

Simulation of Digital Modulation Techniques

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SIMULATION OF DIGITAL MODULATION TECHNIQUES

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Abstract

This report aims to quantitatively compare different radio-frequency signal modulation methods on how much data can be encoded versus how resistant each method is to white-noise interference. The modulation schemes tested are as follows: Amplitude Shift Keying, Binary Phase Shift Keying, Quad Phase Shift Keying, and Quadrature Amplitude Modulation.

To test each modulation scheme in a controlled environment, Matlab Simulink software was used to implement suitable simulation models. The models used ideal signal-processing components in a noise-free environment, allowing the signal interference to be finely controlled, simulating a range of interference conditions.

The results showed that there was a tangible difference between how the different modulations performed. Simple modulations (e.g. ASK) and those designed to encode more information (e.g. QPSK) were less resilient to interference and therefore had higher symbol error rates, while modulations with less symbol ambiguity (e.g. BPSK) had greater tolerance to interference at the cost of encoding less information.

There is therefore a good reason to choose the most appropriate  modulation when designing a radio-communication system, as it can improve or degrade the overall system performance.

Introduction

Amplitude Shift Keying (ASK) is the simplest possible form of digital modulation, where the carrier wave transmit power is adjusted between at least two levels to convey information. Commonly the two levels are completely off and full power, as that reduces the circuitry needed in the modulator to a single multiplier (see Figure 1: ASK Model). This minimal footprint is useful for applications where the transmitter needs to be small and energy efficient, such as in car fobs or in medical devices [1].

Binary Phase Shift Keying (BPSK, or simply PSK) is when the carrier frequency phase is shifted by 180° to convey a different symbol, effectively inverting the signal. PSK is often used in satellite communications [2]. Phase-shifting adds complexity to the receiver, as a reference carrier needs to be derived from the received signal. For the sake of simplicity in evaluating modulation techniques, all simulated demodulators which employ phase shifting have direct access to the reference carrier, but additional components would be required in the real world to recover the carrier.

Quadrature Phase Shift Keying (QPSK) is an extension of PSK wherein the signal phase can be in one of 4 possible states, allowing it to carry twice as much data. QPSK is often used for digital video transmission [3]. Each pair of bits in the message correspond to Real (I) and Imaginary (Q) coordinates on a complex plane, pointing to a particular quadrant on a phasor diagram. This diagram is often called a constellation and provides a visual representation of how the message is modulated.

Quadrature-Amplitude Modulation (16-QAM, or simply QAM) combines amplitude modulation and phase modulation to form three concentric rings in polar coordinates, enabling the encoding of more information and supporting higher data rates. QAM is commonly used in next-generation Wi-Fi to achieve high data rates [4].

This report aims to compare the resilience of these 4 modulation schemes to electromagnetic interference, by implementing each in Matlab Simulink, and measuring how the demodulation process copes with noisy signals.

Simulation Models

For each of the 4 modulation techniques, a model implementing it was created, all designed to be scientifically comparable through sharing blocks wherever possible to eliminate variables. The simulation stop time is set to 100 samples allow each test to acquire a representative capture of the model's performance. Random message input is provided by a Bernoulli Binary Generator, and the same low-pass filter used in each model. The filter has an order of 35, a sample rate of 100, an Fpass of 3, an Fstop of 7, an Apass of 1, and an Astop of 40. These parameters create a filter with a cutoff of approximately 6Hz.

An Additive White Gaussian Noise (AWGN) Simulink block is used to simulate interference on each model's modulated output, so the signal-to-noise ratio (SNR) can be varied. To measure how resilient the models are to this interference, an Error Rate Calculator (ERC) is placed at the end of each model to compare the demodulated output with the original message, which produces a Bit Error Rate (BER). Higher BERs indicate more of the message was received incorrectly. The AWGN SNR values will be tested from -30 to +10, giving a wide range of signal strength measurements. Due to the non-deterministic nature of the Bernoulli Binary Generator, each SNR test will be repeated 30 times to calculate an accurate average BER and calculate a standard deviation for error bars.

ASK

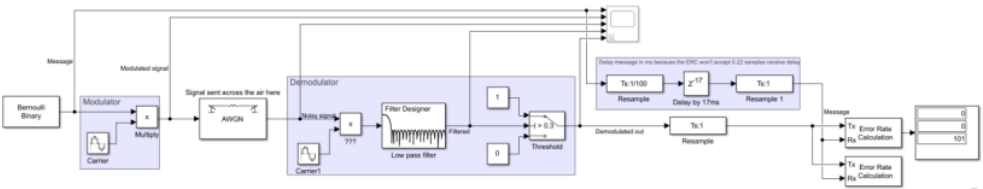


Figure 1: ASK Model

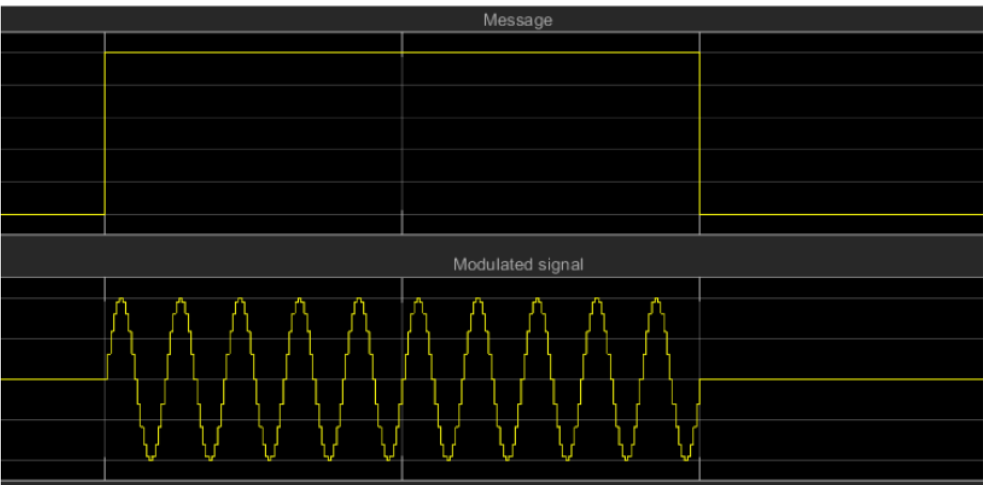


Figure 2: ASK signal compared to message data

PSK

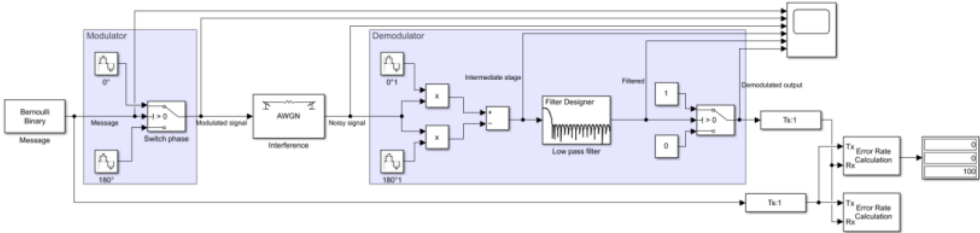


Figure 3: PSK Model

Note that while PSK would have a constellation consisting of two points along one axis, the author was not able to get the constellation diagram correctly representing this.

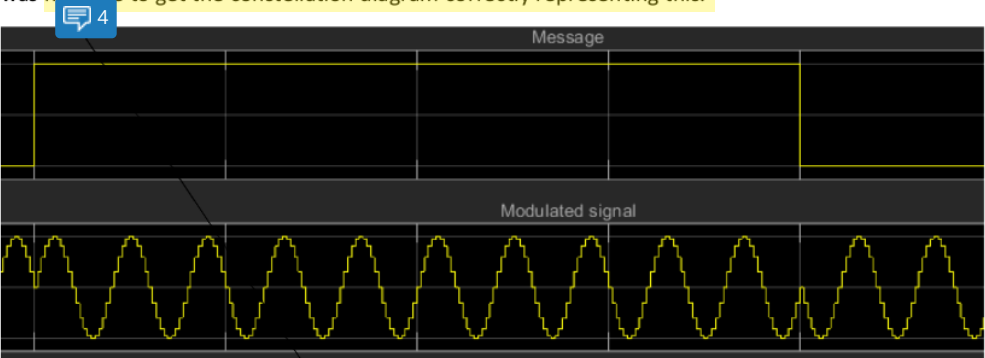


Figure 4: PSK signal compared to message data

QPSK

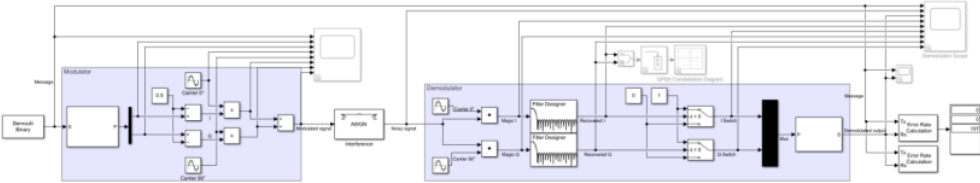


Figure 5: QPSK Model

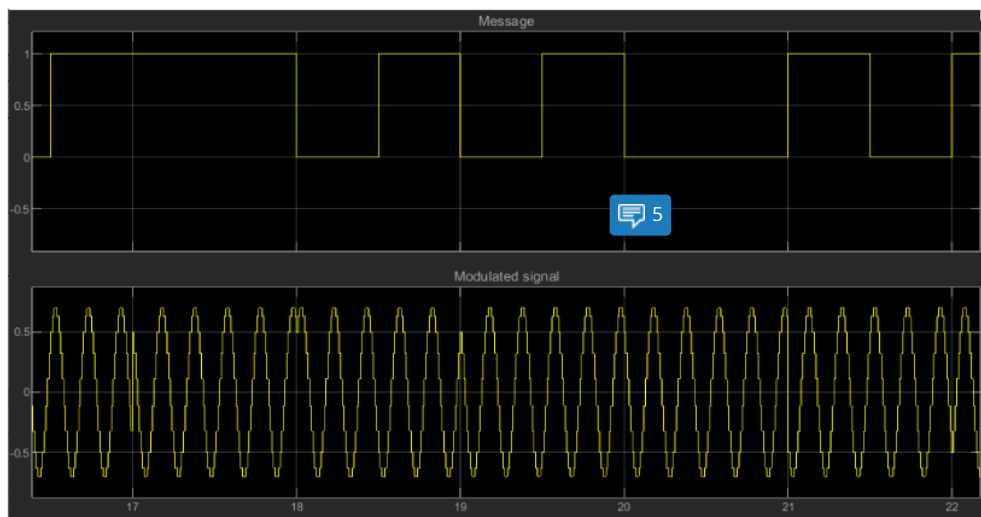


Figure 6: QPSK signal compared to message data

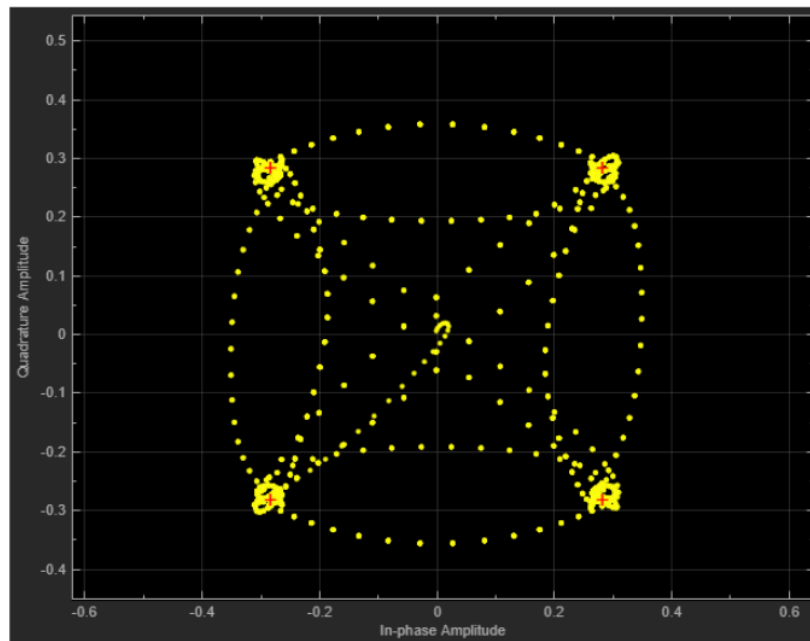


Figure 7: QPSK IQ Constellation

QAM\

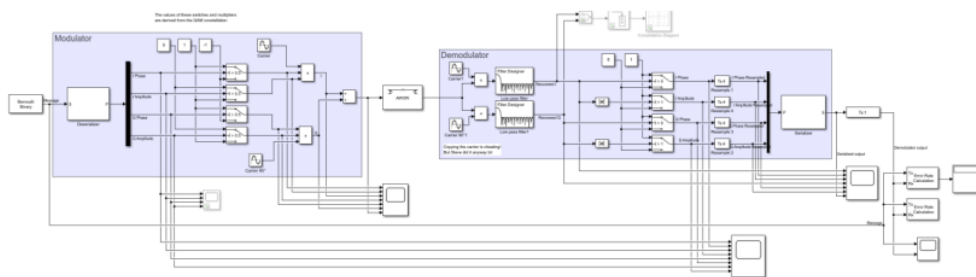


Figure 8: QAM Model

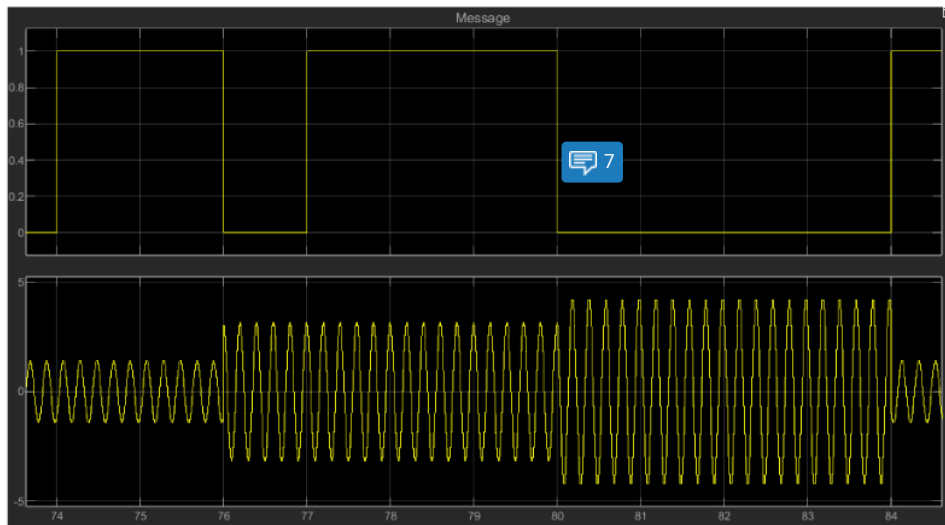


Figure 9: QAM signal compared to message data

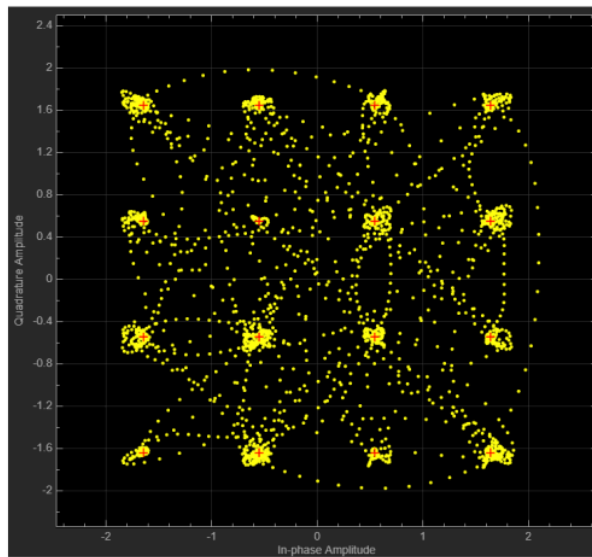


Figure 10: QAM IQ Constellation

Results

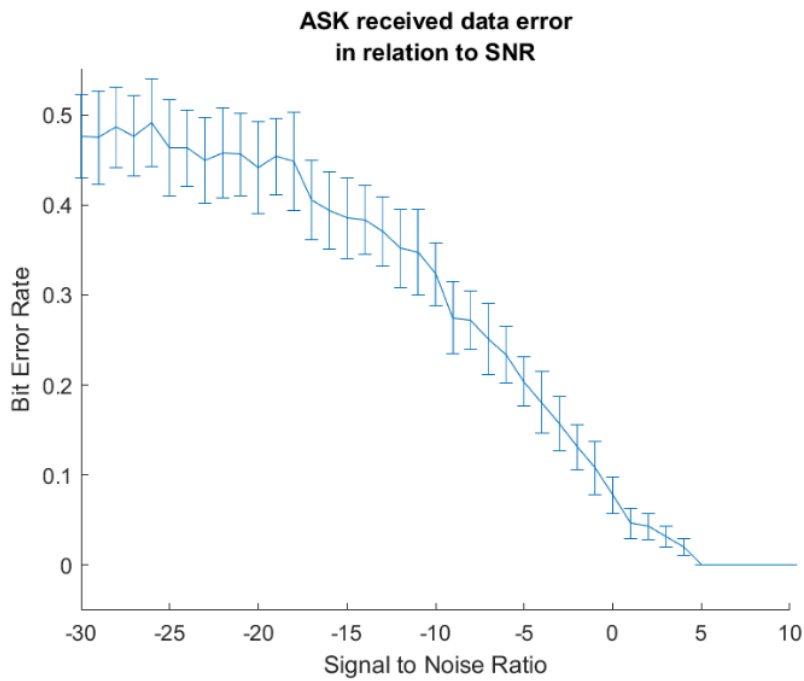


Figure 11: ASK Model performance against SNR

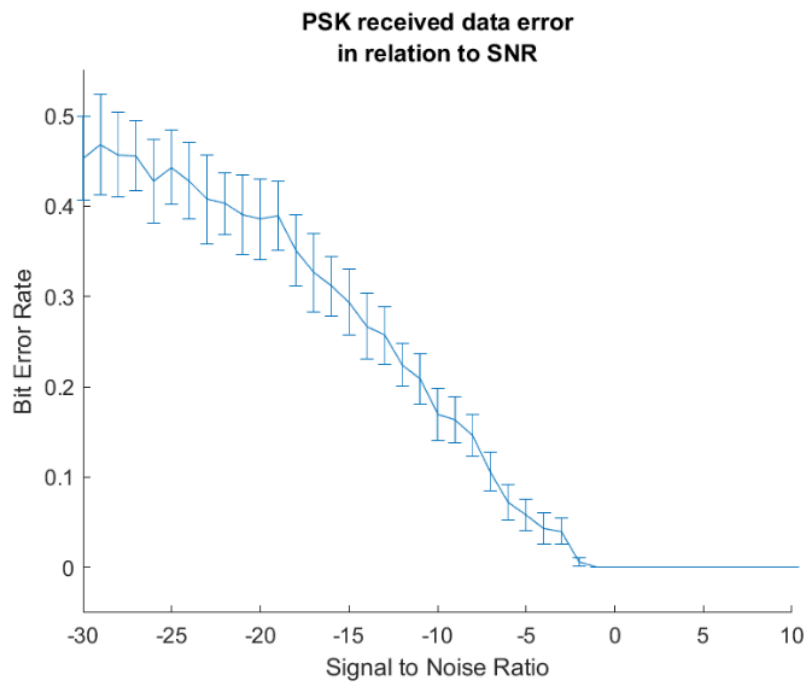


Figure 12: PSK Model performance against SNR

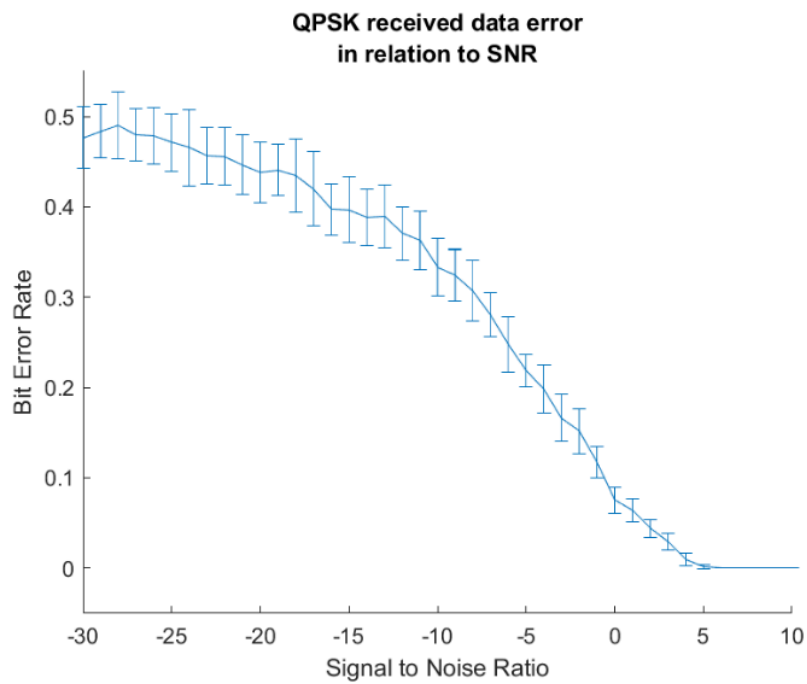


Figure 13: QPSK Model performance against SNR

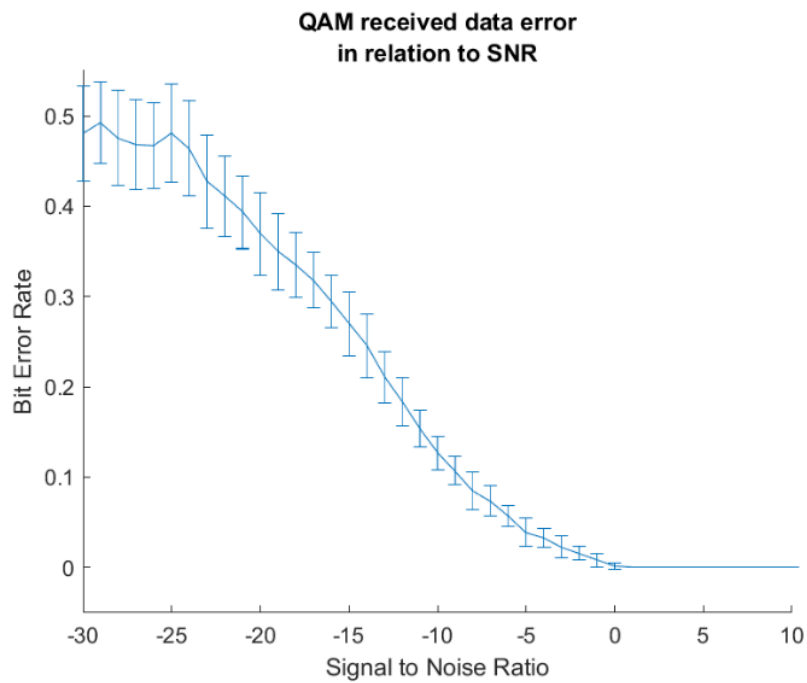


Figure 14: QAM Model performance against SNR

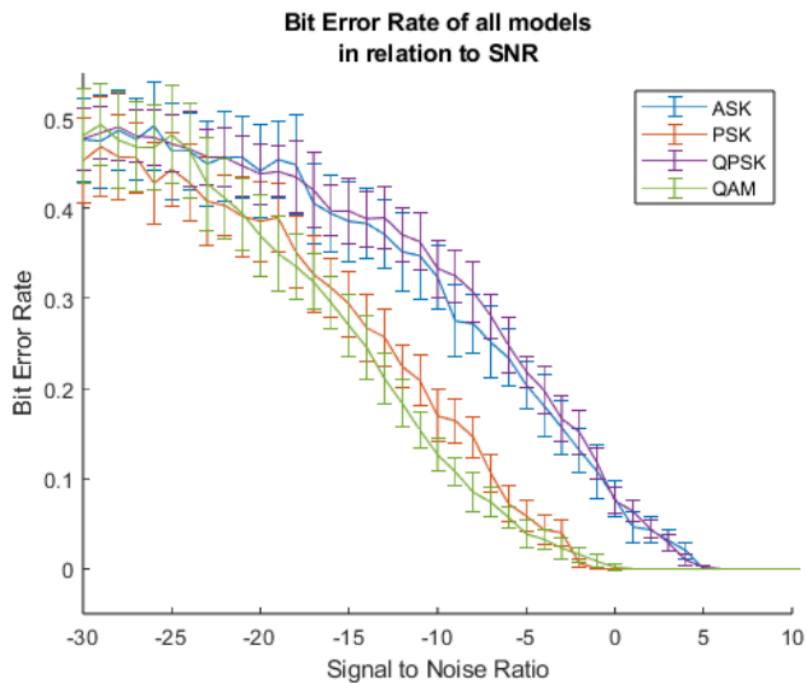


Figure 15: Combination of Figure 11, Figure 12, Figure 13, and Figure 14

Discussion

Since ASK is the simplest modulation technique, the modulator section of Figure 1 consists only of a single multiplier. Recovering this signal on the demodulator side is also relatively straightforward, being smaller than all other demodulators. As each modulation technique becomes more complex, so does the circuitry required to decode the signal. This is a significant consideration when choosing a modulation technique for use in a real-world application, especially if there are physical size constraints which limit the maximum complexity. It may be beneficial to choose a simpler modulation, even at the cost of reduced range and resilience to interference.

In Figure 2, there is a direct 1-1 correlation between the message bits and the carrier signal amplitude; they are directly related. When the message has a 1, the modulated output contains the carrier signal, and nothing is transmitted otherwise. Because the carrier signal ceases transmission entirely, this means the modulation is a subset of ASK called On-Off Keying (OOK).

PSK modulations affect the carrier in a more subtle manner; Figure 4 shows the phase abruptly switching 180° whenever the message input changes, as expected for a BPSK signal. This is visually identical to inverting the carrier's polarity. The sudden change in phase will introduce high-frequency clicks, which should be filtered if this circuit were built in the real world.

Since there are only two symbols in BPSK, this is the slowest form of PSK but is theoretically the most resilient to noise as there is minimal ambiguity in a noisy signal. This also makes it the best candidate for long range communications on low power, especially if the symbols can be transmitted slowly to compensate for poor reception.

For QPSK, Figure 6 shows how every two bits determine the carrier phase, allowing for 4 possible symbols, or two bits per symbol. Going from 2 to 4 symbols does not require an increase in bandwidth, as QPSK is able to utilise the second axis in the constellation orthogonal to that used by BPSK. This only works going from BPSK to QPSK, as further increases to the number of symbols must involve landing between the two polar axes.

The constellation diagram for QPSK is shown in Figure 7. There are 4 distinct spots where the symbols settle, corresponding to the 4 possible combinations of polar coordinates in each corner. During a transition between symbols, the phase either rotates ± 90 degrees, drawing a circle as the signal amplitude stays roughly constant, or the phase rotates ± 180 degrees, in which case a line is drawn through the centre as either the I or Q component flip.

The modulated output for QAM is significantly more complex, as shown in Figure 9. There are 3 possible amplitude levels, and up to 12 different phases to resolve each symbol. Each symbol is encoding 4 bits, so it's not visually obvious how the message influences the modulated output. Constellation diagrams exist to make it much easier to visualize how the symbols are arranged in polar space, as illustrated by Figure 10. In this view, it becomes much easier to count the 16 symbols and deduce that there are $\sqrt{16} = 4$ bits per symbol being encoded. There is also less distance between symbols, theoretically increasing chance of symbol error in cases of high interference.

ASK was not very resilient to noise, as illustrated in Figure 11, where it started accumulating bit errors when the SNR was +4 or lower. This reflects the nature of ASK relying on the signal to be stronger than the interference, otherwise the noise can take precedence over the signal during demodulation.

In Figure 12, BPSK performed better as it maintained zero errors up until an SNR of -2, where single-bit errors began to manifest. This means it was able to perfectly decode the signal even when interference was stronger than the signal.

QPSK cannot tolerate the interference as well, as illustrated in Figure 13 it begins to exhibit bit errors at +5 SNR. This indicates that adding additional symbols causes problems with interference to manifest more readily.

Strangely, Figure 14 shows that QAM performed the best of all the models, overall averaging below the bit error rate for BPSK, except for an outlier at the zero-threshold. At -10 SNR, the average bit error rate was 0.12 while BPSK had 0.17.

In theory, QPSK should perform better than QAM as it has fewer possible symbols and therefore less ambiguity when demodulating a noisy signal, however Figure 15 suggests that QAM is performing much better than all other models. This is most likely to be an error, as the author does not know how QAM is performing  10 There's a possibility that the QAM signal was being accidentally "broadcast" with more power than the other models, but this needs additional research.

Conclusion

ASK has been found to be the simplest modulation method of the ones tested, at the cost of reliability under modest white-noise interference. BPSK offers a significant improvement to interference resistance while at the same data speed of ASK. QPSK doubles the data rate, however it loses the noise resilience, having slightly higher Bit Error Rates than ASK on average. QAM is an outlier in these experiments, as it manages to be more resilient to noise than BPSK while transmitting 4 times as much information. Whether this is due to a mistake in the simulations or a genuine trait of QAM requires further investigation.

In conclusion, different modulations offer a range of traits that should be carefully considered when designing an RF communication system, and choosing the right one appropriate to the situation can have measurable benefits.

References

- [1] C. D. F. Mazzilli, "184 μ W ultrasonic on-off keying/amplitude-shift keying demodulator for downlink communication in deep implanted medical devices," *Electronics Letters*, vol. 52, no. 7, pp. 502-503, 2016.
- [2] Y. H. X. Z. W. Liu, "Generalised binary offset carrier modulations for global navigation satellite systems," *Electronics Letters*, vol. 48, no. 5, pp. 284-286, 2012.
- [3] Analog Devices, "QPSK," [Online]. Available: <https://www.analog.com/en/resources/glossary/qpsk.html>. [Accessed 22 11 2024].
- [4] Z. Xia, "What Is QAM?," Huawei, 2 4 2022. [Online]. Available: <https://info.support.huawei.com/info-finder/encyclopedia/en/QAM.html>. [Accessed 22 11 2024].



Simulation of Digital Modulation Techniques

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

66/100

PAGE 1

PAGE 2

PAGE 3



Comment 1

Good abstract, although you should quantify your results here also



Comment 2

Good background information. May have benefited from some diagrams to illustrate the concepts

PAGE 4



Comment 3

Do you mean 100 seconds?

At 100 samples, with a sample period of 0.01 seconds you will only get one second of data.



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 4

You could have just drawn it, it didn't need to be a simulation output



Comment 5

This does not show the full picture. you only have one channel of message data. Your modulated signal clearly has phase changes where no change is present in the data shown.



Comment 6

You should try to ensure headings are not the last thing on a page.



Comment 7

See comment on figure 6.

you should present all the data, not just one part of it.



Comment 8

Nice graph, although the error bars are a little confusing.



Comment 9

This is not the correct calculation for number of bits. e.g. for 8 symbols, this should require 3 bits, but $\text{SQRT}(8) = 2.828$

You should use $\text{Log}_2(16) = 4$

$\text{Log}_2(8) = 3$

**Comment 10**

This suggests that you are allowing your preconceptions of what the results should be interfere with your results.

**Ref Qty**

I was hoping for more references

GRADING FORM: SMU GENERIC_SMOSEY

DANIEL BRIDGEWATER

65.80

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic honesty



Inclusion of a range of research-informed literature, including sources retrieved independently. Referencing conventions mostly consistently applied.

5.5

KNOWLEDGE & UNDERSTANDING

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



Knowledge is extensive. Exhibits understanding of the breadth and depth of established views.

12.4

Some more diagrams showing how the modulation techniques work would have improved this.

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.



While you have presented some good results, you haven't done much more than describe them. At level 5 you should be trying to explain the reason behind all of your results.

20.4

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

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.

Some figures were not discussed in the text at all.

You should discuss every figure you include, otherwise why include it?

6.5