

# RH\_ACDA5008\_Assignment

*by Rhys Higgins*

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# SIMULATION OF DIGITAL MODULATION TECHNIQUES (ACDA5008)

DIGITAL SIGNAL PROCESSING AND COMMUNICATIONS

## ABSTRACT

The contents of this report consider the effect of AWGN, Additive White Gaussian Noise, on four Digital Modulation Schemes, ASK, PSK, QPSK, and 16-QAM with respect to the BER (Bit Error Rate) of the demodulated signal; each modulation scheme is modelled using the Simulink application in MATLAB. This report has found that the BER is directly proportional to increasing AWGN and data rate. 16-QAM was found to be the most affected modulation scheme by increasing AWGN and PSK was found to be the least influenced by AWGN.

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## Introduction

The aim of this report is to critically compare the performance of digital modulation schemes in the presence of AWGN, using Simulink. Digital modulation being the varying of one, or more, properties of a periodic carrier waveform encoding information from the message signal [1]. In this report, the AWGN is used to simulate the random noise experienced on a communications channel [1]. The performance of each modulation scheme will be measured using the Bit Error Rate (BER), BER referring to the number of bit errors per unit time, commonly given as a percentage derived from **Equation 1** [2]. System failure for BER in communications commercially is given as  $10e - 6$  in this report system failure will be considered at a BER of  $10e - 1$ .

$$BER = \frac{\text{total number of error bits}}{\text{total number of transmitted bits}}$$

Equation 1: Bit Error Rate

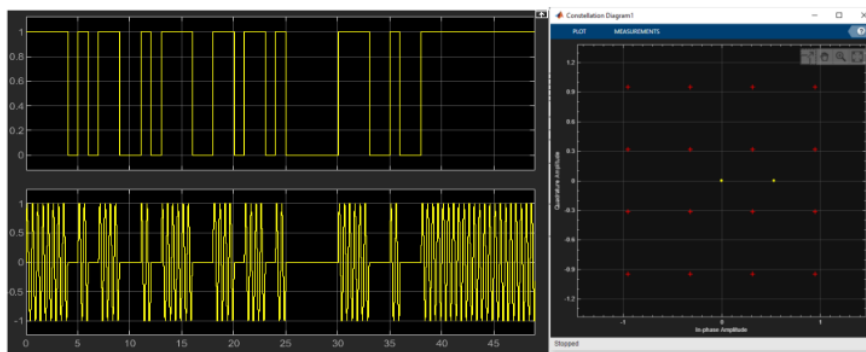
Bit Error Rate (BER) has an inverse relationship to the Signal to Noise Ratio (SNR), which is the ratio of Signal Noise to Signal Power, given in **Equation 2** [3].

$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}}$$
$$SNR(dB) = 10 \log_{10} \frac{\text{Signal Power}}{\text{Noise Power}}$$

Equation 2: Signal to Noise Ratio

The basic modulation schemes to be considered include ASK, Amplitude Shift Keying, and PSK, Phase Shift Keying; the advanced coherent multilevel (M-ary) modulation schemes considered being QPSK, Quadrature Phase Shift Keying, and 16-QAM, Quadrature Amplitude Modulation.

For ASK modulation, the amplitude of the carrier wave is shifted between two discrete levels [5, 6], see **Equation 3**. A carrier-less variant of ASK, OOK (on-off Keying) is often used for low-frequency RF communication, especially in low-power use cases like remote keyless entry as no power is used to transmit the binary '0' data, reducing overall transmission power [7, 23].



$$s(t) = A \cos(2\pi f_c t); \text{ Binary } 1$$
$$= 0; \quad \text{ Binary } 0$$

For PSK modulation, the phase of the carrier wave is shifted between two discrete values, each value being equidistant from the carrier and representing 1 of 2 binary digits [5, 8], see **Equation 4**. Variants of PSK, DBPSK, are used in IEEE 802.11b-1999, GMSK and 8-PSK in 2G GSM/EDGE, and 8-PSK is in satellite broadcasting [9, 10, 11].

In QPSK the phase of the carrier wave is shifted between four discrete values, i.e., 90°, 180°, 270° and 360° offset from the carrier, allowing for the modulation of two bits of a data per symbol [6, 12], see **Equation 5**. QPSK is used in 2G GSM/EDGE and Digital Television Broadcasting (DVB-S2) [11, 13]. For QAM the amplitude of the carrier wave is permitted to shift with phase

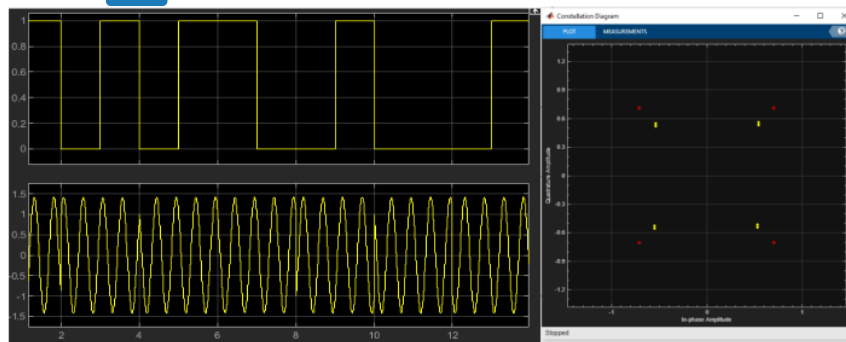


Figure 3: QPSK Modulation & Constellation

$$\begin{aligned}
 s(t) &= A \cos\left(2\pi f_c t + \frac{\pi}{4}\right) = \text{Binary } 11 \\
 &= A \cos\left(2\pi f_c t + \frac{3\pi}{4}\right) = \text{Binary } 01 \\
 &= A \cos\left(2\pi f_c t + \frac{5\pi}{4}\right) = \text{Binary } 00 \\
 &= A \cos\left(2\pi f_c t + \frac{7\pi}{4}\right) = \text{Binary } 10
 \end{aligned}$$

Equation 5: QPSK Modulation [25]

QAM can be viewed as a combination of ASK and PSK [8], see **Equation 6**. QAM is widely used in wireless networking due to its high ratio of bits/symbol and robustness compared to M-ary PSK; 1024-QAM (10 bits/symbol) is used in the current 802.11ax standard [14].

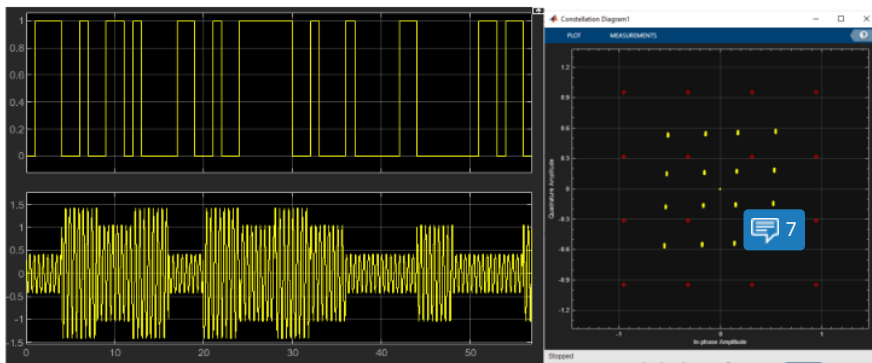


Figure 4: 16-QAM Modulation & Constellation

$$s(t) = d_1(t) \cos(2\pi f_c t) + d_2(t) \sin(2\pi f_c t)$$

Equation 6: QAM Modulation [26]

## Simulation Models

Shown in **Figure 5** to **Figure 8** are models of ASK, PSK, QPSK and QAM modulators and demodulators which have been designed in Simulink, found within MATLAB. To ensure reliability and consistency of results, each model (where practicable) uses identical simulation parameters.

The simulation parameters used are:

- A 10Hz carrier frequency with a sample time of  $f_s = 200\text{Hz}$ , satisfying the Nyquist theorem in that the sampling frequency is greater than 2x that of the modulated signal, or  $f_s \gg 2W$  preventing aliasing [15].
- The carrier frequency is 10x that of the message frequency, 10Hz carrier : 1Hz message frequency.
- The simulation time is set to ~50s to allow for a total of 50 symbols in each model to be transmitted during each run.
- The Lowpass FIR, Finite-duration Impulse Response, filter design for each model is identical. An FIR filter has been used over an IIR, Infinite-duration Impulse Response, as they are stable and can be realised in hardware [16]. Each model uses a single/or multiple of the same 76-order FIR lowpass filter with the following specification:  $f_s = 200\text{Hz}$ ,  $f_{PASS} = 1$ ,  $f_{STOP} = 4$ , Missing Units  $TOP = 30$ , see **Figure 9** for filter design.
- Each model has a Bit Error Rate and Bit Error Ratio (BER) calculation block, which will be used to calculate the error rate of data received from the demodulator (RX) compared to data transmitted (TX) by the Bernoulli binary generator. The Bit Error Ratio is calculated using **Equation 1**.
- The testing procedure started at an SNR of 10:1 (+10dB), progressively adding noise in -5dB steps, using the AWGN block, until an SNR of 1:1000 (-30dB), or until system failure.

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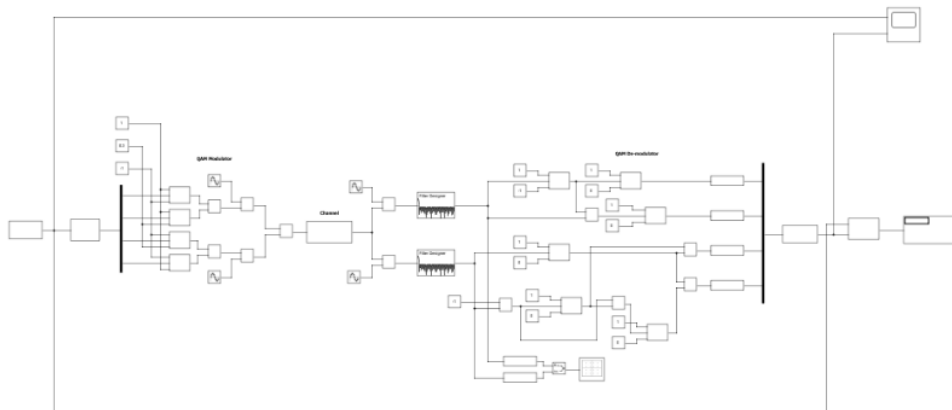


Figure 8: 16-QAM Simulink Model

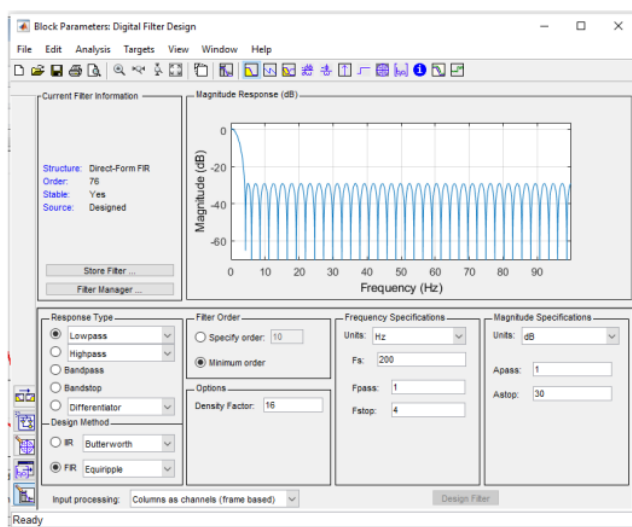


Figure 9: Lowpass Filter Design

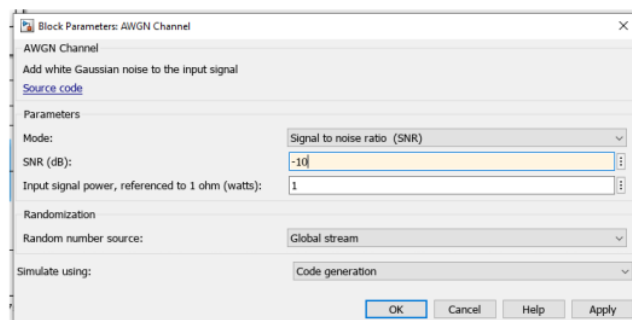


Figure 10: AWGN Channel Setup

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## Results

The graphs shown in **Figure 11**, **Figure 14**, **Figure 17**, and **Figure 23** show BER with respect to SNR for the ASK, PSK, QPSK, and QAM models. The BER value plotted at each test point on each graph is the mean value taken from running the simulation 20 times per test point for varying SNR (10dB, 5dB, 0dB, -5dB, -8dB, -10dB, -12dB, -15dB, -20dB, -25dB). **Figure 11**, **Figure 14**, and **Figure 17** have the standard deviation plotted for each test point to show the variation of results at each test point.

**Figure 23** gives a comparison of BER between the modulation schemes covered in this report, clearly showing the better performance, in terms of BER (%) to SNR, of the PSK and QPSK models when compared to ASK and QAM models.

**Figure 12** and **Figure 13** show the output of the ASK model at 10dB and -10dB noise. Significant degradation of the original message can be observed in **Figure 13**.

**Figure 15** and **Figure 16** show the output of the PSK model at 10dB and -10dB noise. Some degradation of the original message can be observed in **Figure 16**.

**Figure 18** and **Figure 19** show the output of the QPSK model at 10dB and -10dB noise. Like PSK, minor degradation of the demodulated message can be observed in **Figure 19**.

**Figure 21** and **Figure 22** show the output of the 16-QAM model at 20dB and -10dB noise. Clear distortion of the demodulated signal can be observed in **Figure 22**. Regarding the **Figure 21**, it should be noted that this was taken at 20dB; 20dB was chosen as at 10dB SNR, errors were already apparent in the demodulated message.

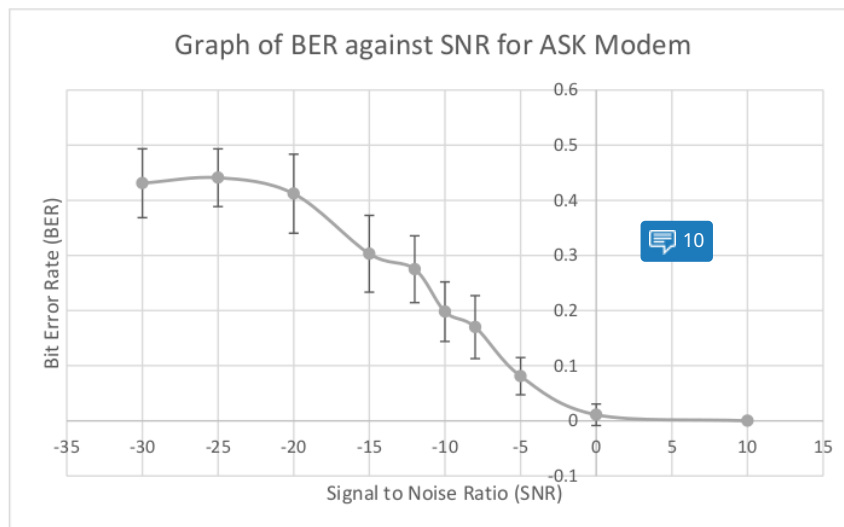


**Figure 11: ASK BER to SNR Graph**

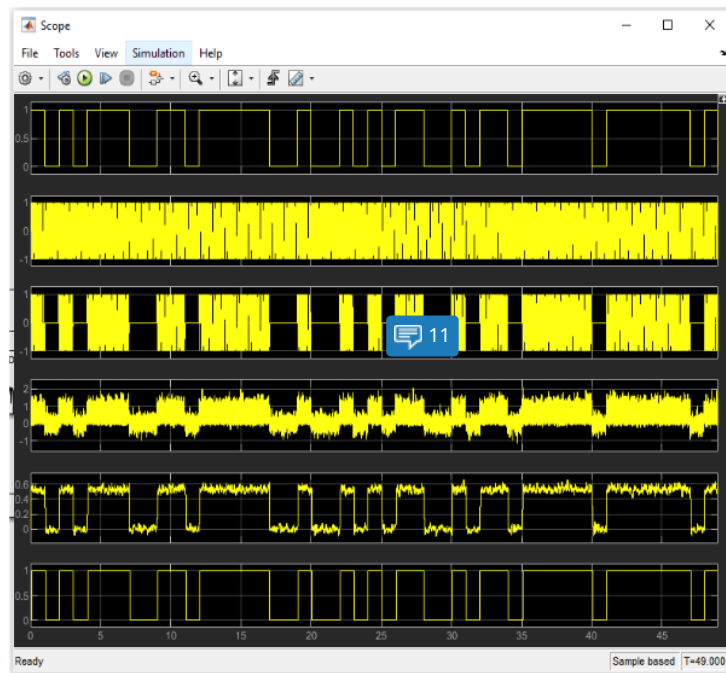


Figure 12: ASK Model (10dB)

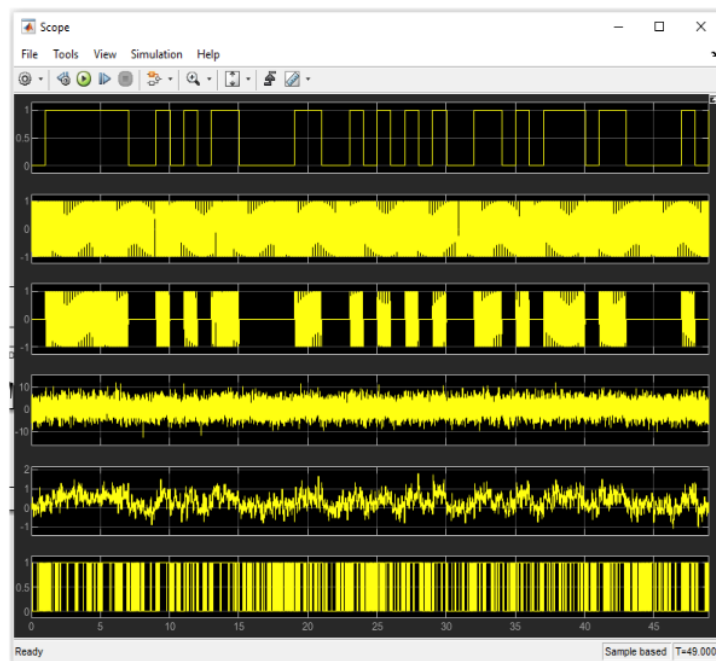
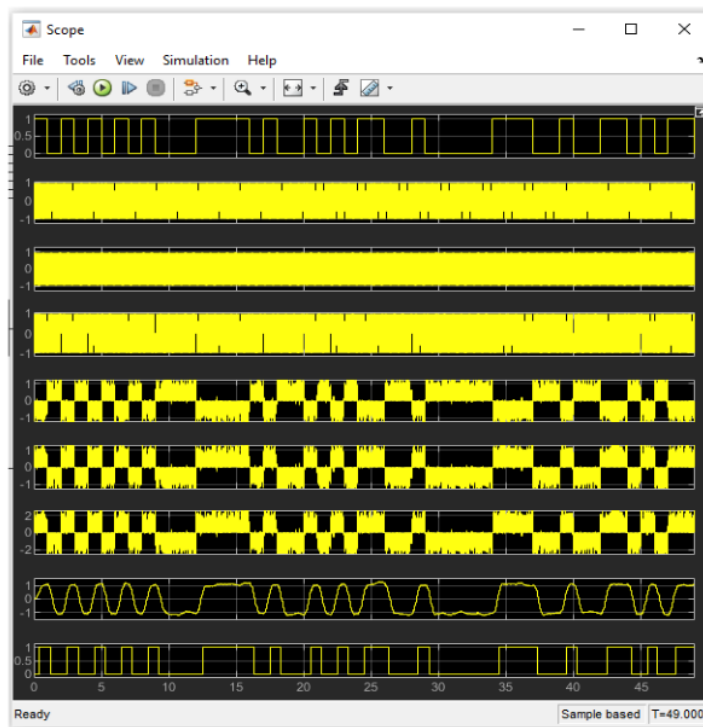
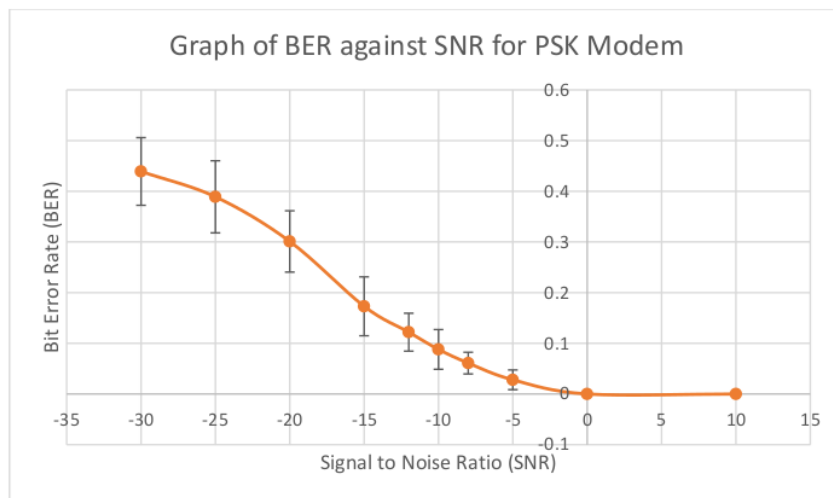


Figure 13: ASK Model (-10dB)



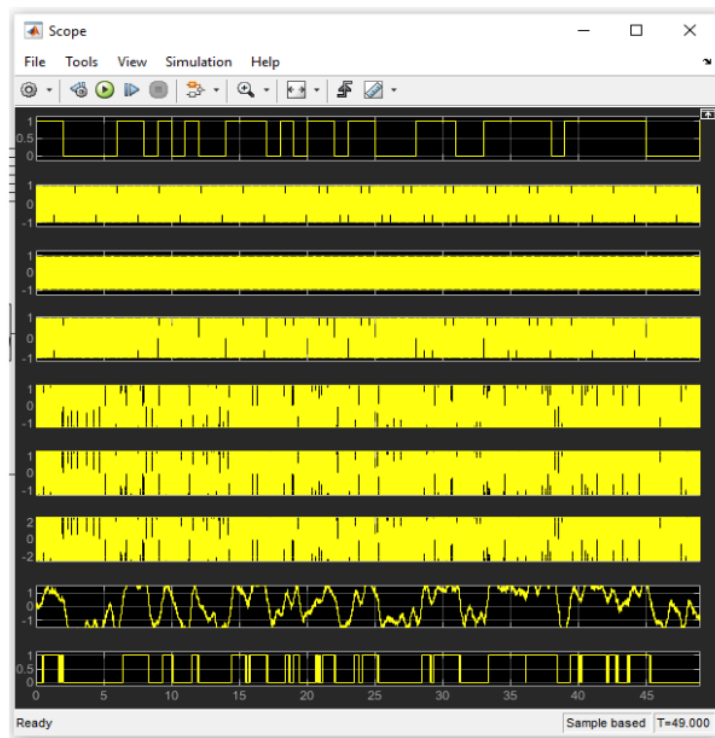


Figure 16: PSK Model (-10dB)

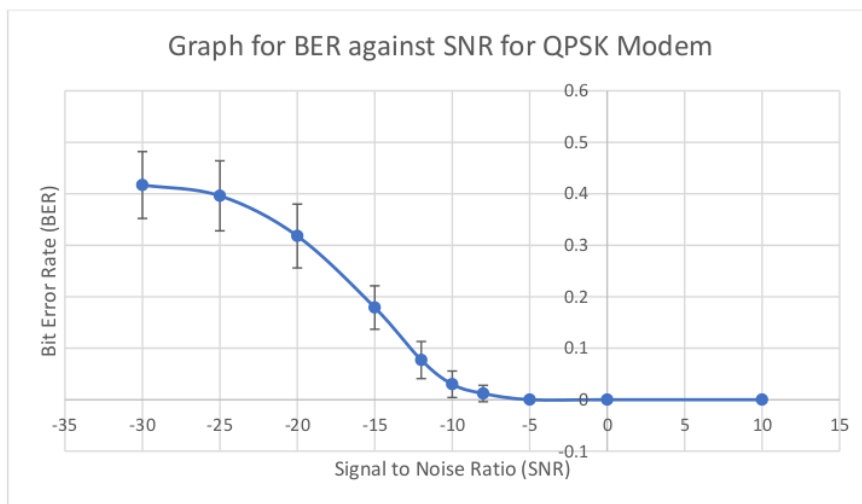


Figure 17: QPSK BER to SNR Graph

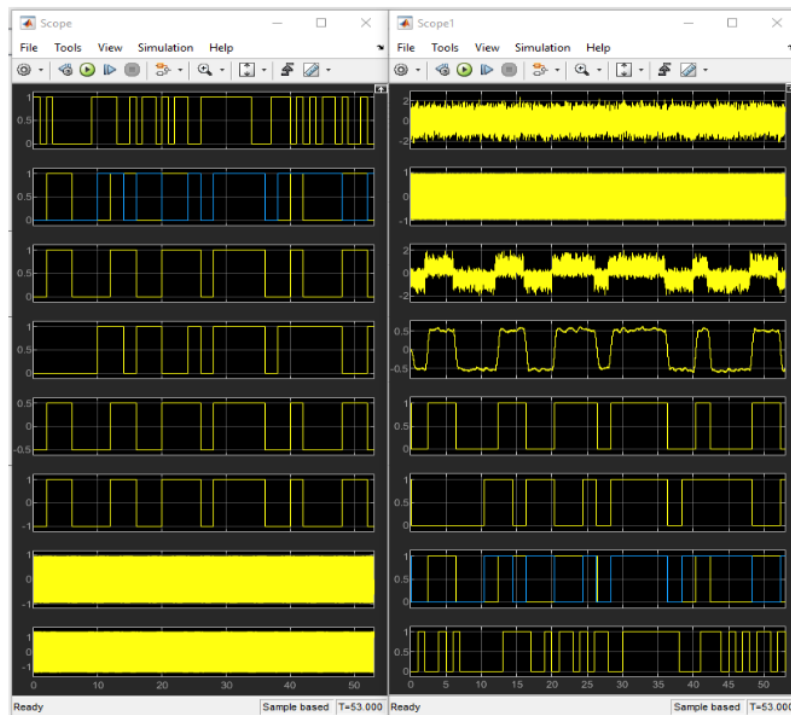


Figure 18: QPSK Model (10dB)

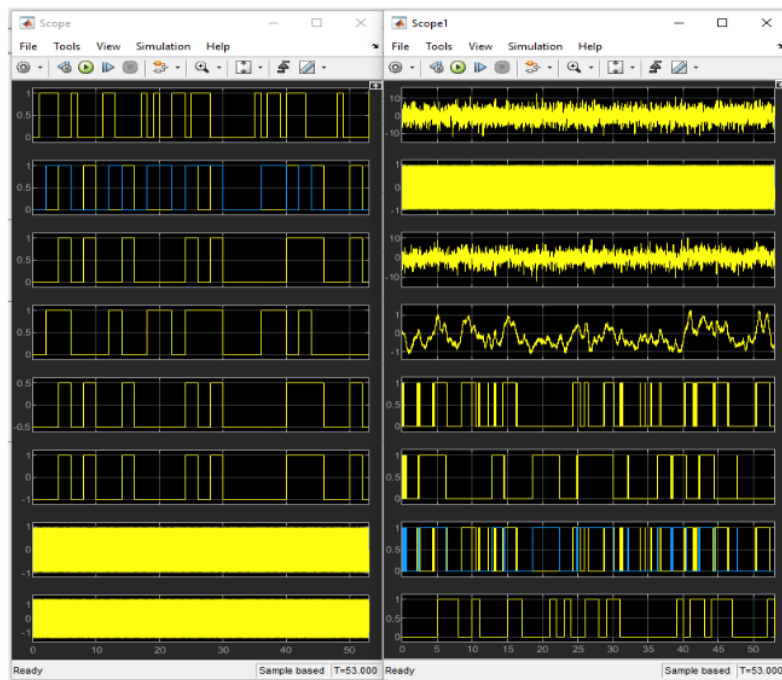


Figure 19: QPSK Model (-10dB)

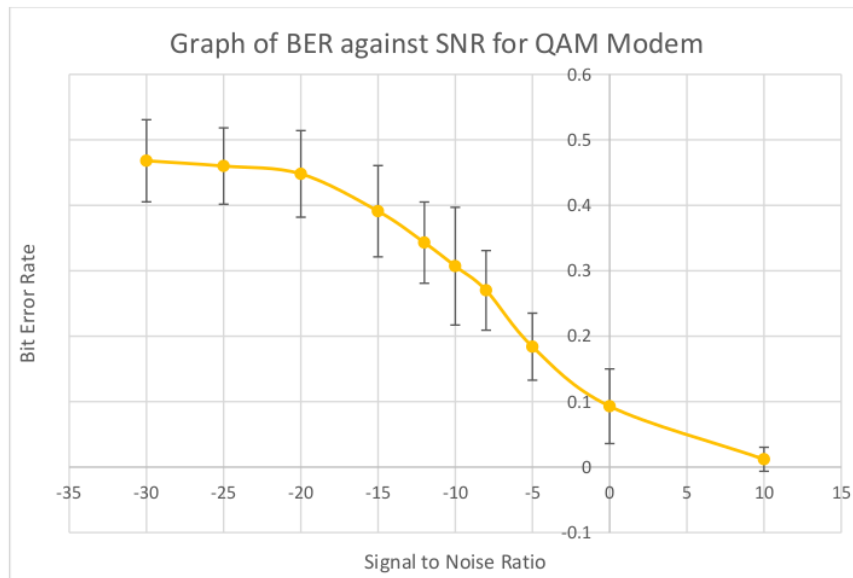


Figure 20: QAM BER to SNR Graph

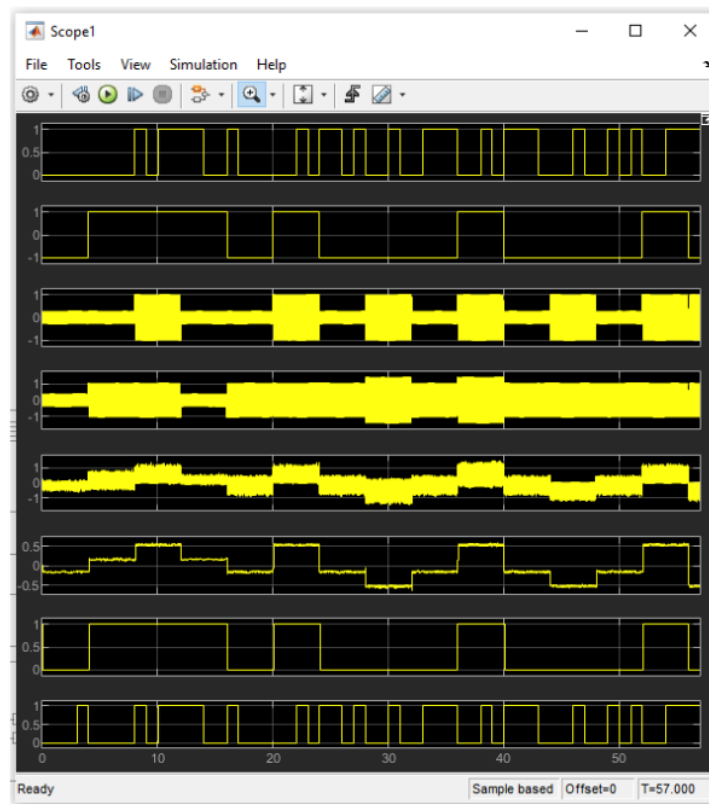


Figure 21: 16-QAM Model (20dB)

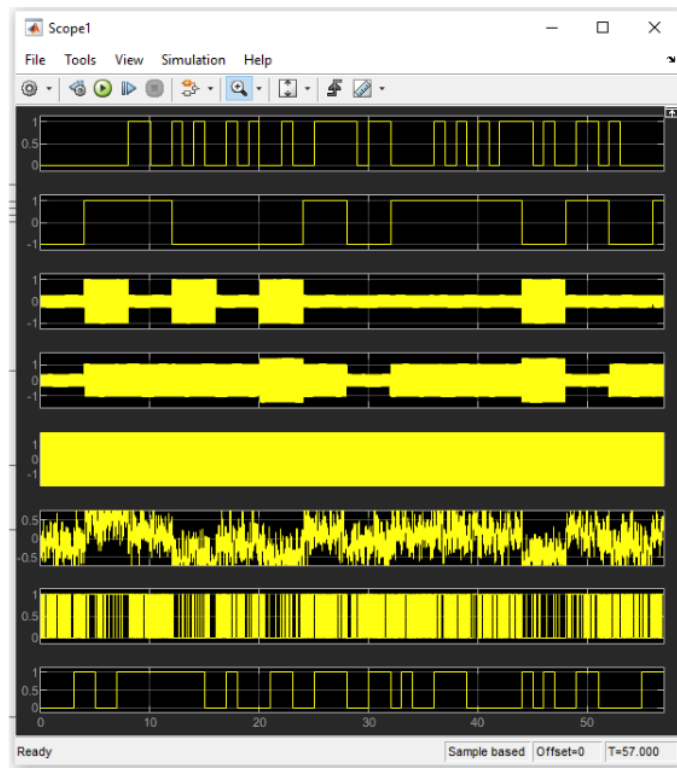


Figure 22: 16-QAM Model (-10dB)

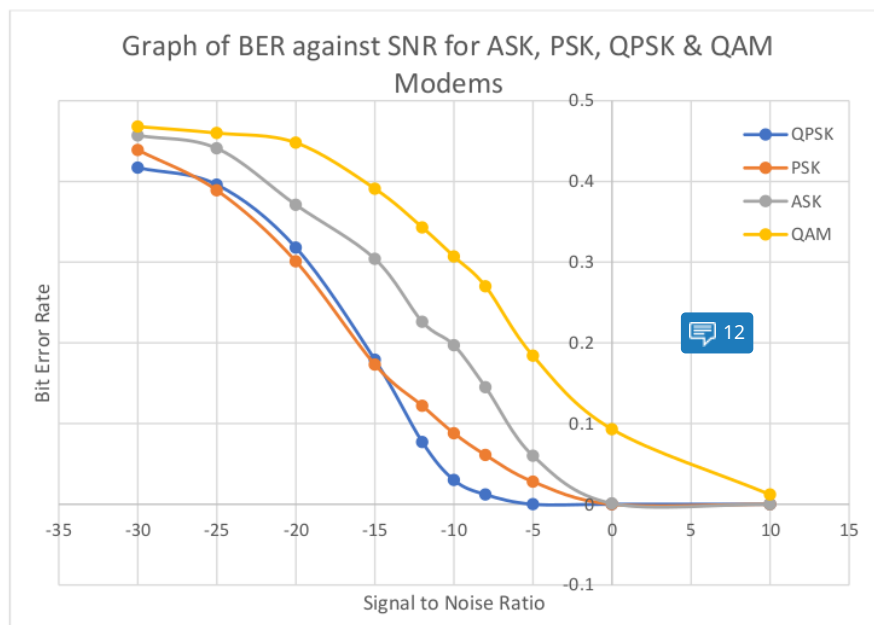


Figure 23: BER to SNR Graph (ALL Schemes)

## Discussion

### Binary Modulation Schemes

In regard to **Figure 11** (ASK) and **Figure 14** (PSK), it is clear from the results that the PSK model had a significantly lower BER (%) with respect to SNR than the ASK model, also evidenced the steeper BER curve of ASK over PSK in **Figure 23**. Indeed, in **Figure 23**, for the ASK model, the BER reaches  $10^{-1}$ , or 10%, at -6dB (SNR of 1:4) – using **Equation 2**. In comparison, in the same Figure, the PSK model does not reach the same BER until an SNR of 1:10 (-10dB). A significant contributing factor to the greater BER, with respect to SNR, for the ASK model is that ASK modulation is significantly more vulnerable to distortion via the channel than PSK – as the noise will be added primarily to the amplitude of the carrier signal, which is the component of the carrier waveform being modulated in ASK [1, 6].

In addition, there is greater degree of deviation of the BER result from the +10dB to -20dB test points for the ASK model than the PSK model. This can somewhat be seen when comparing **Figure 11** to **Figure 14**, but can be better seen when comparing the data at each test point. Taking the -10dB test point, the standard deviation of results for the ASK model is 0.54, compared to 0.38 for the PSK model. Again, this is explained by the fact that ASK model is inherently more vulnerable to additive noise [1].

### M-ary Modulation Schemes

**Figure 17** (QPSK) and **Figure 20** (16-QAM) are the respective BER curves for QPSK and QAM models. QPSK and QAM are M-ary modulation schemes, shown by **Equation 7**, where  $M$  is the number of symbols and  $N$  is the number of bits; for QPSK  $M = 4$  and QAM  $M = 16$  [17].

$$M = 2^N \text{ or } N = \log_2 M$$

Equation 7: M-ary Digital [19]

From these Figures, it can be seen the QPSK model outperformed the QAM model with respect to BER at decreasing levels of SNR. QPSK had a lower BER (%) than 16-QAM due to the lower number of bits per symbol of QPSK ( $N = 2$  or 2bps) when compared to 16-QAM ( $N = 4$  or 4bps); a higher bps, makes 16-QAM more desirable in terms of speed than QPSK, the trade-off that it is more vulnerable to noise due to the greater number of symbols packed more densely together, as can be seen in the constellation diagrams in

**Figure 25** (QPSK) and **Figure 24** (16-QAM), supported by the oscilloscope outputs shown in **Figure 19** (QPSK) and **Figure 22** (16-QAM), where the demodulated signal of the QPSK has suffered from far less distortion than the 16-QAM signal has at -10dB.

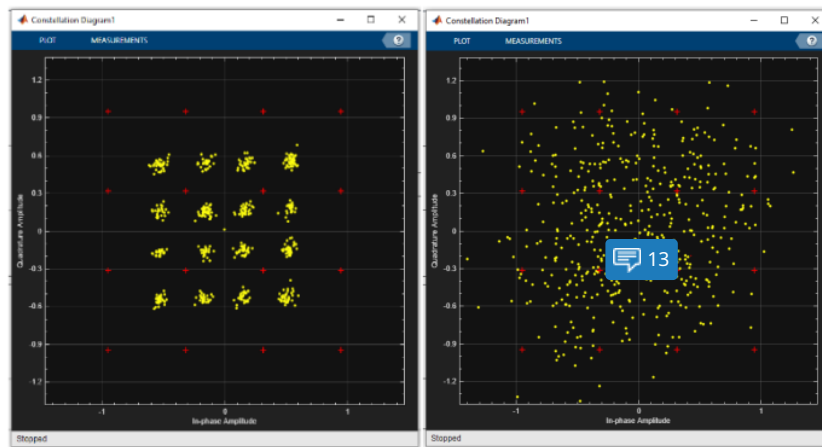


Figure 24: 16-QAM Constellation Diagram L (10dB) & R (-10dB)

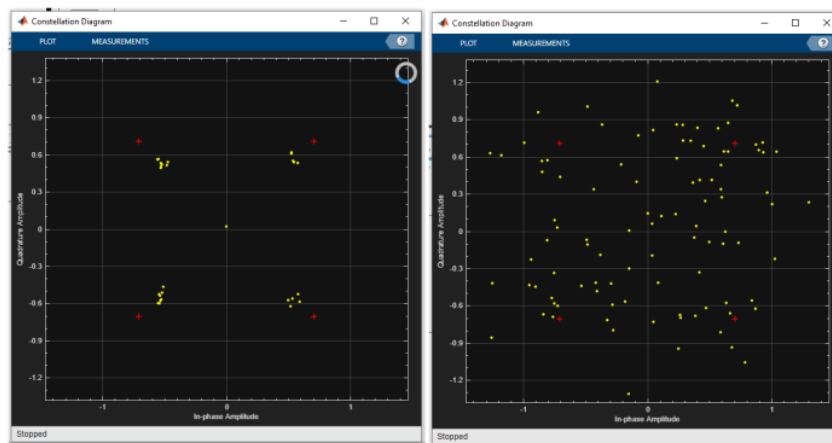


Figure 25: QPSK Constellation Diagram L (10dB) & R (-10dB)

Also, it can be seen that in **Figure 20** (16-QAM) the deviation between results is greater than that in **Figure 17** (QPSK), this can again be explained by the increased symbol rate of QAM, where the greater bits/symbol is directly proportional to a greater BER (%); this effect is known as the Shannon Hartley limit, which is the theoretical upper limit of capacity of an error-free digital communications system with respect to SNR and channel BW - the maximum number of M levels defined by the SNR, as shown by **Equation 8** [18].

$$C = B \log_2(SNR + 1)$$

$C$  = Channel Capacity in bits/s

$B$  = Channel BW in Hz

Equation 8: Shannon Hartley Limit [13]

## Conclusion

In this experiment, it has been determined that the modulation schemes with the lowest BER (%) with respect to increasing AWGN are PSK and QPSK, with QPSK performing marginally better overall when compared to PSK - as shown in **Figure 14** and **Figure 17**. In contrast, ASK and 16-QAM had a higher BER, 16-QAM being the worst performer – as can be seen in **Figure 23**. Also, **Figure 23** shows that at -30dB, or an SNR of 1:1000, the BER (%) across all modulation schemes is approaching 50, meaning that 50% of the data is lost from the original message – showing all the modulation schemes tested will eventually fail with sufficient additive noise [19]. As expected, the AWGN had a significant impact on the demodulated message of all modulation schemes tested; at an SNR of 1:100 (-20dB), even the best performing modulation scheme, PSK, had a BER of greater than the point of system failure at  $1E-1$ , the worst performing modulation scheme, 16-QAM, a BER of nearly  $5E-1$ . For a high SNR channel, 16-QAM would be the best modulation scheme of those tested, due to the high data rate, followed by QPSK; for a low SNR channel, QPSK or PSK would be the best modulation schemes due to the lower BER offered in a channel with low SNR.

With a higher BER, i.e.,  $5E-1$ , the data is unrecoverable, a lower BER figure, i.e.,  $1E-1$ , may be achieved upon through a better FIR filter design, which was a common design for all models in this report. Potential improvements could be, increasing sample rate and tailoring the filter design for each model, the drawback to this being an increased delay in demodulation and greater system complexity [20]. Whilst outside the scope of this report, ED&C, Error Detection and Correction, like CRC, Cyclic Redundancy Check, could be used to lower the BER – at the expense of increased data length and reducing bandwidth for data [21].

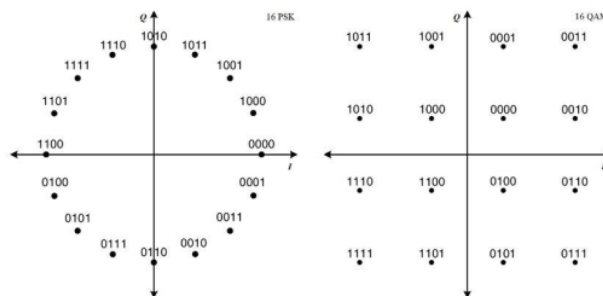


Figure 26: 16-QPSK and 16-QAM [21]

It is worth noting that the type of QAM used, 16-QAM, is not directly comparable to the type of QPSK used, 4-QPSK. The number of constellation points in 16-QAM is a factor of 4 greater than 4-QPSK, meaning that 4-QPSK will always outperform 16-QAM with otherwise identical characteristics of the modulator and demodulator circuit with regards to noise immunity from AWGN. A more fair comparison would be between 16-QPSK ( $M = 16$ ) and 16-QAM ( $M = 16$ ), where it is expected that the 16-QAM modulation scheme would outperform the 16-QPSK scheme, due to the more efficient spacing of the symbols in the I and Q plane, as can be seen in the constellation diagram in **Figure 26** [8, 22].

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# RH\_ACDA5008\_Assignment

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## GRADEMARK REPORT

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FINAL GRADE

GENERAL COMMENTS

74/100

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PAGE 1



### Comment 1

Good abstract. You should quantify your results here. Specify by what margin they were better or worse.

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PAGE 2

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PAGE 3



### Comment 2

You should use the equation editor for this. It should be  $1 \times 10^{-1}$  or 0.1.

"e" has a different meaning - Euler's number (2.7182818....), but I think you mean it to be E for Exponent.



### Comment 3

You should use the equation editor for this. It should be  $1 \times 10^{-1}$  or 0.1



### Comment 4

The citation should be in the equation caption rather than the body text.

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PAGE 4



### Comment 5

is used in



### Comment 6

the amplitude can shift independently of phase as they are both used to represent different bits of the message



### Comment 7

The amplitude of your points seems to be a little low. They should all line up with the red crosses

QM

### Missing Units

What units is this in?

You should always include the units for all quantities you describe in your text. Some quantities have more than one unit. Frequency, for example, can be measured in Hertz (Hz) or radians per sec (rad/s).

Make it clear for your reader and remove any ambiguity.



### Comment 8

How do you define system failure? What metric will you measure it by?



### Comment 9

Excellent description of your experiment,

QM

### Not In Text

You have included a figure without mentioning it in the text. You should refer to the figure in the text, otherwise it is not worth including as the reader will not know what it relates to.



### Comment 10

Nice graph, but you should add units for SNR in the axis title



### Comment 11

What do each data series relate to? You should include this in the caption

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PAGE 13

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### Comment 12

Nice graph, although you should include units in the axis titles

PAGE 16

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PAGE 17

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### Comment 13

Very good - shows corruption of data due to noise



### Comment 14

Excellent analysis

PAGE 18

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### Comment 15

0.5 or  $5 \times 10^{-1}$ , don't use  $5E-1$



### Comment 16

Excellent



### Comment 17

But 16QAM would outperform 16PSK as you have rightly said - the points are spaced more efficiently in QAM. Maybe a better test would be 8PSK vs 16QAM as the spacings would be more closely matched. ... maybe?

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PAGE 20

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PAGE 21

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RHYS HIGGINS

74

**ENGAGEMENT WITH LITERATURE**

*including reading, referencing, academic conventions and academic honesty*



Outstanding knowledge of research-informed literature embedded in the work. Outstanding selection of relevant and credible sources. High-level referencing skills consistently and professionally applied.

9

**KNOWLEDGE & UNDERSTANDING**

*Knowledge of the basic underlying concepts and principles of a subject.*



Excellent knowledge and understanding of the main concepts and key theories. Clear awareness of challenges to established views and the limitations of the knowledge base.

15.6

**COGNITIVE & INTELLECTUAL**

*Evaluate underlying concepts and principles of a subject and interpret qualitative and quantitative data in order to develop lines of argument and make sound judgements.*



Thoroughly logical work, supported by evaluated evidence. High quality analysis, developed independently.

Ability to investigate contradictory information and identify reasons for contradictions.

Strong, persuasive, conclusions, justifiable recommendations.

21

## PRACTICAL APPLICATION SKILLS

*Different approaches to solving problems in particular contexts.*



An advanced application of a range of methods, materials, tools and/or techniques.

The context of the application is well considered, with extensive use of relevant examples.

Application and deployment extend beyond established conventions. Innovation and creativity evident throughout.

21.6

## TRANSFERABLE SKILLS

*Communicate the results of their study/work accurately and reliably, and with structured and coherent arguments; the qualities needed for employment requiring the exercise of some personal responsibility within a structured and managed environment.*



Can communicate well, confidently and consistently in a suitable format.

Work is coherent and fluent and is well structured and organised.

See comments on Figs 10, 11, 12.

6.8

Excellent work

