M-QAM Modulation

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Github: https://github.com/leo09p/COMMII_A1_G8/tree/Practica_5

Abstract
In this laboratory, the M-QAM modulation technique was explored a key concept in modern communication systems. Both theoretical and practical approaches were combined to design, analyze, and optimize digital signals for efficient data transmission. This experience provided a deeper understanding of how M-QAM works and its relevance in everyday technologies, while also encouraging the development of innovative solutions in a continuously evolving field.

I. Introduction

In modern digital communication systems, spectral efficiency and data transmission capacity are essential aspects. One of the techniques that enhances both is Quadrature Amplitude Modulation (QAM). This method combines the amplitude modulation of two carrier signals that are 90 degrees out of phase one in-phase (I) and the other in quadrature (Q) to represent multiple bits per symbol. As a result, QAM is widely used in applications that demand high data rates, such as digital television, broadband systems, Wi-Fi, and mobile technologies like LTE and 5G.

QAM can be implemented with different modulation orders, such as 16-QAM, 64-QAM, or 256-QAM, where the number indicates the total symbols in the constellation. Higher-order modulations allow more bits per symbol but are also more sensitive to noise and interference, requiring a higher signal-to-noise ratio (SNR) for proper decoding. For this reason, adaptive systems often adjust the QAM order dynamically based on channel conditions.

The main goal of this laboratory is to study the operation and characteristics of M-QAM modulation, as well as its representation in the time domain and constellation diagram. Additionally, it aims to explore a generalized approach to programming various constellation-based modulation schemes including PSK, QPSK, 8-PSK, and 16-QAM through the development of flexible simulation tools.

II. METHODOLOGY

For the development of this project, a practical methodology was applied using the GNU Radio software. Various blocks related to digital modulation were explored and configured, allowing the implementation of different modulation schemes. The following steps describe the procedure carried out for each modulation type.

A. Initial analysis

In the first step, a GitHub folder was accessed through a link provided by the instructor, where the base flowgraph required for the modulation processes was located and downloaded. Afterwards, this file was opened in GNU Radio for analysis and editing, as shown in the following figure.

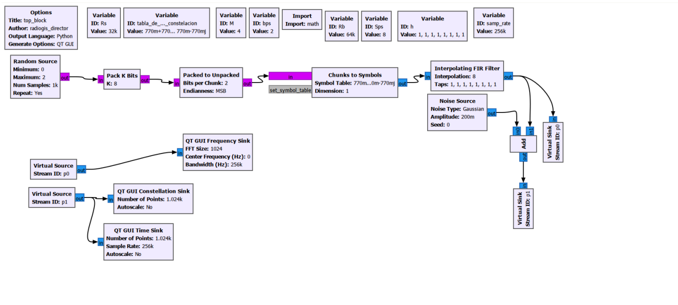

Fig. 1. First modulation flowchart.

Next, the 'Variable' block was configured, specifically the variable named “tabla_de_constelacion.” This variable was adjusted according to the constellation table corresponding to each modulation type, and then the simulation was executed within the GNU Radio environment.

B. Second analysis

In the analysis of the system in its passband version, an up-converter was implemented, consisting of a series of interconnected blocks, as illustrated in the corresponding figure.

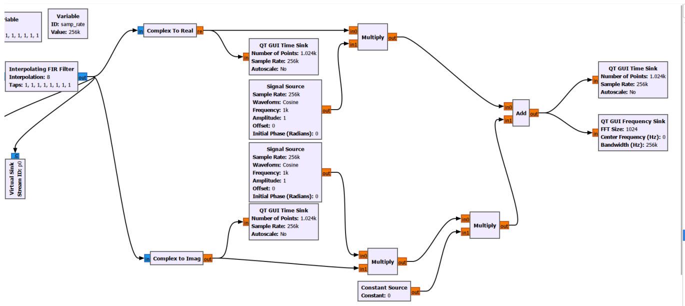

Fig. 2. Second modulation flowchart.

From the flow diagram, it was possible to visualize both the real and imaginary parts of the signal, as well as the bandpass signal s(t) and the power spectral density.

III. ANALYSIS OF RESULTS

For the results analysis section, the content was divided into sections in order to facilitate the interpretation of the data obtained from the flowcharts corresponding to Figure 1 and Figure 2.

A. Results of the first analysis

The first modulation to be analyzed is Binary Phase Shift Keying (BPSK), a digital modulation technique in which the constellation consists of two points located on the real axis of the complex plane. These correspond to the two possible carrier phases: 0° and 180°, representing bits 0 and 1, respectively. In this modulation scheme, only the in-phase (I) component is used to transmit data, taking values of +1 or −1 depending on the signal phase. The quadrature (Q) component does not play a role in BPSK, as its value is 0. This modulation relies solely on phase shifts to encode information, making it robust but offering a lower data rate compared to more complex modulation schemes, as illustrated in the following figure:

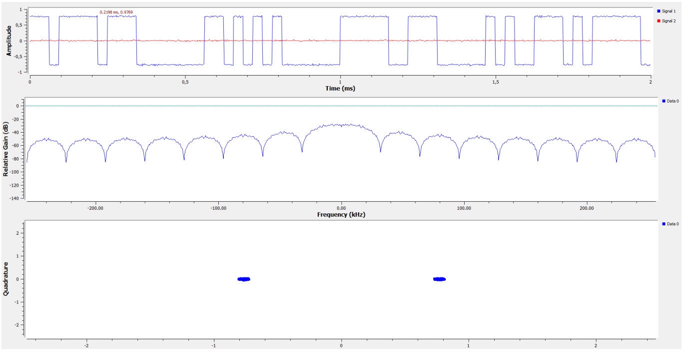

Fig. 3. BPSK Modulation.

In the previous figure, we can observe that the first plot displays the in-phase and quadrature components of the modulation, consistent with the earlier description. However, since it is a more realistic representation, the signal includes noise. On the other hand, the frequency spectrum shows a bandwidth of approximately 32 kHz (Rb). In the constellation diagram, the two points are separated by 180 degrees, as previously mentioned, though noise is also present in the signal.

The second modulation scheme used was 8PSK (8-Phase Shift Keying), a modulation technique that employs eight different phase states, evenly distributed in the complex plane, to represent 3 bits per symbol. In the 8-PSK constellation, the points are arranged along a circle in the complex plane, with an angular separation of 45° between each. This configuration allows for all possible combinations of three bits, with each point corresponding to a unique binary value. The in-phase (I) component of the signal is used to encode the information, while the quadrature (Q) component enables differentiation and proper demodulation of the signal, as illustrated in the following figure.

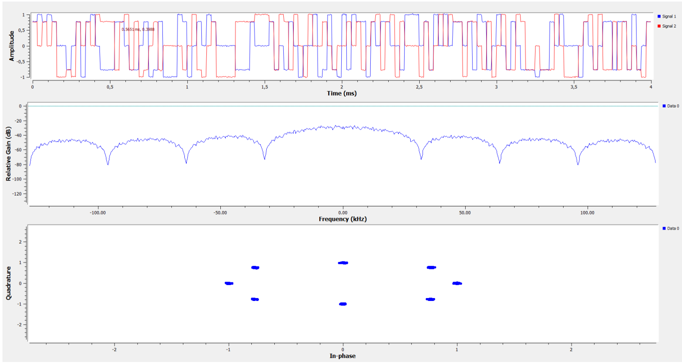

Fig. 4. 8-PSK Modulation.

From the previous image, it can be observed that 8-PSK signals offer greater spectral efficiency compared to modulations such as BPSK and QPSK, as they allow more bits to be transmitted per symbol. However, they are also more susceptible to noise and interference due to the closer spacing of the points in the constellation, which makes accurate symbol detection more challenging in noisy environments. In terms of frequency, the spectrum of 8-PSK is similar to that of BPSK, since both modulations share the same bandwidth and bit rate (Rb). This means that their spectral performance in terms of bandwidth is equivalent, although 8-PSK achieves higher efficiency by transmitting more bits per symbol.

The third modulation implemented was QPSK (Quadrature Phase Shift Keying), a digital modulation technique that uses four distinct phase shifts, separated by 90 degrees in the complex plane, to represent two bits per symbol. In the QPSK constellation, the points are positioned at phase angles of 0°, 90°, 180°, and 270°, which provides greater spectral efficiency than BPSK since it transmits two bits per phase change. In terms of components, QPSK makes use of both the in-phase (I) and quadrature (Q) components to encode the information, as illustrated in the following figure.

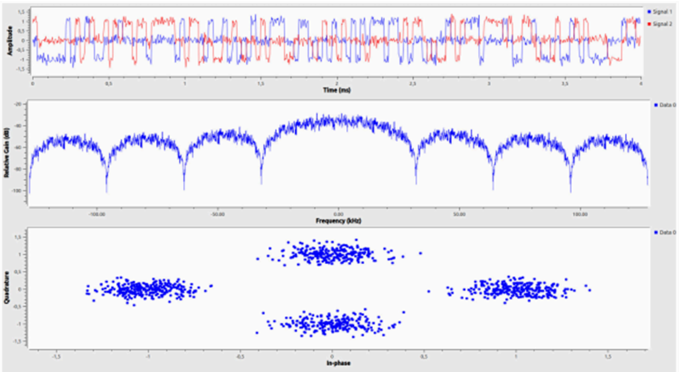

Fig. 5. QPSK Modulation.

From the previous figure, it can be concluded that QPSK offers greater spectral efficiency than BPSK because it transmits two bits per symbol using four distinct phase shifts, each separated by 90 degrees in the complex plane. This means that QPSK can send twice as much information as BPSK within the same bandwidth, improving overall spectral efficiency. However, while QPSK is more efficient than BPSK, it is still not as efficient as 8-PSK, and it remains susceptible to noise.

Finally, 16-QAM (16-Quadrature Amplitude Modulation) was implemented. This modulation technique combines variations in both amplitude and phase to transmit information. It uses 16 different symbols, each represented by a point in a two-dimensional constellation, where every point corresponds to a unique 4-bit combination. The 16-QAM constellation is arranged in a 4x4 grid, with each axis representing the in-phase (I) and quadrature (Q) components, as illustrated in the following figure.

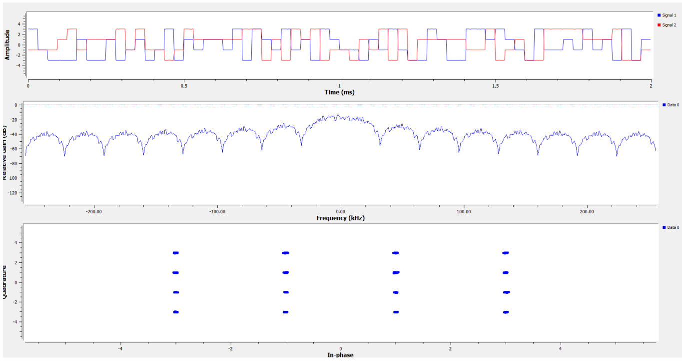

Fig. 6. 16-QAM Modulation.

From the previous image, it can be concluded that this modulation scheme is more efficient than lower-order techniques such as BPSK or QPSK, as it transmits more bits per symbol. However, it is also more vulnerable to noise and interference due to the closer spacing of the points in the constellation. For this reason, 16-QAM is commonly used in high-speed communication systems, including data networks and digital television.

B. Results of the second analysis

In the analysis of the system in its bandpass version, an up-converter was implemented, composed of a series of interconnected blocks, as illustrated in the following figure.

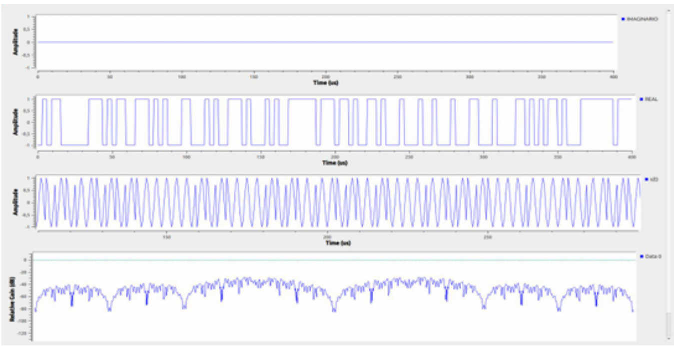

Fig. 7. BPSK passband modulation.

From the previous figure, it can be observed that passband BPSK modulation involves shifting the baseband signal to a higher carrier frequency. This is achieved by multiplying the baseband signal by a cosine waveform at frequency Fc, producing a passband signal centered around that carrier. In this form, the transmitted bits are represented by two distinct carrier phases—0° and 180°—preserving the fundamental structure of BPSK while relocating it to the carrier's frequency spectrum.

Next, to generate the QPSK modulation, the Constellation Table block was configured using the truth table corresponding to this scheme. This resulted in the following plot.

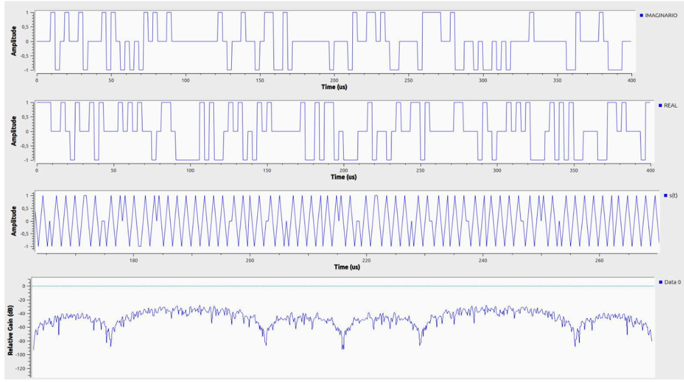

Fig. 8. QPSK passband modulation.

From Figure 8, it can be inferred that passband QPSK (Quadrature Phase Shift Keying) works by transmitting two quadrature components (I and Q), each shifted by 90° in phase. This allows two bits to be encoded per symbol, giving QPSK higher spectral efficiency compared to BPSK. The modulated signal is then shifted to a carrier frequency, enabling effective transmission in RF systems.

The 90-degree separation between the components reduces interference and improves resistance to noise. Unlike baseband modulation, which remains at low frequencies, passband QPSK shifts the signal to higher frequencies, making it suitable for wireless communication and long-distance transmission.

Now for 8-psk modulation, we have the result shown in Figure 9.

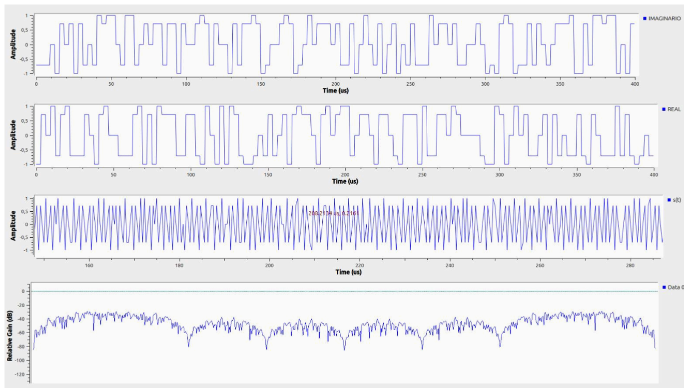

Fig. 9. 8-PSK bandpass modulation.

From the previous image, it can be observed that in the frequency domain, the bit rate (Rb) exhibits a higher frequency, and the graphs show a certain degree of instability.

Finally, the modulation graphs are presented. 16 - QAM

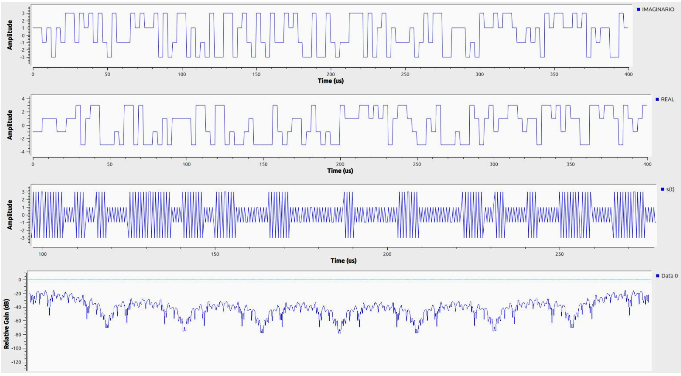

Fig. 10. 16-QAM bandpass modulation.

From the previous figure, it can be concluded that passband 16-QAM (Quadrature Amplitude Modulation) consists of 16 distinct combinations of amplitude and phase, allowing the transmission of 4 bits per symbol ($\log_2(16) = 4$). The modulated signal is shifted to a carrier frequency, which enables efficient transmission in RF systems.

The symbol rate, Rs, represents the number of symbols transmitted per second. Since each 16-QAM symbol carries 4 bits, Rs is lower than the bit rate Rb. The bit rate Rb corresponds to the number of bits sent per second and is four times Rs, given that each symbol contains 4 bits.

In the frequency domain, two main components can be observed: the modulated carrier and its sidebands, whose separation is determined by Rs. As Rs increases, the occupied bandwidth also increases. However, the bit rate Rb remains higher due to the spectral efficiency provided by 16-QAM.

IV. *CONCLUSIONS*

- Modulation techniques such as BPSK, QPSK, 8-PSK, and 16-QAM offer different levels of spectral efficiency, with 16-QAM providing the highest efficiency by transmitting more bits per symbol. However, as efficiency increases, so does the sensitivity to noise and interference. Therefore, choosing the appropriate modulation scheme requires balancing data-rate demands with channel conditions. A well-selected modulation not only maximizes performance but also ensures reliable communication under varying system constraints.
- Each modulation scheme has its own strengths and limitations depending on the communication channel conditions. BPSK is highly robust but offers lower efficiency, whereas 8-PSK and 16-QAM can transmit more information per symbol but demand a cleaner channel due to their increased sensitivity to noise.
- The main difference between passband and baseband modulation lies in how the signal is positioned within the frequency spectrum. In passband modulation, the signal is shifted to a higher carrier frequency and transmitted within a specific frequency range outside the baseband—similar to how FM radio operates. In contrast, baseband modulation keeps the signal at its original, low-frequency range without shifting it to a higher band. This distinction affects how the signal propagates, the type of channel it can use, and the applications for which each modulation method is best suited.

V. *REFERENCIAS*

[1] H. Ortega y O. Reyes, «Comunicaciones Digitales basadas en radio definidas por sofware», Google Docs. Accedido: 29 de agosto de 2025. [En línea]. Disponible en: https://drive.google.com/file/d/1fd9M4_bIjwLOajQdkdN9ex2plYRoXomz/view?usp=drive_link&usp=embed_facebook