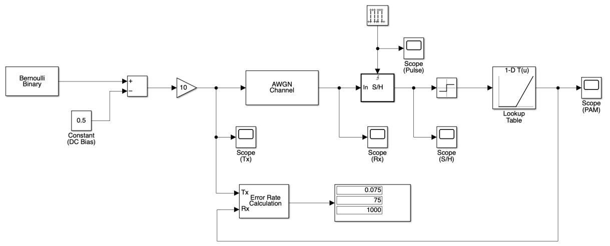

Figure 8: The AWGN System

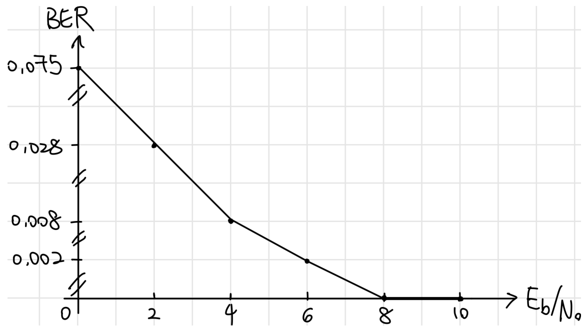

Figure 9: The BER-versus-Eb/No Curve

Figure 9 illustrates the BER-versus-Eb/No curve obtained from the simulation of the AWGN system depicted in Figure 8. The curve shows a typical inverse relationship between BER and Eb/No, where the BER decreases as Eb/No increases. This trend demonstrates the improved performance of the communication system with increasing signal-to-noise ratio, as higher Eb/No values correspond to a lower probability of bit errors during transmission.

Part 2: Basic Digital Modulation Schemes

A. Binary ASK Modulation

This part of the lab guided us through the process of constructing and analyzing a Binary ASK modulation and demodulation system. Utilizing a Bernoulli Binary Generator to create a binary data stream with a probability of zero at 0.5 and an integrate-and-dump filter with an integration period of 8, we modulated a sine wave based on the binary input. The parameters set for the sine wave (Mod) and sine wave (Demod) included a sample-based type with 5000 samples per period and a sample time of 1e-7. We monitored the modulation through the Scope (Mod) to visualize how the binary data stream influenced the signal's amplitude and used a 1-D Lookup Table for demodulation, which was observed on Scope (Demod) to verify the integrity of the signal recovery process.

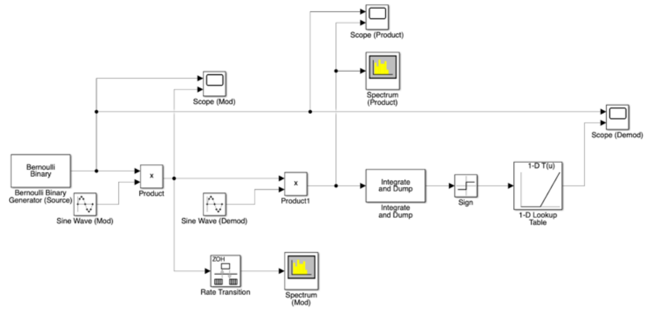

Figure 10: Binary ASK Modulation

Q5. Consider binary ASK. Observe the output on Scope (Mod). Describe how the transmitted signal is generated from the binary data streams. Observe the output on scope (Demod) and explain the results.

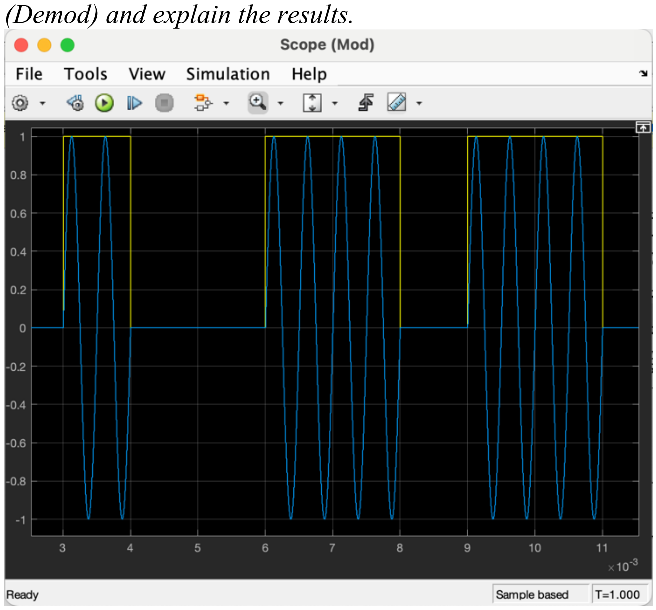

Figure 11: Scope (Mod) for BASK

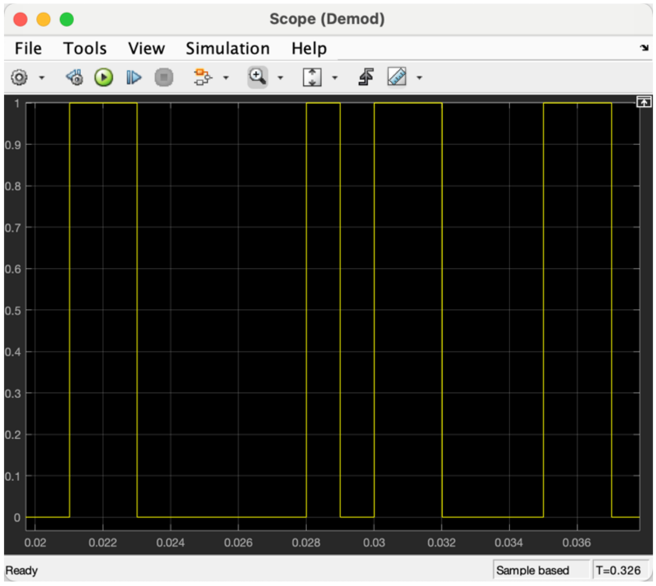

Figure 12: Scope (Demod - Source) for BASK

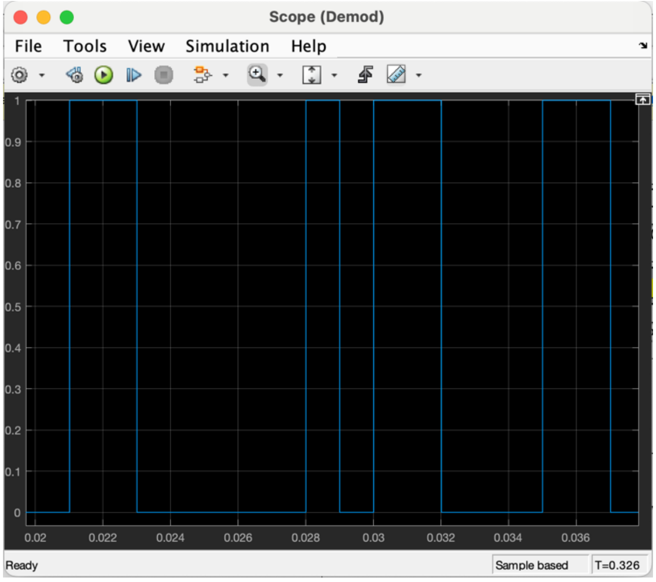

Figure 13: Scope (Demod - Output) for BASK

In Amplitude Shift Keying (ASK), digital data is transmitted by varying the amplitude of the carrier wave. '1' is represented by a high amplitude, while '0' corresponds to a zero amplitude. The Scope (Mod) image shows these variations corresponding to the binary data stream—highs and zeros in the signal indicate '1's and '0's, respectively.

The demodulated signal, as seen in the Scope (Demod) image, shows the recovered binary data as a series of square waves. A high level in this waveform represents a binary '1', and a low level indicates a binary '0'. The demodulation process aims to accurately extract the original digital data from the modulated carrier wave. As we can see from the two Demod scopes, the source and output signals perfectly overlap each other.

In essence, ASK is a simple and effective way to encode and transmit digital data over a carrier wave, with the modulation process involving amplitude changes, and the demodulation process involving the detection of these amplitude variations to reconstruct the original binary sequence.

B. Binary PSK Modulation

In this part of the lab, we constructed a Binary PSK modulation and demodulation model. The key component, a Bernoulli Binary Generator, produced a binary data stream with equal probabilities for '0' and '1'. Using a 1-D Lookup Table with specified data and breakpoints, we modulated a sine wave with 5000 samples per period and a sample time of 1e-7. This setup allowed us to convert the binary data stream into a phase-modulated signal. We then observed and analyzed the modulated signal through a Scope (Mod) to discern how phase changes represented the binary data. Similarly, we examined the demodulated output using another Scope (Demod) to validate the accuracy of the binary PSK demodulation process.

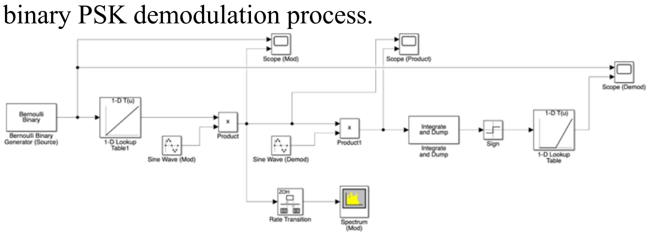

Figure 14: Binary PSK Modulation

Q6. Consider binary PSK. Observe the output on Scope (Mod). Describe how the transmitted signal is generated from the binary data streams. Observe the output on scope (Demod) and explain the results.

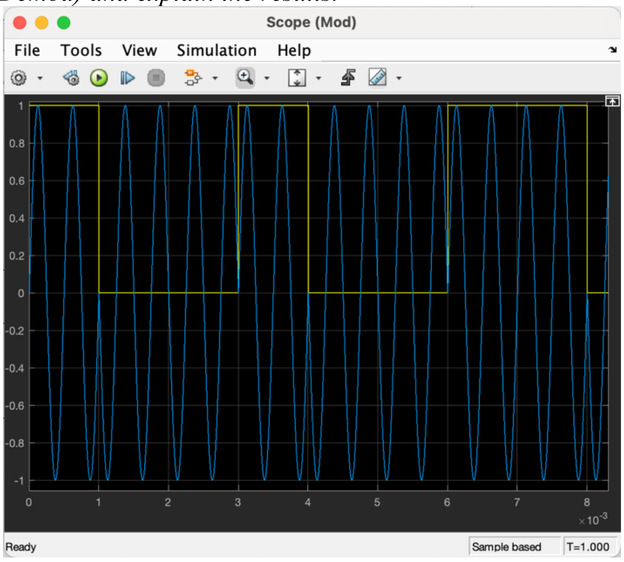

Figure 15: Scope (Mod) for BPSK

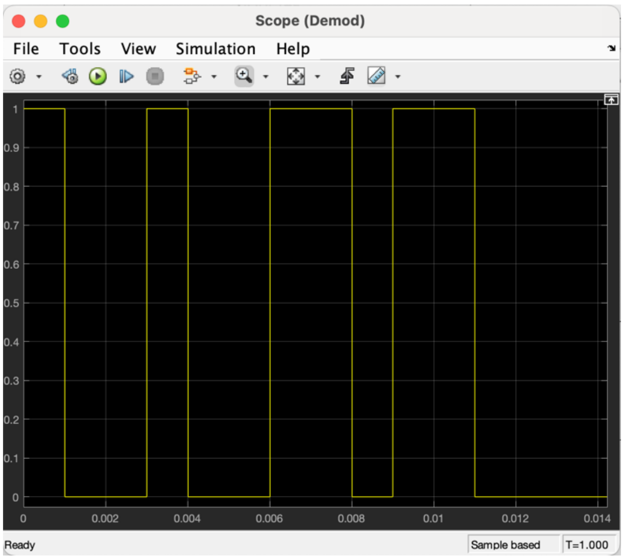

Figure 16: Scope (Demod - Source) for BPSK

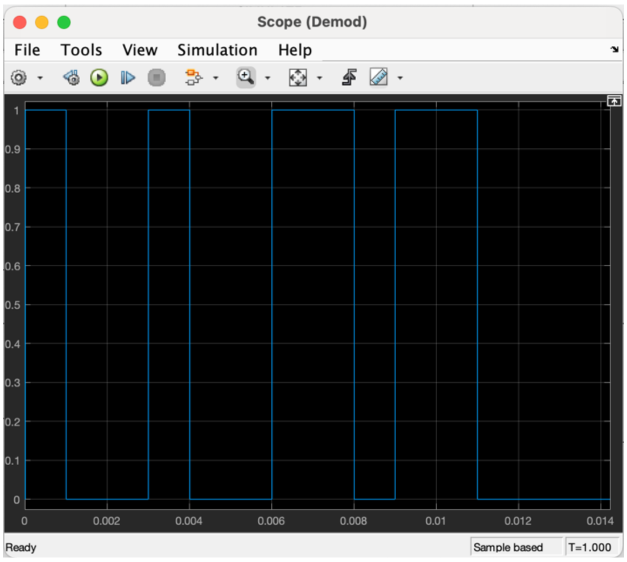

Figure 17: Scope (Demod - Output) for BPSK

Binary Phase Shift Keying (PSK) encodes digital data by altering the phase of a carrier wave. In the Scope (Mod) image, the signal changes phase to represent binary '0' and '1'. A change in binary bit is indicated by a phase shift, 180 degrees from the original signal. These phase changes are abrupt, creating the distinct pattern seen on the oscilloscope.

Demodulation of PSK involves mapping the received phase shifts back to binary data. The Scope (Demod) image displays a rectangular waveform representing the demodulated binary data. Each level of the waveform corresponds to the phase of the modulated signal, with a high level for '1' and low level for '0'. As we can see from the two Demod scopes, the source and output signals perfectly overlap each other.

In essence, binary PSK uses phase shifts to transmit data, with the modulated signal showing these shifts, and the demodulated signal presenting the original binary sequence in a clear, square waveform.

C. Binary FSK Modulation

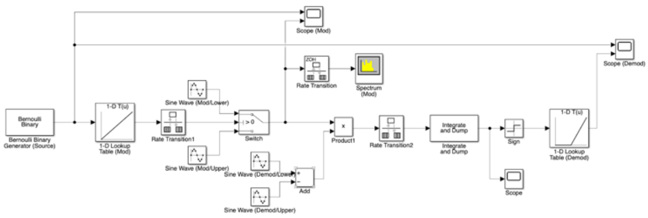

Figure 18: Binary FSK Modulation

This part of the lab focused on constructing a model for Binary FSK modulation and demodulation. We used a Bernoulli Binary Generator to simulate a source of binary data with equal probability for '0' and '1'. The modulation process involved using two sine waves for the lower and upper frequencies, each with a sample-based type, but with different samples per period—4000 for the lower and 2857 for the upper frequency. We examined the modulation output with a Scope (Mod) to observe how the frequency of the carrier wave changes according to the binary input and used a 1-D Lookup Table for the demodulation process. The results on the Scope (Demod) provided insights into the effectiveness of the Binary FSK demodulation technique.

Q7. Consider binary FSK. Observe the output on Scope (Mod). Describe how the transmitted signal is generated from the binary data streams. Observe the output on scope (Demod) and explain the results.

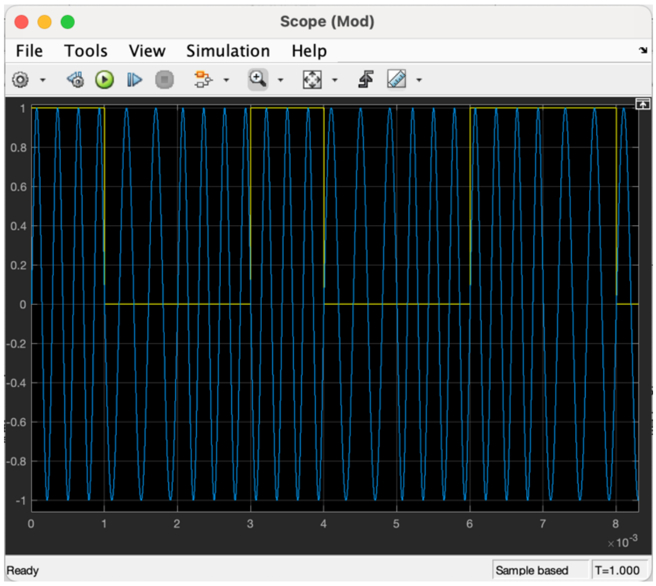

Figure 19: Scope (Mod) for BFSK

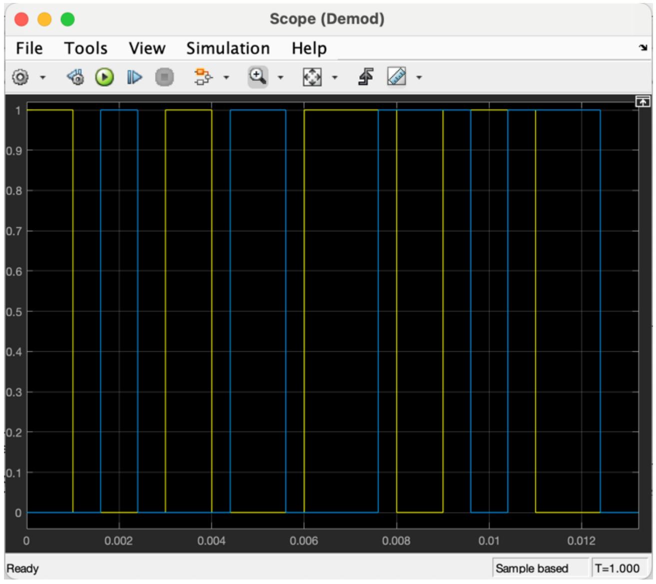

Figure 20: Scope (Demod) for BFSK

Binary Frequency Shift Keying (FSK) is a form of frequency modulation where binary data is represented by changes in the frequency of the carrier wave. In the Scope (Mod) image, the transmitted signal shows two distinct frequencies. One frequency represents a binary '1' and a second, usually lower frequency, represents a binary '0'. The transitions between these frequencies are aligned with the edges of the binary data stream.

Demodulation of FSK involves detecting these frequency changes and converting them back into binary data. The Scope (Demod) image illustrates the demodulated signal as a series of high and low levels, corresponding to the frequencies representing '1's and '0's, respectively. The demodulator's task is to interpret the incoming frequencies and output the correct binary sequence. From the Demod scope, it's evident that the source and output signals have a phase shift comparing to the original signal. In the demodulated BFSK signal, these phase shifts are usually manifested as a gradual transition from one level to another, rather than an instant jump. This is observable on an oscilloscope as a slight diagonal slope instead of a vertical line during the bit transitions. The important point for BFSK is that the data is still recoverable despite these phase shifts, as the demodulator is designed to interpret the frequency changes correctly.

In summary, binary FSK transmits digital data through distinct frequencies for each binary state, as seen in the modulated signal Scope (Mod), and the demodulated signal Scope (Demod) reveals a binary waveform that reconstructs the original data from the frequency variations.

Q8. Specify the carrier frequencies used for modulation and the corresponding frequency separation.

The signal frequency for a binary value of 0 was 4000 Hz, while for a binary value of 1 it was 2857 Hz. Therefore, the carrier frequency is 3428.5 Hz, the frequency separation between the two binary values is 1143 Hz, and the half frequency spacing is 571.5 Hz in this case.

D. 4-QAM Modulation

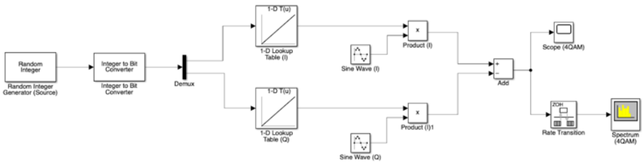

Figure 21: 4-QAM Modulation

In this part of the lab, it instructs on building a Quadrature Amplitude Modulation (QAM) system that conveys two bits per symbol, effectively combining both amplitude and phase modulation. Parameters were set using a Random Integer Generator with a set size of 4 and an Integer to Bit Converter to map these integers into two-bit sequences. For the in-phase (I) and quadrature (Q) components, 1-D Lookup Tables and Sine Waves with 5000 samples per period were used, with the Q component having an offset. These components were then integrated to form the 4-QAM signal, which was observed on Scope (Mod) to analyze the resultant waveform that combines both amplitude and phase variations to represent the binary data streams.

Q9. Consider 4-QAM. Observe the output on Scope (Mod). Describe how the transmitted signal is generated from the binary data streams.

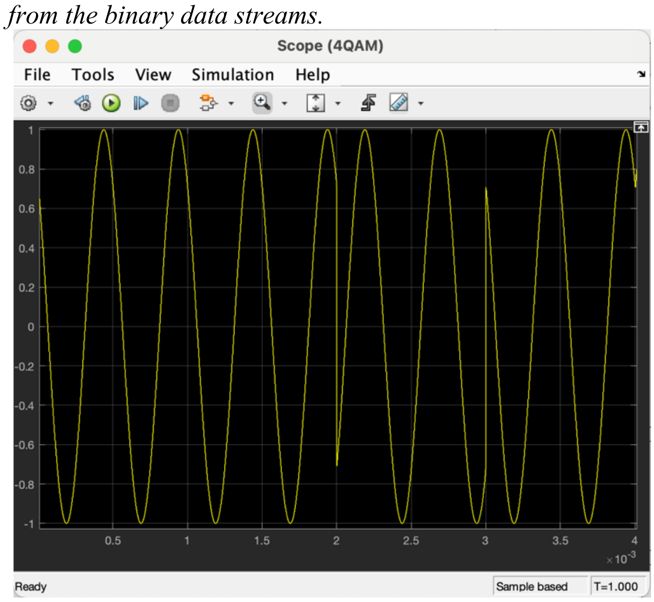

Figure 22: Scope (Mod) for 4-QAM

In this part of the lab, we analyze the modulation process of 4-QAM (Quadrature Amplitude Modulation), as observed in the provided Scope (Mod) output. 4-QAM, also known as QPSK (Quadrature Phase Shift Keying), is a modulation scheme that transmits two bits per symbol, effectively doubling the bit rate compared to traditional binary modulation schemes.

The Scope (Mod) image is interpreted as the visualization of a 4-QAM modulated signal. This signal is generated by superimposing two carrier waves that are 90 degrees out of phase—known as the in-phase (I) and quadrature (Q) components. Each bit pair from the binary data stream determines the amplitude of these carrier waves. The I and Q channels carry different bits, and their superposition creates the final signal with unique amplitude and phase for each symbol.

For 4-QAM, the binary stream is first divided into pairs, where each pair maps to one of four distinct symbols. These symbols correspond to specific amplitude and phase changes in the I and Q carriers. The Scope (Mod) output likely shows these amplitude variations, representing the encoded binary data.

Q10. Explain how 4-QAM can be implemented from binary PSK. Explain how the power spectrum of 4-QAM is related to that of binary PSK.

In digital communications, 4-QAM or QPSK can be conceptualized as an evolved form of Binary PSK (BPSK). BPSK is a simple form of phase modulation that uses two phases to represent binary '0' and '1'. To implement 4-QAM from BPSK, we utilize two orthogonal BPSK signals, where one signal modulates the in-phase component (I) and the other the quadrature component (Q).

Each BPSK signal is capable of transmitting one bit per symbol period. By combining two such signals, we effectively transmit two bits per symbol period with 4-QAM. This is achieved by mapping pairs of bits to four different phase shifts, each 90 degrees apart. This technique allows us to increase the data rate without increasing the bandwidth of the signal.

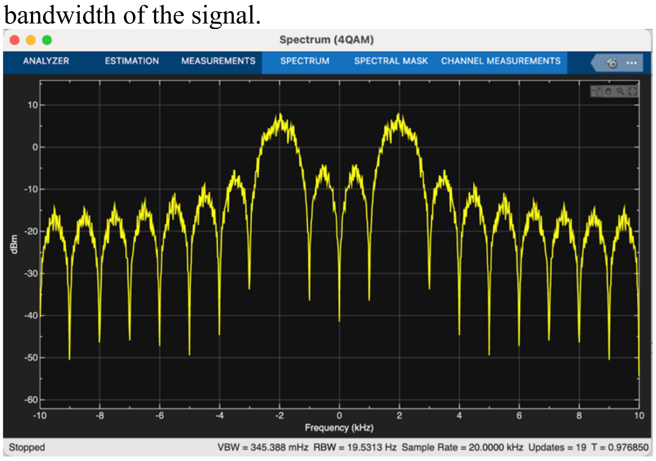

Figure 23: Spectrum for 4-QAM

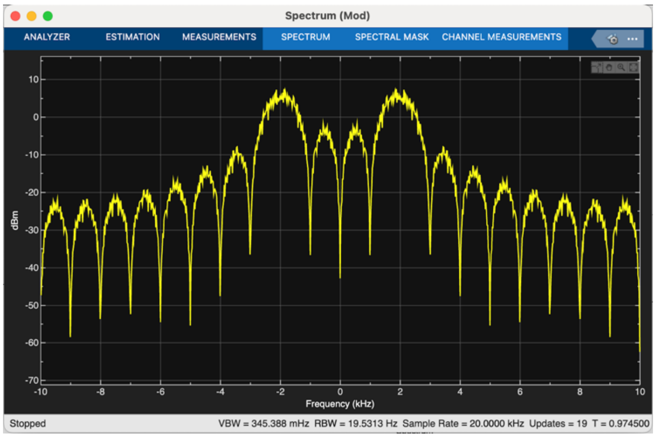

Figure 24: Spectrum for BPSK

From the above figures obtained from Simulink, they depict the spectrums of 4-QAM and BPSK. The power spectrum of a modulated signal provides a representation of its energy distribution over a range of frequencies. For BPSK, the spectrum has a single main lobe, with the bandwidth being a function of the bit rate. The transition to 4-QAM retains the same overall bandwidth but effectively doubles the bit rate because it transmits two bits per symbol period instead of one.

The similarity in the shape of the power spectrum between BPSK and 4-QAM stems from the fact that they both modulate a carrier in phase; however, 4-QAM is more spectrally efficient. In 4-QAM, the energy is distributed across the same bandwidth as BPSK but carries twice the information, thanks to the two orthogonal carriers. This characteristic is crucial in bandwidth-constrained systems where maximizing data throughput is essential.

In conclusion, 4-QAM can be seen as two BPSK systems overlaid on each other, utilizing the same bandwidth to double the data rate. This efficient use of bandwidth is evidenced by the power spectrum, which remains similar in width to BPSK but supports a higher data transmission rate.

Conclusion

In conclusion, this lab has analyzed the fundamental principles and implementation techniques of various digital modulation schemes, including Binary ASK, Binary PSK, Binary FSK, and 4-QAM. Each modulation method offers a unique approach to encode binary data onto a carrier wave, whether through amplitude, phase, or frequency variations. 4-QAM, as an extension of BPSK, leverages quadrature carriers to double the data rate within the same bandwidth. The power spectra of BPSK and 4-QAM have been compared to highlight the spectral efficiency of 4-QAM. These modulation techniques are critical in optimizing the use of bandwidth and improving data transmission rates in communication systems, underpinning the continuous advancement in digital communications.

References

[1] "L3: Digital Transmission Techniques" McGill University. https://mycourses2.mcgill.ca/d2l/le/lessons/688501/topics/7661048 (accessed Feb. 12, 2024)

Experiment was taken in the laboratory section of ECSE 308 at McGill University, Montreal, QC, H3A 0E9, Canada.