Lab 3: Digital Transmission Techniques

ECSE 308 Introduction to Communication Systems and Networks

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Abstract: The lab is divided into three sections. The first part has a focus on baseband digital transmission where the goal is to understand the basic concepts of analog to digital and digital to analog conversions, baseband digital transmission over AWGN channels, SNR and BER. The second session have an objective of understanding digital modulation schemes like binary PSK, ASK, FSK, and 4QAM, and the modulated signal power spectra. The goal of third section is to understand the basic principles of 16-QAM modulation and demodulation, the effect of noise through scatterplots, the relationship between SNR and BER, and the power and bandwidth efficiencies.

Introduction

Analog-to-digital is a system that converts an analog signal that is continuous in terms of both time and amplitude into a digital signal that's discrete in terms of both time and amplitude. Digital-to-analog is the reverse where a system converts the digital signal to analog.

PSK also known as phase shifting key is a modulation process conveys data by changing the phase of the wave.

ASK also known as amplitude shift keying is a modulation technique based on amplitude. If transmitting data is 1, ASK modulated signal is carrier signal, otherwise 0.

FSK also known as frequency shift keying is a modulation technique in which information is encoded on the carrier signal by periodically shifting the frequency of the carrier between several discrete frequencies.

4QAM conveys two bit streams by modulating the amplitude of two carrier waves. These waves share the same frequency but are out of phase with each other. The carrier signal can exist in four distinct states, each representing a unique two-bit combination.

16QAM is a more complex modulation technique, allowing the carrier to exist in 16 different states. Each state represents a unique four-bit combination, enabling higher data rates.

Analysis

Part I: Baseband digital transmission

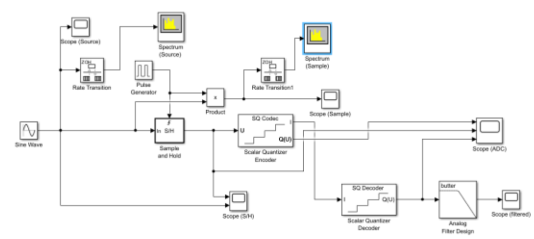

Figure 1: ADC/DAC System Set Up

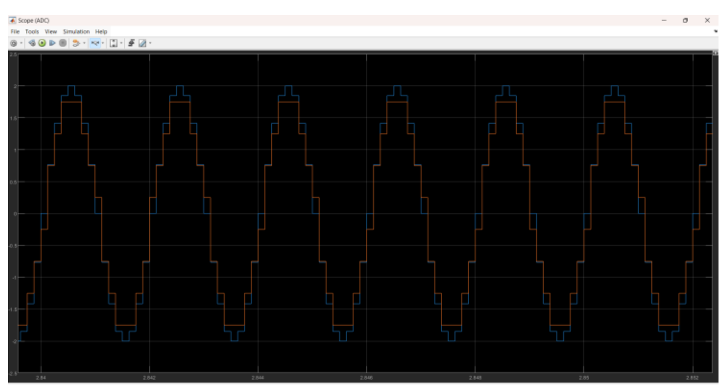

Figure 2: Scope (ADC)

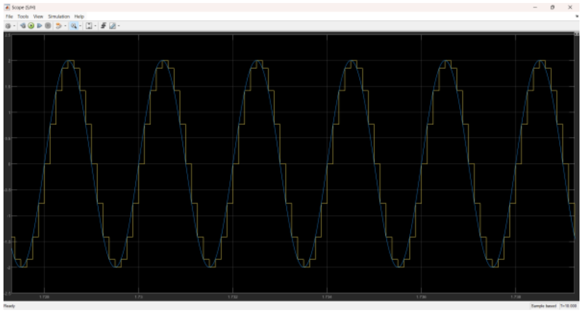

Figure 3: Scope (S/H)

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.

The output of the Scope (ADC) is blockier than the output of the Scope (S/H). Which means that the sample-and-hold circuit output is being processed by a quantizer that maps it to one of a fixed discrete number. In the process of converting analog to digital, the signal goes through the sample and hold (S/H) stage and processes by the S/H circuit. This circuit captures the amplitude of the analog signal at each sampling time and holds it until the next sample. Then the scalar quantizer encoder converts the sampled and quantized signal into a digital binary output, which allows further processing.

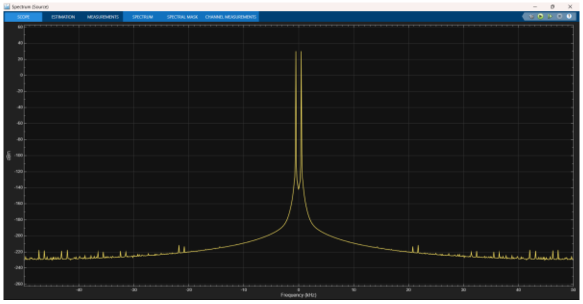

Figure 4: Spectrum (Source)

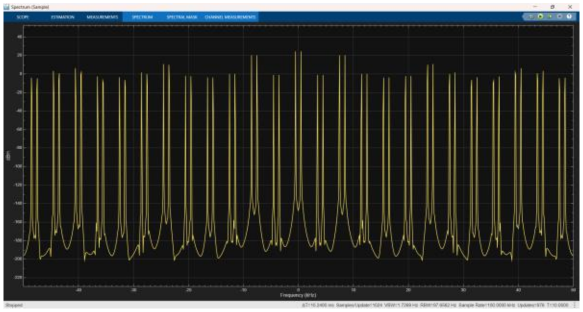

Figure 5: Spectrum (Sample)

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

The effect on the spectrum of the source signal when multiplied with a pulse train gives a spectral replica at intervals equal to the sampling frequency. The spectrum has been duplicated many times. Using a low pass filter will remove all but the original spectrum.

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]; Scalar Quantizer Decoder Codebook values: [-1.5:1:1.5]

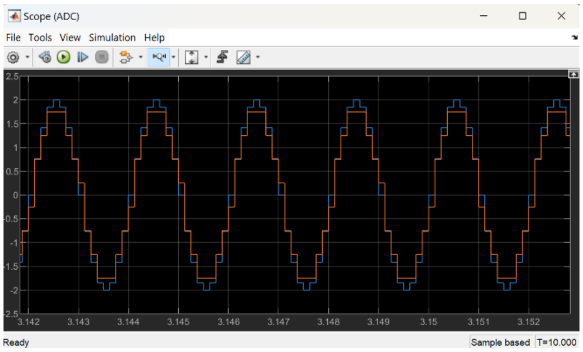

Figure 6: Scope (ADC) with original parameter

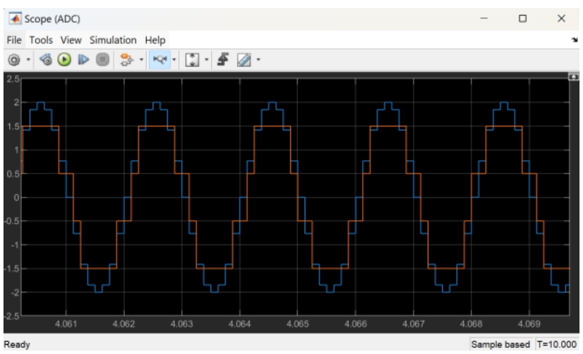

Figure 7: Scope (ADC) after parameter change

The number of quantization level of the ADC scope prior to the change of parameters is 7, and the bits required to represent the 7 level is 3 bits. After the change of parameters, the quantization level is 4 and the quantization bits required is 2 bits.

Q4: plot the BER-versus-Eb/No curve with Eb/No (dB) = 0, 2, 4, 6, 8, 10

Eb/No (dB)	BER
0	0.1416
2	0.1032
4	0.05784
6	0.02369
8	0.0057
10	0.001

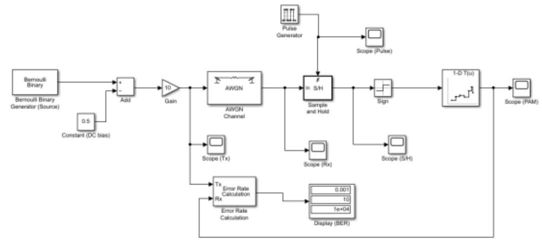

Figure 8: Illustration for Q4

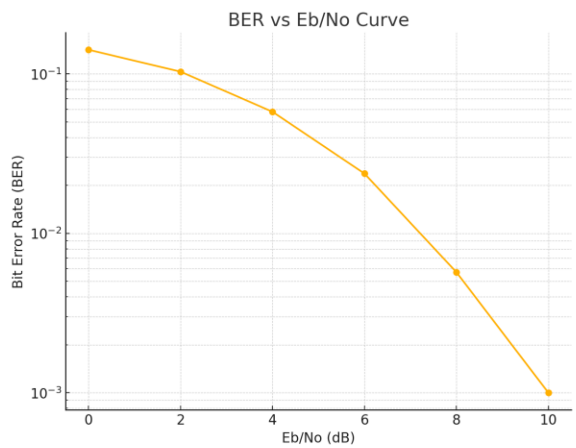

Figure 9 BER vs Eb/No Curve

Part II: Basic Digital Modulation Schemes

A). Binary ASK Modulation

Q1: Consider binary ASK. Observe the output on Scope(mod). Describe how the transmitted signal is generated from the binary data streams.

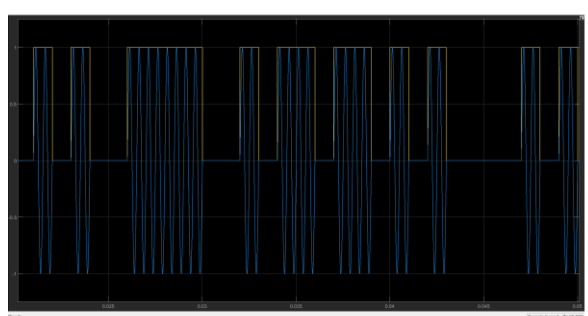

Figure 10 Binary ASK Modulation Scope

Binary ASK is also known as on and off keying. Binary one is represented by the presence of a carrier, while binary zero is represented by absence of the carrier. As shown in the Figure above, when the carrier is one, the signal is transmitted. When the carrier signal is zero, no signal is transmitted.

B). Binary PSK Modulation

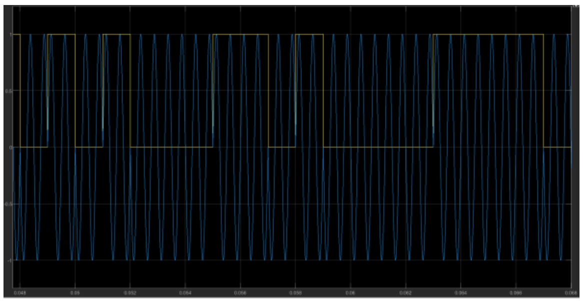

Figure 11 Binary PSK Modulation Scope

Q2: Consider binary PSK. Observe the output on Scope (Mod). Describe how transmitted signal is generated from the binary data streams.

In BPSK, the carrier signal is modified by altering its phase by 180 degrees. For binary 0, the phase shift is 180 degrees. For binary 1, there is no phase shift. From the graph above, we can observe the phase difference.

C). Binary FSK Modulation

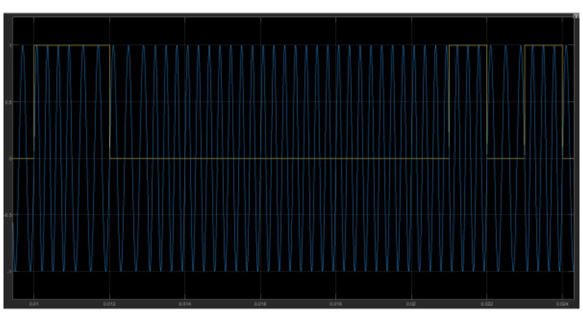

Figure 12 Binary FSK Modulation Scope

Q3: Consider binary FSK. Observe the output on Scope (Mod). Describe how the transmitted signal is generated from the binary data streams. Specify the carrier frequencies used for modulation and the corresponding frequency separation

Frequency shift keying is a frequency modulation scheme. Binary zero and binary one has different operating frequency. It can be observed from the figure above. The signal frequency for are 2500 Hz and 3500 Hz respectively. The carrier frequency is 3000 Hz and the frequency separation was 500 Hz.

C). 4-QAM Modulation.

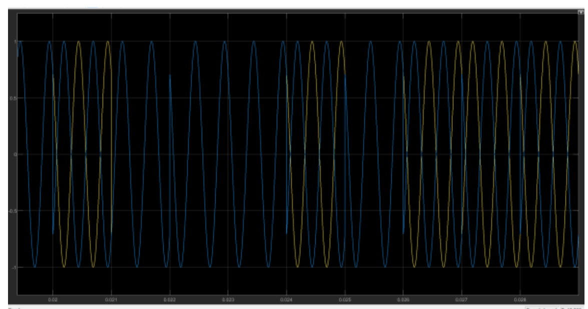

Figure 13 4 QAM Scope

Q4: Consider 4-QAM. Observe the output on Scope (Mod). Describe how the transmitted signal is generated from the binary data streams. 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.

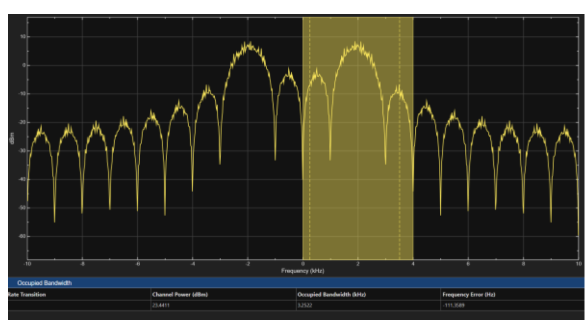

Figure 14 Binary PSK Spectrum

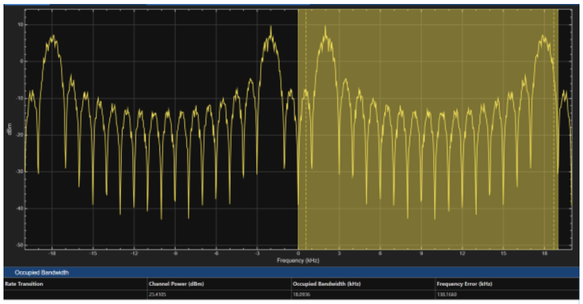

Figure 15 4 QAM

4-QAM is a modulation technique that employs both phase modulation and amplitude modulation. It is represented by 2-D vector to show all possible symbols that may be selected by a given modulation scheme as points in 2-D plane. It groups every 2 bits to form a symbol represented by phase change. The core idea is similar to binary PSK. The shift of 4-QAM are 45, 135, 225, 315 degrees. The binary data can be split into two streams with same frequency, one for each bit of the two-bit symbol. Apply BPSK to each stream independently. Combining both components lead to one of four possible phase shifts, forming 4-QAM constellation points. Noting we would add onto it a change in amplitude of the two carrier waves.

Since 4-QAM and BPSK use similar modulation techniques, they exhibit similar shape. However, 4-QAM has a faster bit rate and therefore better efficiency. They have a very similar power. Since power is proportional to amplitude, both didn't have any modulation toward the amplitude. Thereby, they should display similar channel power. As shown in the Figure above, they both exhibit channel power around 23 dB.

Q5: What are the transmission bandwidth of binary ASK and binary PSK? Explain how their power spectra are related.

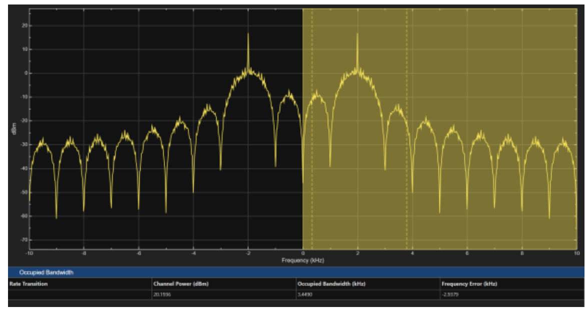

Figure 16 ASK Spectrum

The Bandwidth of PSK is 3.252 kHz and the bandwidth of ASK is 3.44 KHz. Binary ASK modulates the amplitude of the carrier signal while binary PSK only modulates the phase. Both produces power spectra with a central lobe and side lobes. The width of the main lobe is similar for both ASK and PSK, as they transmit data at the same rate. The side lobes of ASK are more pronounced as it involves on and off of the amplitude. PSK is generally more efficient than ASK.

Q6: What is the transmission bandwidth of binary FSK? For binary ASK, PSK, and FSK, which ones is most bandwidth efficient.

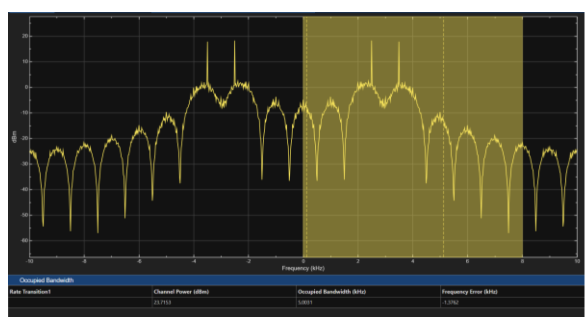

Figure 17 Binary FSK Spectrum

Transmission bandwidth for FSK is 5 kHz. For ASK, its 3.449 kHz. For 4-QAM, it's 18.09 kHz. For PSK, its 3.252 kHz. PSK has the highest efficiency. It only changes the phase of the carrier while keeping the amplitude constant. It results in a more compact spectrum for the same bit rate.

Part III

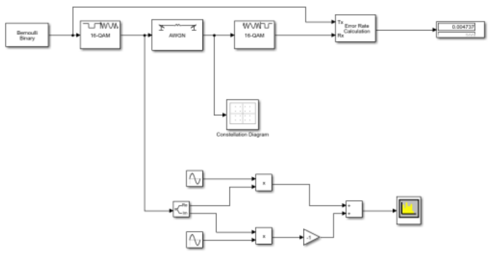

Figure 18: Part 3 Illustration

Q1: *Observe the output on constellation. How many bits does each symbol carry? Describe the mapping between bits and symbols. Explain how 16QAM can be expressed as an orthogonal superposition of two lower-order real modulation schemes.*

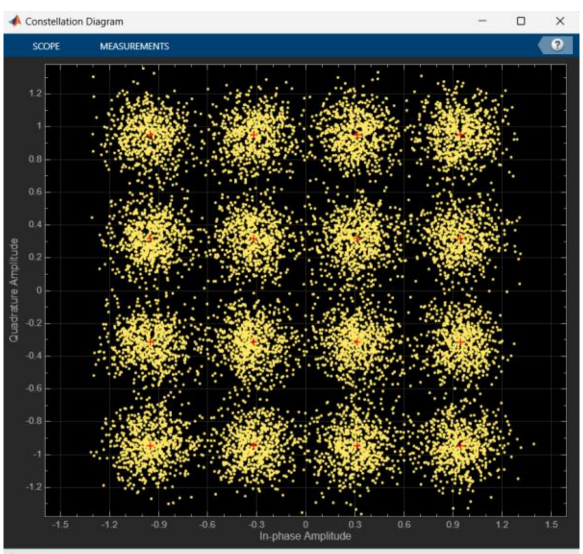

Figure 19: Es/No = 15

In 16QAM, each symbol carries 4 bits, because 16 = 2^4. In the constellation, each symbol represents a unique 4 bits sequence. In order to modulate the 16 QAM signals, each of the unique 4 bits are separated into 2 streams. The two MSBs are the in-phase component, and the two LSBs are the quadrature component. The in-phase component varies the amplitude on the horizontal axis and the quadrature component varies along the vertical axis and thus they are perpendicular to each other, so they are orthogonal. The in-phase and quadrature component can also be thought of as two independent 4 level PAM schemes, which is two lower order real modulation schemes.

Q2: Describe how a noisy received signal is demodulated.

The constellation is also a decision region that is being divided into 16 non overlapping regions. Using these decision regions, the receiver can map each of their received signal to the appropriate constellation point given that its representation in the (I, Q) plane falls into the decision region of this constellation point.

Q3: Observe the output on Constellation Diagram. Explain the effect of additive white Gaussian noise on the transmitted signals.

The AWGN allows the dots on the constellation to spread out randomly around the 16 symbols, which may cause the demodulator to misinterpret the noisy symbols which leads to errors.

Q4: change Es/No(dB) in AWGN Channel. Run the simulation. Observe the output on Constellation Diagram. Explain how SNR affects the received constellation and therefore the BER.

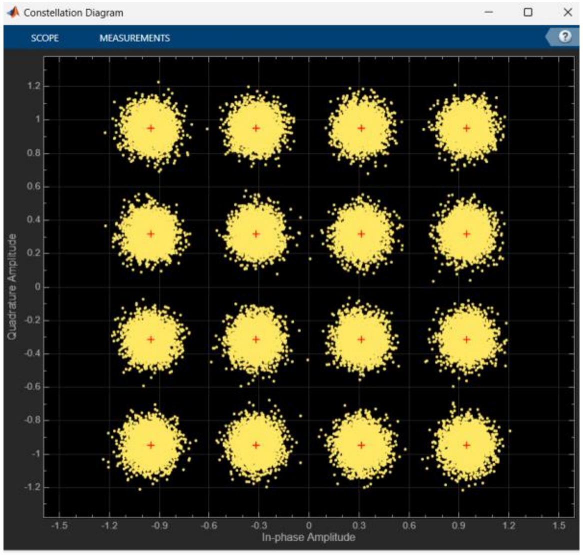

Figure 20: Es/Eo = 20

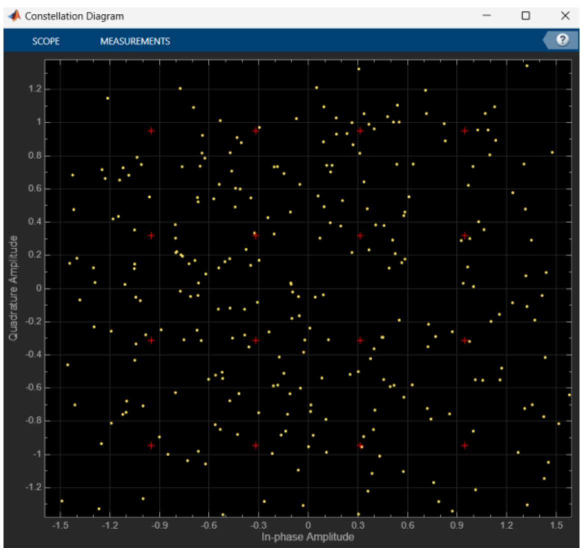

Figure 21: Es/No = 5dB

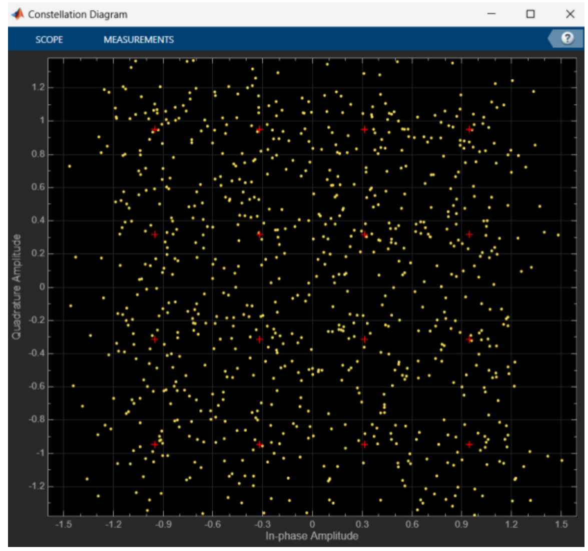

Figure 22: Es/No = 10 dB

If the SNR is higher, meaning that there is less noise, which gives less impacts. Only a group of points that are closer to the ideal position can allow the noise to have low impact on the receiver's interpretation. So according to the figures, the higher SNR, the more centralized each group of point is to their intended positions, the less likely the symbol is being mistaken for each other and thus a lower BER.

Q5: Plot the BER-versus-Es/No from 5 dB to 20 dB

	5 dB	10 dB	15 dB	20 dB
BER	0.1701	0.05852	0.004737	1e-6

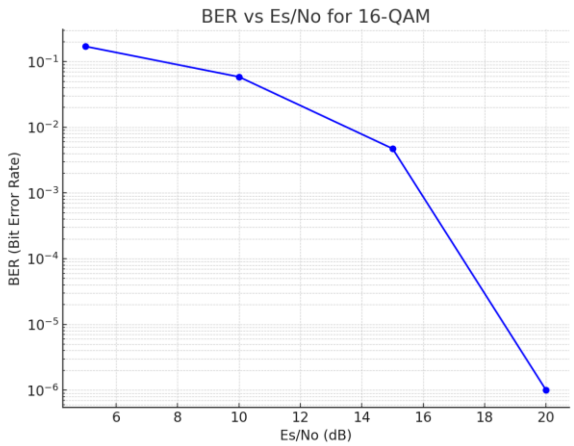

Figure 23 BER vs Es/No for 16 QAM

Q6:

1) Observe the output on constellation. How many bits does each symbol carry? Describe the mapping between bits and symbols. Explain how 64 QAM can be expressed as an orthogonal superposition of two lower-order real modulation schemes.

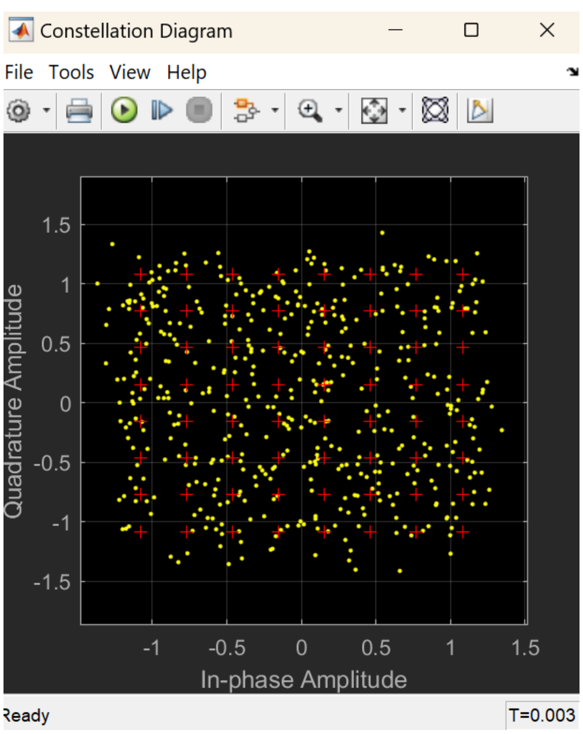

Figure 24 64QAM 15 dB

In 64QAM, each symbol carries 6 bits, because 64 = 2^6. In the constellation, each symbol represents a unique 6 bits sequence. In order to modulate the 64 QAM signals, each of the unique 6 bits are separated into 2 streams. The 3 MSBs are the in-phase component, and the 3 LSBs are the quadrature component. A pattern of 000000 may maps to a point in the bottom left corner and a pattern of 111111 may map to the symbol point in the top right corner

The in-phase component varies the amplitude on the horizontal axis and the quadrature component varies along the vertical axis and thus they are perpendicular to each other, so they are orthogonal. The in-phase and quadrature component can also be thought of as two independent 8 level PAM schemes, which is two lower order real modulation schemes.

2): Describe how a noisy received signal is demodulated.

The constellation is also a decision region that is being divided into 64 non overlapping decision regions. Using these decision regions, the receiver can map each of their received signal to the appropriate constellation point given that its representation in the (I, Q) plane falls into the decision region of this constellation point.

3): Observe the output on Constellation Diagram. Explain the effect of additive white Gaussian noise on the transmitted signals.

The AWGN allows the dots on the constellation to spread out randomly around the 64 symbols, which may cause the demodulator to misinterpret the noisy symbols which leads to errors.

4): change Es/No(dB) in AWGN Channel. Run the simulation. Observe the output on Constellation Diagram. Explain how SNR affects the received constellation and therefore the BER.

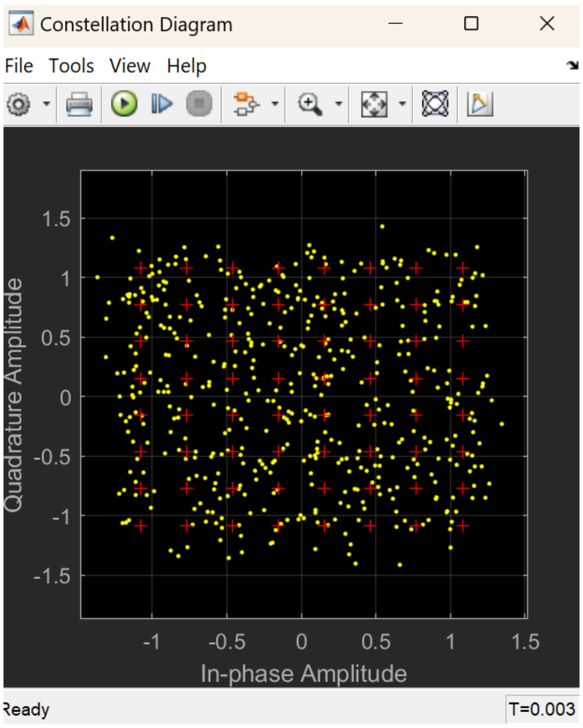

Figure 25 64QAM 15 dB

If the SNR is higher, meaning that there is less noise, which gives less impacts. Only a group of points that are closer to the ideal position can allow the noise to have low impact on the receiver's interpretation. So according to the figures, the higher SNR, the more centralized each group of point is to their intended positions, the less likely the symbol is being mistaken for each other and thus a lower BER.

5): Plot the BER-versus-Es/No from 5 dB to 20 dB

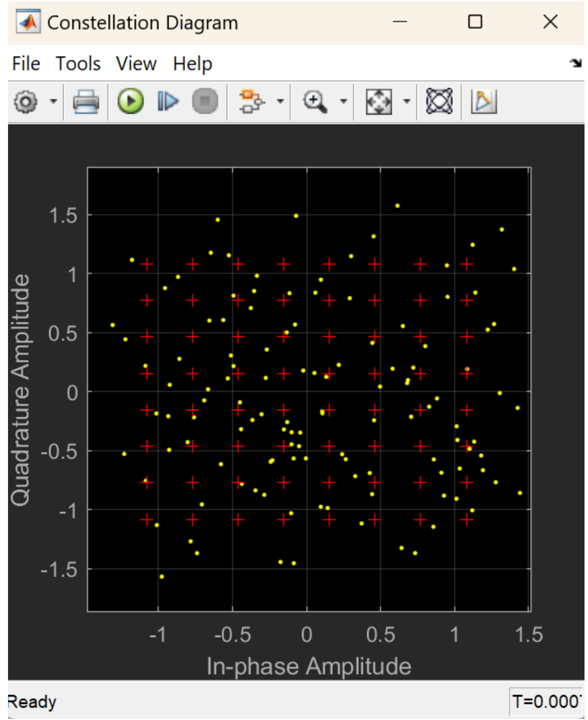

Figure 26 64QAM 5 dB

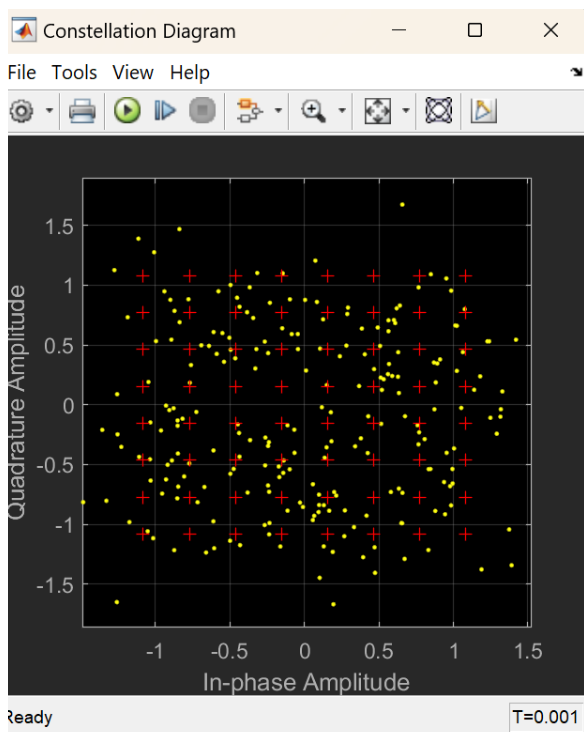

Figure 27 64QAM 10 dB

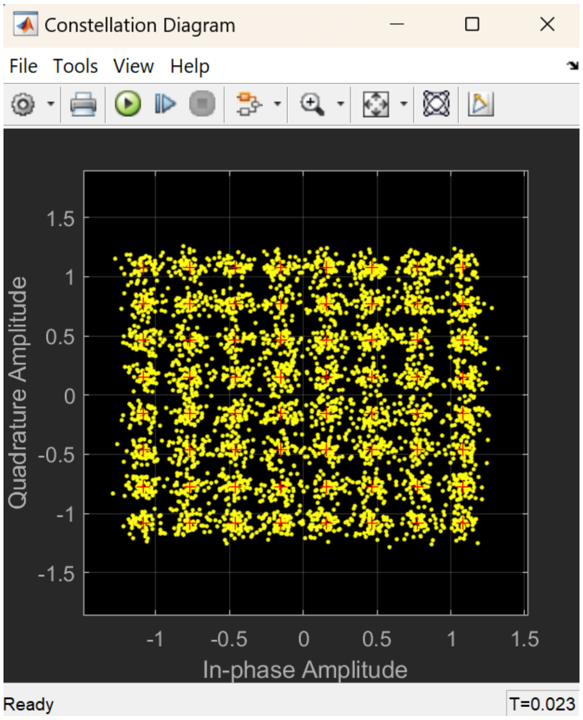

Figure 28 64 QAM 20 dB

	5 dB	10 dB	15 dB	20 dB
BER	0.2659	0.1508	0.06887	0.008804

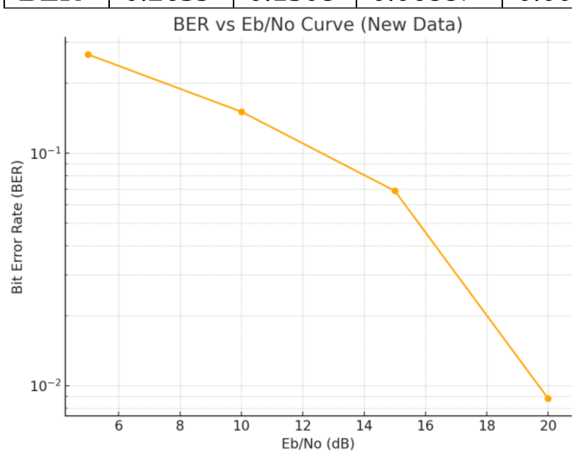

Figure 29 BER vs Eb/No for 64 QAM

*Q7: Repeat Step 5 for 256-QAM. How to set **Bernoulli Binary Generator (Source)**, **Rectangular QAM Modulator Baseband**, **Rectangular QAM Demodulator Baseband**, **AWGN Channel**, and **Constellation Diagram**? Comment on the differences in BERs. Observe the outputs on **Constellation Diagram** and **Spectrum**. Explain why the BER performances are different from the viewpoint of transmission bandwidth and the distance between constellation symbols.*

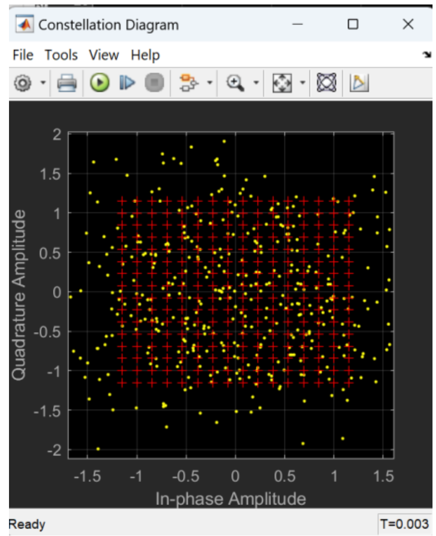

Figure 30 256 QAM 5 dB

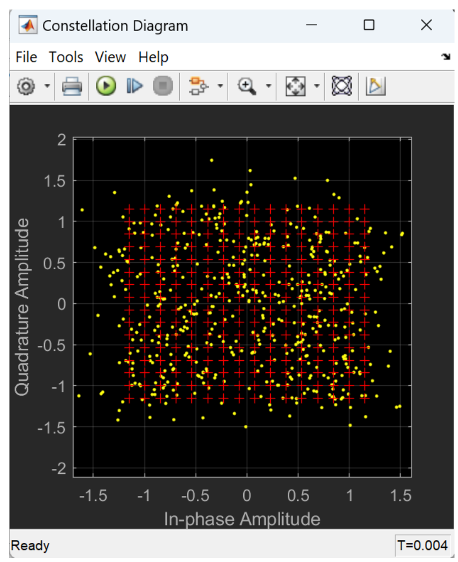

Figure 31 256 QAM 10 dB

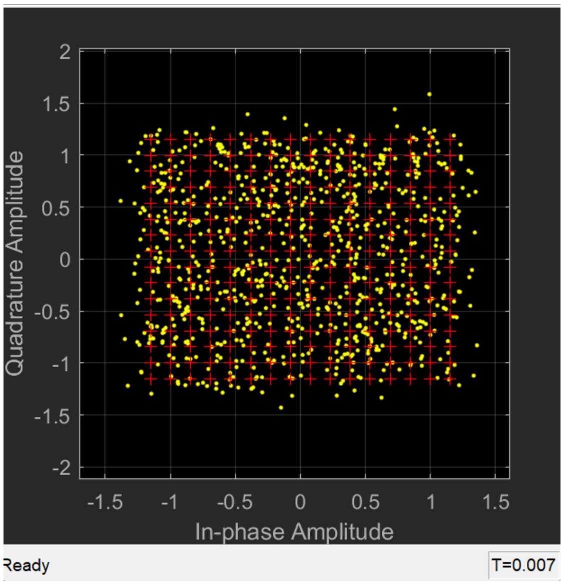

Figure 32 256 QAM 15 dB

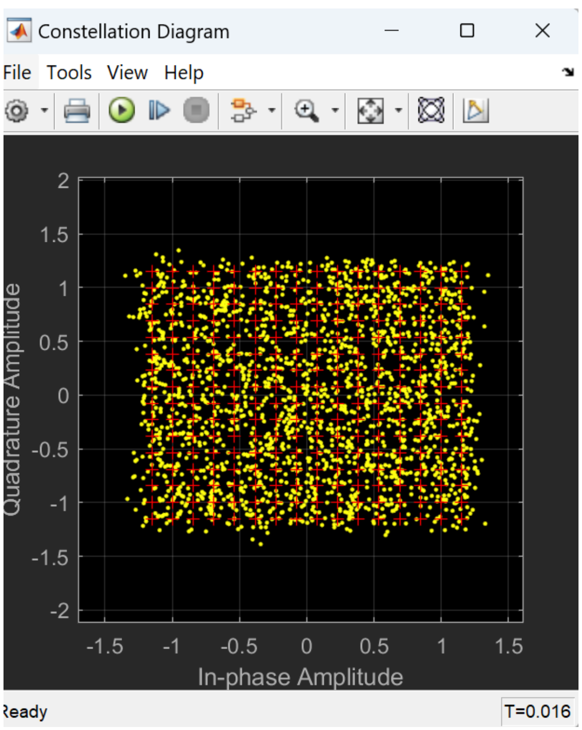

Figure 33 256 QAM 20 dB

	5 dB	10 dB	15 dB	20 dB
BER	0.3102	0.2294	0.1316	0.06562

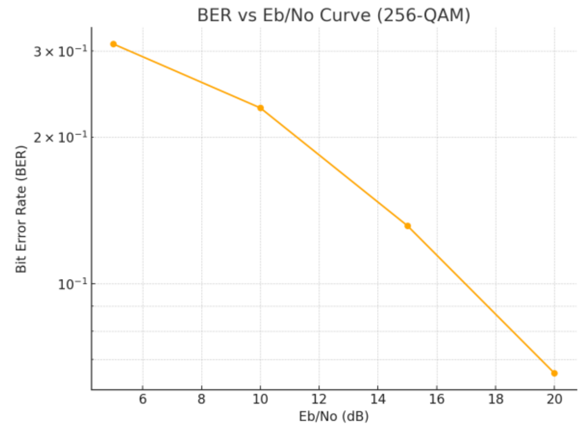

Figure 34 BER vs Eb/No for 256 QAM

In 256QAM, each symbol carries 6 bits, because 256 = 2^8

For the parameter setup, only the changed settings are listed below:

Bernoulli Binary Generator (Source): Samples per frame: 8, because 256 is 2^8.

Rectangular QAM Modulator Baseband: M-ary number: 256

AWGN Channel: Symbol period = 8e-6

Constellation Diagram: Reference constellation: Set to 256-QAM

Rectangular QAM Demodulator Baseband: M-ary number: 256

Error Rate Calculation: Target number: 1000, because 200 limited the amount of samples and caused the spectrum analyzer to not be able to perform the Fourier Transform.

The 256 QAM constellation has many more symbol points. These symbols occupy the same amount of space as those of the 16QAM and 64QAM, leading to the higher chance of misinterpretation and noise because of the shorter Euclidean distance between them. Thus, the BER of the 256 QAM is higher than the 64 QAM and significantly higher than that of the 16 QAM.

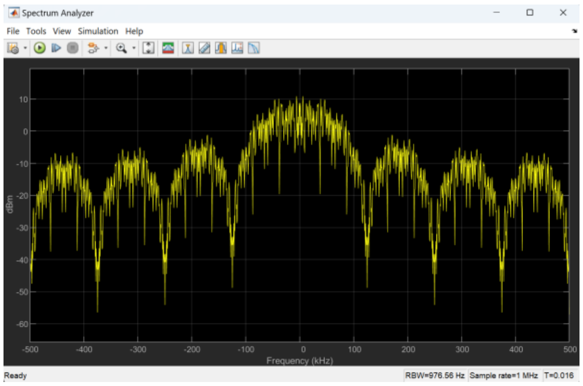

Figure 35 Spectrum at 20 dB

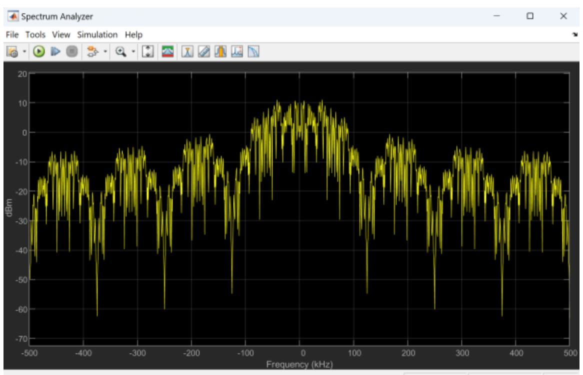

Figure 36 Spectrum at 15 dB

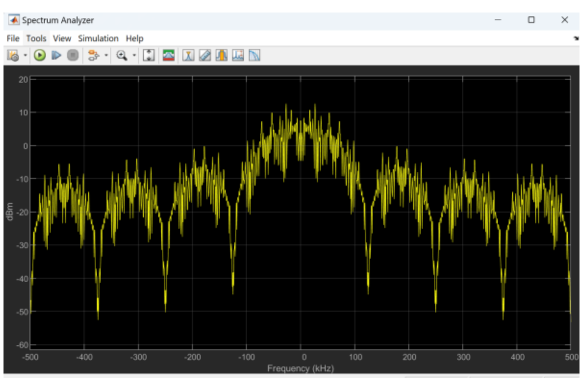

Figure 37: Spectrum at 10 dB

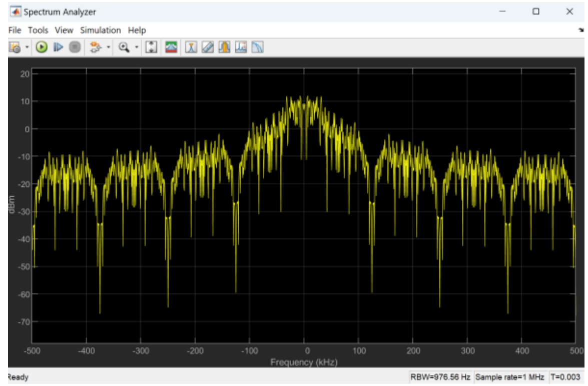

Figure 38 Spectrum at 5 dB

From the spectrum, it can be seen that as the Es/No decreases, there is more noise, and the noise floor is raised. A higher order modulation scheme like 256 QAM require higher transmission bandwidth because there are more information contained per symbol. When the bandwidth is fixed, the 256 QAM has higher bits per Hz, but it is more prone to noise and thus a higher BER.

Conclusion

In conclusion, the processes of analog-to-digital and digital-to-analog conversions serve as fundamental steps in digital communication, translating continuous signals into discrete forms and vice versa. Digital modulation techniques like PSK, ASK, and FSK enable efficient data transmission by encoding information through various signal properties—phase, amplitude, and frequency. Advanced techniques such as 4QAM and 16QAM increase data throughput by allowing multiple bits per symbol.