Performance Analysis, Characteristics, and Simulation of Digital QAM

Nikolaos F. Voudoukis

Abstract—Quadrature Amplitude Modulation or QAM is a form of modulation which is widely used for modulating data signals onto a carrier used for radio communications. QAM, when used for digital transmission for radio communications applications is able to carry higher data rates than ordinary amplitude modulated schemes and phase modulated schemes. This paper presents the various fields where QAM can be implemented, describes modulator/demodulator block diagrams for transmitters as well as receivers, provides an introduction of certain performance indicators of modulation and a list of applications using alternative implementations of QAM. Also the paper presents a simulation of QAM using Simulink (example of 16-QAM signal) with signal trajectories and constellation plots. It is compared the theoretical and simulated Bit Error Rate (BER) for 16-QAM with Gray coding in an AWGN channel. Some general conclusions are also cited.

Index Terms— Quadrature Amplitude Modulation (QAM) Constellation diagram, Modulator/Demodulator, Simulation, Bit error rate (BER), Signal to noise ratio (SNR).

I. INTRODUCTION

Quadrature amplitude modulation (QAM) is both an analog and a digital modulation scheme. It conveys two analog message signals, or two digital bit streams, by changing (modulating) the amplitudes of two carrier waves, using the amplitude-shift keying (ASK) in digital modulation scheme or amplitude modulation (AM) in analog modulation scheme. QAM is a common choice in digital data modulation. The procedure involves the modulation of an analog carrier signal by a discrete signal. This means that during modulation, digital is converted to analog, while during corresponding demodulation, analog is converted to digital. There is a finite number of M alternative symbols that is used to represent the changes in the carrier signal.

The use of Quadrature Amplitude Modulation basically consists of the combination of two amplitude modulated signals into the same channel. QAM doubles the amount of the bandwidth, thus making it more effective. This combination of analog and digital modulation is very often encountered in digital telecommunication systems. Also, in wireless applications using pulse amplitude modulation. QAM is the path used to encode digital channels and send them through cable television providers [1].

QAM consists of two signals, an in-phase one called the I signal and a quadrature phase one, known as the Q signal. Through amplitude modulation, with a specific number of amplitudes, the signals are summed and they form a two

channel system, using Amplitude Shift Keying (ASK) on both channels. This results to a signal equivalent to one that combines PSK and ASK.

There are alternative implementations of the QAM modulation. The most popular types of QAM include 16, 32, 64, 256 QAM. Different forms of QAM such as rectangular, circular etc. are available. We convert analog modulation to digital in order to achieve extra capacity, more secure data, higher quality of communications, better compatibility with digital data services and quicker system availability. The most usual issues for researchers and developers of communicational systems are the available bandwidth, the congenital noise level that maximum admissible power and the fact that there is only on certain R/F spectrum to be distributed equally to all users. That last issue is the main constraint, as more and more users claim to share the available spectrum, causing great increase in the demand of communications services. Digital modulation patterns have higher ability to carry larger amounts of information than analog modulation schemes. In the QAM we use a confined number of amplitudes and phases. By confined we mean at least two [2].

Constellation diagrams consist of constellation points, placed in a rectangular grid with equal space both vertically and horizontally. The possible states of a particular configuration are noted very reliably on a constellation diagram. As we have binary data in digital communication, the points on the diagram are often the result of successional multiplications by 2 (2, 4, 8, 16, 32, etc.). The most common ones are 16, 64, 128 and 256 QAM [1].

The different positions for the states in different forms of QAM are represented at constellation diagrams. The number of points on the QAM constellation diagram increases as the order of the modulation increases.

Square constellations of QAM do not provide optimal reflection, as there cannot be maximum spacing of the points for a given energy. On the opposite side, they present the advantage of being easily received as two burst signals which have been amplitude modulated by quadrature conveyers and they can be demodulated very easy. From the other side, non-rectangular diagrams offer a more reliable bit-error rate, but aren't as easy to modulate and demodulate.

In theory, the possibility of using QAM with higher order for transferring bigger number of bits / symbol (higher order constellations) is a solid one. But, in practice, this would arise a reliability issue. Higher order constellation means constellation points very close to one another, if we intend to maintain the mean energy of the system at the same level. That kind of configuration concludes in extra noise and distortion. So, while higher order QAM indeed carries more

data, it in facts delivers the data with a higher fit error rate, thus causing it to be less reliable than lower order QAM.

At the figure below there are constellation diagrams for various formats of modulation:

Fig.1. QAM with different bits per symbol.

Here the diagrams reveal the number of perspicuous conditions that can exist represented by the same number of points on the constellation. Most of the sequences of constellations can be configured in various ways due to the nature of QAM.

Rectangular quadrature amplitude modulations are easier to modulate and demodulate than non-rectangular quadrature amplitude modulations. So rectangular QAM is preferable to non-rectangular QAM [2].

Quadrature amplitude modulation technique is basically used in digital communication for coded signal transmission. The QAM technique uses two orthogonal signals. These two signals with appropriate scaling will form them into variant values of amplitude and phase. The waves are depicted in a graphical way as points, in the diagram. With this method we have the name of the QAM as 16, 32... 256 state QAM. Cosine wave and sine wave modulation factors are in fact the coordinates (Cartesian) in the constellation diagram. They represent the quality and distortion of a received signal. A square lattice of 16 message points consists the signal constellation for 16-state QAM. The quadrature and the in-phase components are modified in a way that the conveyer wave undergoes amplitude modulation as well as phase modulations. One signal may be attenuated while the other signal gets magnified. As a result of this the on demodulation scaling factors obtained will describe in a good way the distortions which may be obtained in the amplitude in and in the phase angle at the two signals (in phase signal and quadrature signal). So the point in the constellation diagram tends to shift in a definite position. The noise which will be added to the signals can be measured by the distance between the points of the received signal and the points of the transmitted (intended) signal. If the noise influenced during

transmission is small, the point that corresponds to the received signal looks like a small spot around the point that corresponds to the intended signal. In the case that we have big noise, the point of the received signal may be found any were (and not in a specific area) in the diagram. If someone wants to take the information delivered from the received signal first they have to clarify the point of the indented signal in the diagram and after that to encode from same point the information. There are several algorithms doing this job, that they have been developed by scientist and engineers for identifying the intended signal point.

Estimating the shortest possible distance between the perceived signal and one of the constellation points leads the algorithm to recognition of the most possible point intended by the received signal.

The estimation of the distance is a process that takes time and generates delays. There are few algorithms that face this problem with a satisfactory way. For the shortest distance between points might be developed a (performance) pattern based on a combinational logic. This pattern must be as small as possible in area, so the small dimensions in silicon can achieve maximum speed and performance. Then QAM receiver can be prosecuted with high-velocity and less packaging consistency circuitry to reduce the coded information at highest rate possible. QAM achieves a greater distance between constellation points.

Generally, there is a non-quadratic constellation that is best used for a specific. But this non-quadratic constellation is not often implemented because the quadratic QAM is much easier to modulate and demodulate [1].

II. ADVANTAGES AND CHARACTERISTICS OF QAM

QAM is a form of modulation that has many advantages: Bit Packaging Ratio is increased, Bandwidth efficiency is increased, Overall channel capacity is increased, More number of customers can be catered, The trade-off between bandwidth and signal to noise analogy can be made i.e. same channel capacity is achievable at a lower signal to noise ratio value because of higher bandwidth, Less transmission power is being required by the transmitter, Power budget of both the transmitter and receiver reduces by many folds thus reducing the overall cost of the system. In a telecommunication link the data rate (bits/sec) can be increased by the selection of a QAM format with higher order than the already existing QAM format. [1], [2].

At the following table we have an overview of the relation between symbol rate and bit rate of different formats of QAM.

Bits per symbol	Symbol Rate	Modulation
1	1 x bit rate	BPSK
2	1/2 bit rate	QPSK
3	1/3 bit rate	8PSK
4	1/4 bit rate	16QAM
5	1/5 bit rate	32QAM
6	1/6 bit rate	64QAM

Much faster data rates and higher levels of spectral efficiency can be offered by higher order modulation rates for the radio communications systems. This benefit comes at

a price. The communicational patterns with higher order modulation techniques are not as resistant to noise and insertion.

This has resulted to increased use of dynamic adaptive formation techniques by radio communications systems. That means that they adapt the modulation scheme after sensing the channel conditions in order to achieve the highest data rate for the specific status. As SNR (signal to noise ratio) increase, error rate will decrease. On reverse, as SNR decrease, error rate will increase. The variation of SNR has as a result the variation of system throughput (increasing or slowing it). The reliability of the link can be restored only with the conversion to a lower order modulation scheme [2].

III. DESCRIPTION OF THE QAM MODULATOR/DEMODULATOR

All telecommunication systems, regardless whether they use digital or analog modulation, are made up of a number of modules (amplifiers, filters etc.). Transmitter and receiver are the most significant devices with a structure that relies on the modulation pattern. Here we have QAM.

The digital modulation scheme (just the same as the analog modulation scheme as well) demands a demodulator in the receiver block that recovers the message (information signal) from the received signal. The demodulator makes the reverse job compared with modulator (take apart – split, information signal and carrier).

The stream of binary digits to be transmitted is divided into two equal parts. So, in this way we have two congregational signals to be conveyed. These two signals are encoded separately. The way is the same as the ASK modulation. After that one signal (in channel that is called in phase) is multiplied by a cosine. The other signal (in channel that is called quadrature) is multiplied by a sine. As between cosine and sine there is a phase of 90° the same phase there is between the two signals. At the end the two signals are added. The final signal (sum of the in phase and quadrature) is sent through the real channel [1].

It is possible to extract the component in phase (or in quadrature), if we multiply by a cosine (or a sine) and by a low-pass filter (LPF). So there is only an ASK demodulator and the two flows of data (bits) are merged back.

There is an undefined phase delay between the transmitter and receiver. This phase delay must be indemnified by synchronization of the receiver's local oscillator; (i.e., the sine and cosine functions). In mobile applications, due to the potential presence of a Doppler shift proportional to the respective velocity of the transmitter and receiver, there will be a counterbalance in the respective frequency.

The following picture shows the bit-to-symbol Simulink subsystem of 16-QAM digital communication system [3].

Fig.2. The bit-to-symbol subsystem

The following picture shows the QAM Modulator Simulink subsystem of 16-QAM digital communication system [3].

Fig.3. QAM Modulator

The receiver simply realizes the converse procedure of the transmitter.

The following picture shows the IQ correlation Receiver Simulink subsystem of 16-QAM digital communication system [3].

Fig.4. 16-QAM IQ correlation Receiver

The following picture shows the 16-Level Bit to IQ Symbol Simulink subsystem of 16-QAM digital communication system [3].

Fig.5. 16-Level Bit to IQ Symbol

Both the frequency and phase differentiations imported by the channel must be counterbalanced. We can accomplish that by adequately adjusting the sine and cosine elements. The above procedure demands a phase reference, and is achieved by using a Phase-Locked Loop (PLL) [4].

IV. SIMULATION - RESULTS

In case of 16-QAM, the four bits in each point at the constellation diagram (Gray coded) can be considered as two pairs of two bits each on 4-PAM modulation independently, on I-axis and Q-axis respectively.

In digital communication systems, the receiver's basic job is to select precisely the transmitted message symbols out of a finite set. The fact that there is noise in the communication

channel makes the task more difficult and causes bit-errors. In a digital communication system, one significant performance criterion is the Bit Error Rate (BER). BER is the proportion of the number of wrongfully received bits to the total number of transmitted bits. Signal-to-Noise Ratio (SNR) is the ratio (energy per bit)/ (noise power spectral density). When SNR increased, BER decreased (for the same QAM format, eg 16-QAM).

We will compare theoretical and simulated Bit Error Rate (BER) for 16-QAM with Gray Coding in an AWGN channel [3].

We can measure the 16-QAM BER (numerically) by computer simulation and can verify our analytical results. For 16-QAM modulation we can see that amplitude estimation error gives 1-dB degradation in average SNR (signal-to-noise ratio) and combined amplitude-phase estimation error gives 2.5-dB degradation for the parameters we consider [4].

TABLE II: 16-QAM GRAY-CODED CONSTELLATION MAPPING

b0b1	I	b2b3	Q
00	-3	00	-3
01	-1	01	-1
11	+1	11	+1
10	+3	10	+3

Fig.6. Gray coded bit mapping for 16 QAM

The BER of QAM can be calculated through Monte Carlo simulations. However, this becomes quite complex as the constellation size of the modulation schemes increases. Therefore, a theoretical approach is sometimes preferred.

Fig.7. Bit Error Rate plot for 16QAM modulation with Gray mapping

Fig.8. 16 QAM constellation plot with Gray coded mapping (another example)

In wireless communications, the bit-error rate (BER) representation of M-QAM is significantly degraded by the severe amplitude and phase variances (congenital to wireless channels). This happens as the demodulator needs to scale the received signal in order to regularize channel utility. So its estimation districts correspond to the transmitted signal constellation. This scaling process, which is requisite, is known as automatic gain control (AGC) [4]. The AGC wrongfully scales the received signal, if the channel utility is estimated in error, which can cause false demodulation even without the presence of noise. In order for the communication with M-QAM to be reliable (e.g. 16, 32, 64 etc.) we need accurate fading compensation techniques at the receiver. A truly efficient technique in M-QAM demodulation, to counterbalance channel amplitude and phase distortion, is channel sounding.

Example:

The following picture shows a 16-QAM signal with amplitude $A=5V$ peak, $f_c=20$ KHz, $T_s=4$ msec for the data bits $b_i=1100001111$.

Fig.9. 16-QAM signal

The following pictures show Signal Trajectory and Constellation Plot for a 16-QAM signal with 4bits/symbol and for five different values of E_b/N_0 (4, 8, 12, 16, 20 dB)

Fig.10. Signal Trajectory and Constellation Plot for $E_b/N_0 = 4\text{dB}$

Fig.12. Signal Trajectory and Constellation Plot for $E_b/N_0 = 12\text{dB}$

Fig.11. Signal Trajectory and Constellation Plot for $E_b/N_0 = 8\text{dB}$

Fig. 13. Signal Trajectory and Constellation Plot for $E_b/N_0 = 16\text{dB}$

Fig.14. Signal Trajectory and Constellation Plot for $E_b/N_0 = 20\text{dB}$

From the above pictures we can see that as E_b/N_0 increased (from 4 to 20 dB, in our example) the Signal Trajectories are clearer and the Constellation Plots have the points in a more specific area (small error). So if we consume (give) more power we have better telecommunication link.

V. DISCUSSION

Digital modulation, like analog modulation, changes a transmittable signal (carrier) based on the information received by a message signal (information signal).

In digital transmission applications [1], QAM allows higher data rates than usual phase modulated and amplitude modulated patterns. The number of points on the constellation diagram, which are the points at which the signal can rest, as with phase shift keying (PSK), is outlined in the modulation format display, for example 64-QAM uses a 64-point constellation. The most usual types of QAM use a number of points on the constellation diagram which is equal to a multiplication by 2 such as, 2, 4, 8, 16 etc. because QAM constellation points are usually cited in a plexus with even vertical and horizontal spacing. Using higher order modulation formats enables transmitting more bits per symbol, but presents the disadvantage of being more vulnerable to noise and data errors as the points are closer together.

Drawbacks of QAM are: a. Susceptibility to noise is higher due to the closeness of the states. The slightest noise is sufficient to cause movement of the signal to an alternative decision point and provoke data corruption. b.

When a radio Tx amplifies phase or frequency modulated signal, there is no need to use linear amplifiers. Linearity must be maintained when using QAM because it includes amplitude components. However, since linear amplifiers are inefficient and use up more power, they have become less popular for use on mobile applications.

Link conditions and requirements such as BER, SNR, data rate etc. are responsible for the choice of the modulation pattern in a radio communication system. QAM modulation is a method for reducing the bandwidth which is needed for transmission of digital data. In case of QAM the exchange between bandwidth and power is more beneficial than in M-PSK.

As mentioned, for each symbol both phase and amplitudes are varied to represent different bits. There are two levels of amplitudes for each phase d1 and d2. There are many variants to this technique. Most popular are 16-QAM, 64-QAM and 256-QAM. In 16-QAM each symbol represents 4 bits as mentioned in the constellation diagram.

In 64-QAM, each symbol is represented by 6 bits and in 256-QAM, each symbol is represented by 8 bits. As it increases in level QAM technique becomes more bandwidth efficient but it requires very robust algorithms to decode complex symbol at receiver into bits. For example, 256-QAM is complex than 16-QAM.

QAM is less robust but it is more bandwidth efficient compared to BPSK. Thus for poor CINR (Carrier to Interference and Noise Ratio) BPSK is employed, but for better CINR, QAM is employed, which leads to better data rate. Numerous radio communications and data delivery applications use QAM. Despite this, a few particular variations of QAM are implemented in specific applications and standards. In example, for domestic broadcast applications 64 QAM and 256 QAM are often encountered in digital cable television and cable modem applications. In the US, 64-QAM and 256-QAM are the binding modulation patterns for digital cable as standardized by the SCTE in the standard ANSI/SCTE 07 2000. In Great Britain, 16 QAM and 64 QAM are presently applied in digital terrestrial television using DVB (Digital Video Broadcasting). Other types of QAM are also applied in various cellular and wireless technology applications [4]. Direct modulation of a laser has always been used in optical telecommunications. Although distance-capacity product capabilities using this approach have been limited, it represents a very cost-effective solution, making it a prime choice especially when transmission distance is limited, for example, within a data center or a supercomputer (hundreds of thousands within a single supercomputer) or in 'last-mile' telecommunications. [5], [6].

Application examples: CDMA WiMAX-16d, 16e, WLAN-11, an OFDM Satellite DVB, Cable modem. Equipment like videophones, mobiles and in numerous defense applications often uses large scale circuit integration schemes based on QAM technique.

VI. CONCLUSION

From the simulation we can conclude (expected from the theory) that as E_b/N_0 increased (so SNR increased), BER reduced. Interference typically increases when we are moving to a higher order QAM constellation (more

constellation points, higher data rate and mode) in hostile environments, such as RF/microwave, wireless, cellular QAM applications (e.g. in broadcasting or cellular telecommunications multipath). There is reduced noise immunity because of a spreading of the spots in the constellation, which as a result gives a decreasing of the separation between adjacent states, thus making it difficult for the receiver to decode the signal appropriately. Estimation of signal to noise ratio for the received signal is an important task in communication systems. The knowledge of the SNR is a requirement on many systems in order to perform efficient signal detection and link adaptation. We are able to determine an optimal QAM mode for a specific operating environment because there are several test parameter measurements to support the best solution, for a given application.

REFERENCES

- [1] J. G. Proakis, *Digital Communications*, New York, NY, McGraw-Hill, 2001.

- [2] B. Sklar, *Digital Communications - Fundamentals and Applications*, Prentice Hall, New Jersey, 2001.
[3] D. Silage, *Digital Communications Systems using Matlab and Simulink*, Bookstand Publishing, 2009.
[4] W. T. Webb and L. Hanzo, *Modern Quadrature Amplitude Modulation*, New York, IEEE Press, 1994.
[5] Schindler P. C. et al. "Monolithic GaAs electro-optic IQ modulator demonstrated at 150 Gbit/s with 64QAM." *J. Lightwave Technol.* 32, 760–765, 2014
[6] Chiba A. et al. "16-level QAM by monolithic quad-parallel Mach-Zehnder optical modulator", *Electron. Lett.* 46, 220–221, 2010.

Nikolaos F. Voudoukis received a BSc degree in Physics from Athens National University, Greece, in 1991, a BSc in Electrical and Computer Engineering from the National Technical University of Athens, Greece, in 2012, his MSc degree in Electronics and Telecommunications from Athens National University, in 1993, and his PhD degree from Athens National University, in 2013. He has worked as telecommunication engineer in Greece. Dr Voudoukis now is Assistant Director at a high school and a part-time Lecturer at the School of Pedagogical & Technological Education, Athens, Greece.