Quadrature Amplitude Modulation, QAM

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1 Introduction

In modern world, we use lots of electronics in our everyday life, for these electronics to function, it is important to transmit information between each others, communication system plays a key role in the process. Generally, the communication process goes through a transmitter and send the signal out, then the receiver receives the signal and processes it into the information we want.

During the whole process, many things might affect, such as the humidity and temperature of the atmosphere since the signal has to penetrate through atmosphere, the bandwidth of the device, etc... These different conditions can degrade the quality of the signal greatly or make the signal impossible to be reconstructed. So, in order to encounter with the problems we face, **modulation** is invented.

The general concept of modulation is to embed an information-bearing signal into a second signal, this process allows the signal to contain more information to transmit, making the signal more immune to noise and make efficient use of the bandwidth. With these properties, signals after modulation can be transmitted further and more robust signals can be received, allowing the communication system to be more effective and reliable.

There are three ways to modulate signals: amplitude modulation, frequency modulation and phase modulation[1]. Amplitude modulation is the oldest and simplest form of modulation, the amplitude of the carrier signal is varied in accordance with the instantaneous amplitude of the modulating signal. Frequency modulation changes the frequency of the carrier signal according to the instantaneous amplitude of the modulating signal. Phase modulation changes the phase of the carrier signal according to the instantaneous amplitude of the modulating signal.

1.1 Problem Statement

For signals without modulation, there are three major problems: First, unmodulated signals will be less immune to noise, causing the signal to become distorted or lost. Second, unmodulated signals can only travel a short distance before they become too weak to be received. This is due to they are not able to overcome the attenuation of the transmission medium, for radio signals, the medium to that attenuates the signal will be atmosphere. Last, unmodulated signals have low bandwidth, which makes the signal capable to carry limited amount of information, because they are limited to the frequencies that are presented in the original signal.

Input signal	Received signal

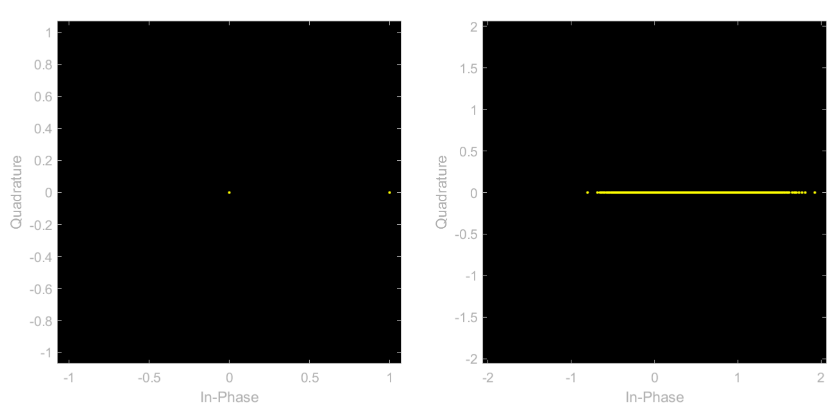


Figure 1. The input signal is 0 or 1, the received signal is added noise

From the image above, we can see that if we send signals with out modulation, although the input signal is as simple as only altering between 0 and 1, the received signal is heavily distorted turning the signal into a line between 0 and 1. So it is important to modulate the signal to make the signal immune to the noise we get during transmission.

We know that signals with higher frequency can transmit further, so after modulating the signal, the signal will be capable of transmitting signal further, because the carrier signal has higher frequency. Also the signal will be absorbed less during transmitting in the atmosphere when the frequency is high.

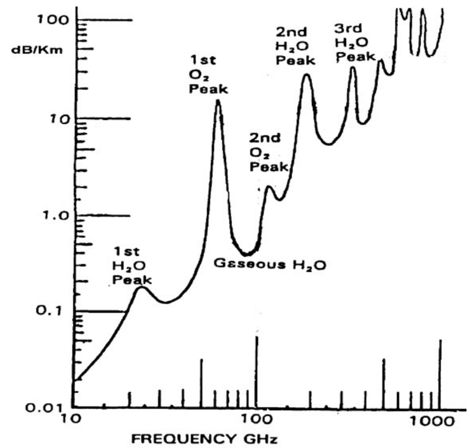


Figure 2. The relationship between frequency and energy after transmitting a certain distance[2]

2 Literature Review[1]

Amplitude modulation (AM), which alters the amplitude of the carrier signal by the amplitude of the input signal. This causes the sideband to be created, and they are important because they carry the information that is being transmitted. The simplest AM technique is double sideband (DSB) AM, which is represented as:

$$f_{DSB}(t) = \frac{A}{2}\big[1 + m(t)\big]cos\omega_c t, \tag{1}$$

where $m(t)$ is the modulating signal and ω_c is the carrier frequency, with a maximum efficiency of 33.333%[3]. We can see that DSB AM is not efficient, so the DSB AM can be simplified by the use of double sideband suppressed carrier (DSB-SC) AM. The general form of DSB-SC signal is:

$$f_{SC}(t) = Am(t)cos\omega_c t. \tag{2}$$

And the efficiency can be improved to 50% maximum[3]. Both DSB techniques involve the transmission of a redundant sideband. However, when spectral efficiency is important, we can use single sideband (SSB) modulation. The SSB signal can be written as:

$$f_{SSB}(t) = A\big[m(t)cos\omega_c t + \hat{m}(t)sin\omega_c t\big], \tag{3}$$

where $\hat{m}$ is the Hilbert transform of $m(t)$. The maximum efficiency of the signal can be increased to 100%. However SSB AM is more complex to generate and receive than standard AM, because the transmitter and receiver must be able to suppress one of the sidebands. In order to cutoff one of the sidebands, a sharp cutoff is needed, so bandpass filter are often implemented. Also, signal after SSB AM will have lower quality, especially if the signal have a wide range of frequency, because one of the sideband is suppressed, which might cause distortion and a narrower bandwidth, reducing the fidelity of the signal.

DSB AM	DSB-SC AM	SSB AM

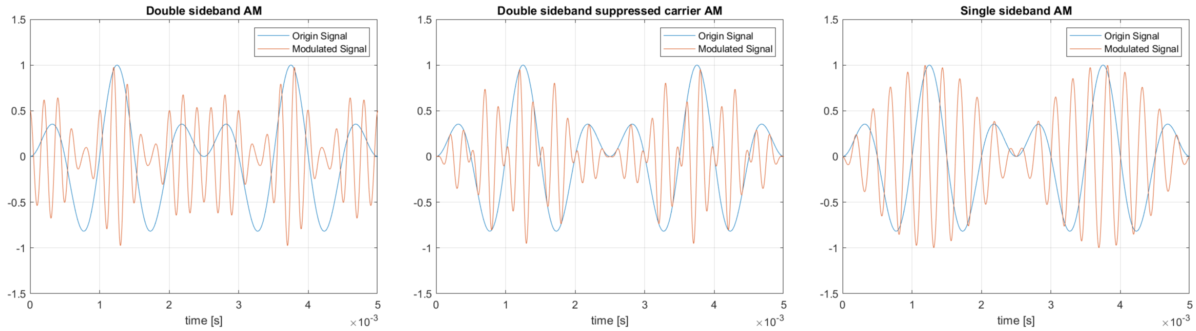


Figure 3. DSB, DSB-SC, SSB AM result with signal=$(cos(1600\pi t) - cos(2400\pi t))/2$, carrier signal=$cos(10000\pi t)$

3 Proposed Method

Traditional AM methods, each has some defect, DSB AM transmits both sidebands of the signal, causing at least 50% of power wastage. SSB AM is improved from DSB AM, transmitting only one sideband only, making the transmitted signal 100% efficiency, but in order to transmit only one sideband, a sharp cutoff filter is needed to remove the other sideband, causing distortion and a narrower bandwith to the signal.

To deal with these problems, another extension of AM is invented, Quadrature amplitude modulation (QAM). QAM transmits the signal by summing two DSB-SC signals 90° apart in phase, the QAM signal can be written as:

$$f_{QAM}(t) = A[m_I(t)cos\omega_c t + m_Q(t)sin\omega_c t] \tag{4}$$

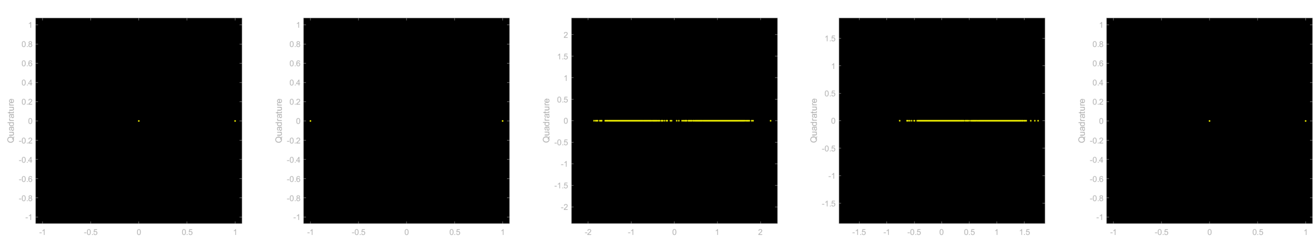
Since the carriers are 90° apart, QAM uses both amplitude and phase to modulate the signal, making it more robust to noise, allowing the receiver to recover the original data even if some signal is lost due to noise. And QAM consists two signals, so it can achieve higher data rates than traditional modulation methods, because it carries more information.

4 Experimental Results

I have tried QAM on discrete time signals, in 2-bits per symbol, 16-bits per symbol and 64-bits per symbol. The result is in below.

4.1 2-QAM

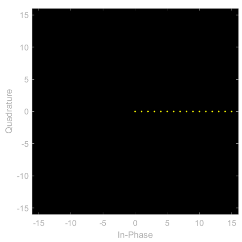
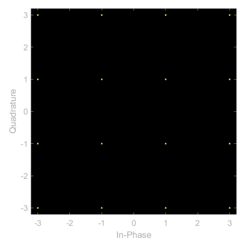
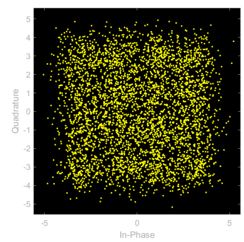
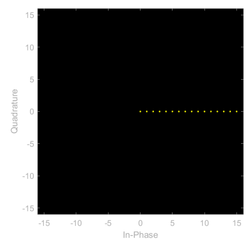
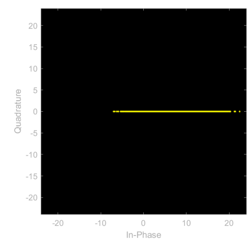
Input	Modulated signal	Received Signal with Modulation	Received Signal W/O Modulation	Signal after Demodulation



Bit error rate (BER) for Modulated signal: 0.001
Bit error rate (BER) for Unmodulated signal: 1.000

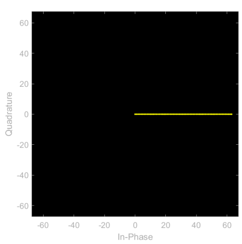
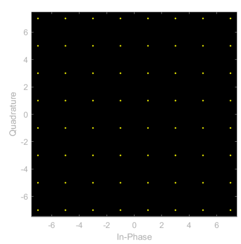
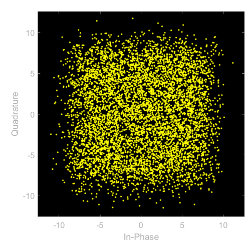
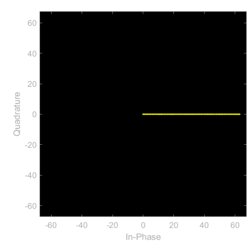
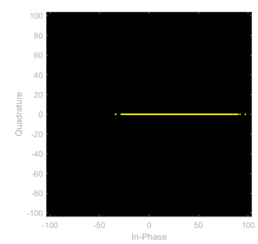
We can see that the signal without modulation became noisy, and became a line after noise added to the input signal. And the signal demodulated from the received modulated signal, perfectly reconstructed the input signal.

4.2 16-QAM

Input	Modulated signal	Received Signal with Modulation	Received Signal W/O Modulation	Signal after Demodulation
				

Bit error rate (BER) for Modulated signal: 0.2172
Bit error rate (BER) for Unmodulated signal: 1.000

4.3 64-QAM

Input	Modulated signal	Received Signal with Modulation	Received Signal W/O Modulation	Signal after Demodulation
				

Bit error rate (BER) for Modulated signal: 0.6757
Bit error rate (BER) for Unmodulated signal: 1.0000

5 Conclusion

From the result, we can see that, when the signal is transmitted with QAM, the signal become more robust to noise, and the receiver can reproduce the input signal a lot better than without QAM. Also, when the bits become higher, the bit error rate (BER) increases, so when the bits are high, maybe QAM would not be the optimal way to modulate the signal. In the future, maybe the modulation can be extended to QPSK, since QAM modulates the signal by shifting on of the carrier 90°, so it is similar to phase-shift key modulation.

References

[1] John Oetting, "A comparison of modulation techniques for digital radio," *IEEE Transactions on communications*, vol. 27, no. 12, pp. 1752–1762, 1979.

[2] Barry Warmkessel, "Frequency energy relationship," `http://barry.warmkessel.com/fig1a.jpg`, 2013, [Online; accessed 14-June-2023].

[3] Wikipedia, "Double-sideband suppressed-carrier transmission," `https://en.wikipedia.org/wiki/Double-sideband_suppressed-carrier_transmission`, 2019, [Online; accessed 13-June-2023].