Analysis of the noise immunity of quadrature modulation method for turning signal constellations

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Abstract: *The paper considers the effect of the rotation of the signal constellation on the noise immunity of quadrature multi-point modulation methods. Based on the error vector in the Matlab + Simulink simulation environment, models of M - QAM modulators and demodulators with rotation of the signal constellations at an arbitrary angle are proposed. Considered the most commonly used in digital data transmission systems modulation: 4-QAM, 16-QAM, 64-QAM and 256-QAM. The simulation results of the proposed models confirmed the coincidence of the values of the rotation angles of the signal constellations recommended by the DVB-T2 standard, and also revealed the values of other angles that can be used to improve the noise immunity of multipositional quadrature modulation methods.*
KEYWORDS: ERROR VECTOR, NOISE IMMUNITY, SIGNAL CONSTELLATION, ROTATION OF THE SIGNAL CONSTELLATION

1.Introduction

To effectively use the allocated bandwidth of the communication channel, multi-position signals are used - multipoint phase shift keying (M - PSK (Phase Shift Keying)) and multiposition quadrature amplitude keying (M - QAM (Quadrature Amplitude
On the other hand, in case of loss of information about one of the coordinates, it can be restored
most often built on quadrature circuits [1,3].
In the presence of nonlinear and phase distortions, interference and channel noise, transient interference between quadrature channels occurs. In this case, the signal constellations become blurred, that is, in each measure, the constellation point has random coordinates. The BER (Bit Error Ratio) is the best indicator to evaluate the quality of a transceiver, but BER testing is not always possible when developing an RF unit, because for measuring BER, along with the RF unit, you must have an information path for full digital processing of the received signal. An alternative to measuring the BER type of testing is to study the quality of the demodulated signal using vector analysis [7 - 10].
One of the most widely used quantitative indicators of the quality of modulation in digital communication systems is the EVM (Error Vector Magnitude). The magnitude of the error vector should not be confused with the magnitude error and the phase of the error vector with the phase error.
The value of the EVM vector makes it possible to determine the sources of errors and their contribution to the process of generating and processing signals in digital systems. It is sensitive to any degradation in signal quality that affects the magnitude and phase trajectory of the demodulated signal. The most difficult from the point of view of correlation of the measured signal vector to the ideal is the case when the real measured signal falls exactly in the middle between the points of the signal constellation, as shown in Fig. 1.1 a.
In this case, the calculation of the minimum of the metric (Δr) gives an ambiguous result. The DVB-T2 standard uses a turn of the signal constellation at a certain circular angle [2], which allows to improve the noise immunity of the system. Table 1.1 shows the values of the rotation angle of the constellation depending on the type of modulation.

Table 1.1. *The values of the rotation angle of the constellation for different types of modulation*

Modulation type	QPSK	16-QAM	64-QAM	256-QAM
The rotation angle of the constellation	29°	16,8°	8,6°	arctg(1/16)

Such a turn can significantly increase the stability of the signal with typical problems of the ether. Each vector of such a constellation acquires its individual coordinates I and Q (Fig. 1.1b). In this case, the values of the error vector Δr’’ and Δr’ have different values and there are no ambiguities in the calculation of the minimum of the metric.

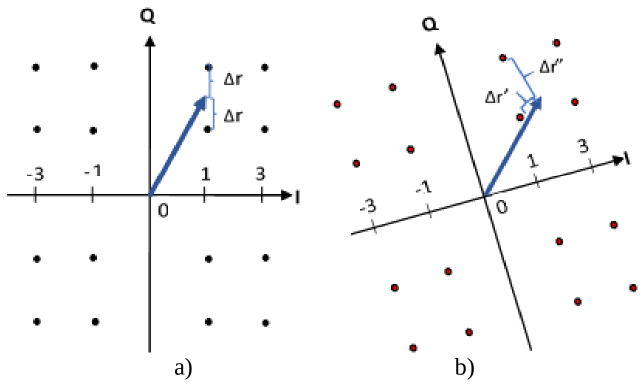

Fig.1.1. *Ambiguity in determining the minimum of the metric (Δr)*

On the other hand, in case of loss of information about one of the coordinates, it can be restored. As a rule, to reduce the likelihood of packet errors, the original digital data is interleaved. As a result of interleaving, the components I and Q are transmitted separately, which reduces the probability of their simultaneous loss. Thus, if one carrier or symbol is lost as a result of interference, information about the other coordinate is saved, this will allow restoring the symbol, albeit with a lower signal-to-noise level.
By now, a number of studies on the effect of the turn of the signal constellation have been performed [5, 6], however, to this day, the effect of the turn of the signal constellation has not been fully investigated. In particular, the mutual influence of signals carrying the same information at different angles of rotation of the signal constellation was not studied.
The possibility of turning a signal constellation on angles other than those recommended by the standard, and studying the mutual influence of the same signal turned on different angles, is of particular interest for practical application.

2. Preconditions and means for resolving the problem

2.1. Theoretical Data

To analyze the effect of the signal constellation rotation on the quadrature modulation noise immunity, an improved model of the “QAM-modulator” →"AWGN" → "QAM-demodulator" subsystem was developed, which takes into account the rotation of the signal constellation at a given angle. The model was developed using the computer math system MATLAB / SIMULINK 9.0 (R2017b). Processing and analysis of the simulation results were carried out using the program Origin Pro 2017 [11,12].

The standard Simulink block "Rectangular QAM-Modulator" outputs a quadrature amplitude-modulated signal that can be considered as a vector of complex numbers, the real part of which is the in-phase component of the quadrature signal, and the imaginary part is the quadrature component:

$$QAM = Re^{QAM} + Im^{QAM} = I + jQ. \quad (1.1)$$

From the mathematical theory of complex numbers, we know a linear transformation on the complex plane, leading to a rotation of a point by a given angle **φ**:

$$x' = x \cdot \cos\varphi - y \cdot \sin\varphi,$$
$$y' = x \cdot \cos\varphi + y \cdot \sin\varphi, \quad (1.2)$$

Since the abscissa of the complex plane is the real part of the complex number, and the ordinate is its imaginary part, formula (1.2) can be rewritten:

$$Re' = Re \cdot \cos\varphi - Im \cdot \sin\varphi,$$
$$Im' = Re \cdot \cos\varphi + Im \cdot \sin\varphi. \quad (1.3)$$

Thus, in terms of quadrature modulation, taking into account (1.1) – (1.3), we can write this:

$$I' = I \cdot \cos\varphi - Q \cdot \sin\varphi,$$
$$Q' = I \cdot \cos\varphi + Q \cdot \sin\varphi. \quad 1.4)$$

Based on formula (1.4), the Simulink model was created. To divide the quadrature signal into real (Re) and imaginary (Im) components, the standard block of the Simulink library "Complex to Real-Imag" is used, and the "Rectangular QAM-Modulator" block is used as the source of the quadrature signal. The block "Random Integer Generator" simulates the low-frequency signal of digital television broadcasting.

From the blocks of the library Simulink created subsystem "Transmitter" and "Receiver" taking into account the rotation of the signal constellation. In the receiver it is necessary to restore the initial position of the signal constellation. Therefore, before applying to the demodulator input, the received signal must be rotated through an angle that complements the rotation angle to 360^0 (denote it by φ ').

In order to manually transfer the value of the angle φ from degrees to radians each time and calculate the value of the additional angle φ ', we supplement the model of the system with a subsystem for performing these calculations.

2.2. Experimental Data

The final model for studying the effect of the rotation angle of the signal constellation on the noise immunity of the quadrature modulation schemes of M-QAM will take the following form (Fig. 1.2).

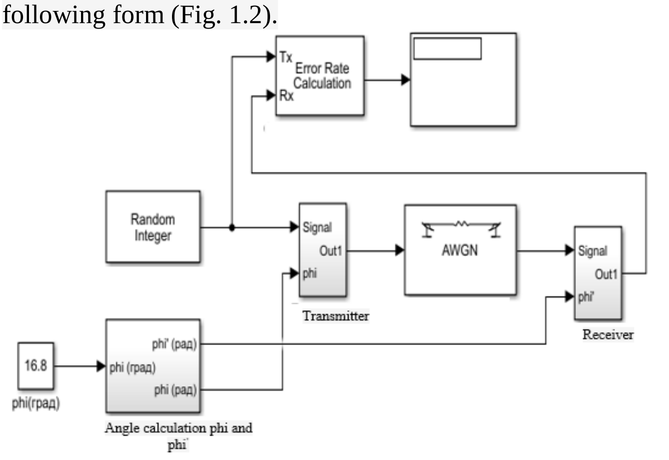

Fig.1.2. Model for studying the effect of the angle of rotation of the signal constellation on the noise immunity of quadrature modulation schemes

Setting the value of the angle of rotation in degrees (0 for the initial state without rotation), select the value of the parameter "E_b / N_0" in the settings of the block "AWGN" at which the specified error is observed for before. Enter the values of the rotation angle φ and the corresponding values of this angle "E_b / N_0" in the table for building graphs of the functions "E_b / N_0" = f (φ). Repeat the previous action for all angles in the range (0: 1: 90) for each type of modulation. The simulation results are shown in Fig.1.3 - Fig.1.6.

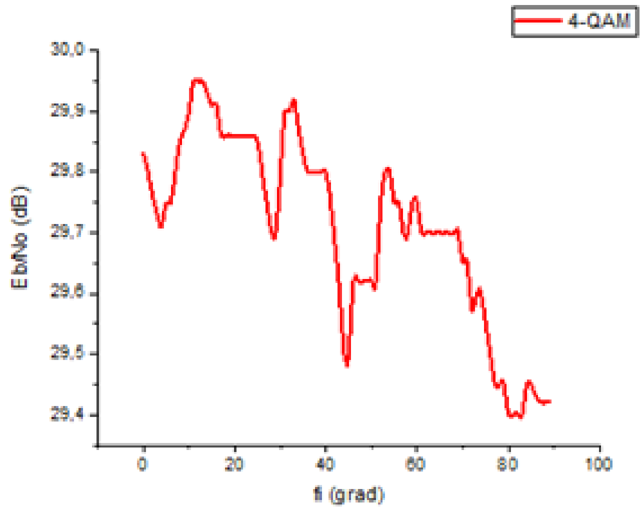

Fig.1.3. *Graph of "E_b / N_0" = f (φ) for 4-QAM*

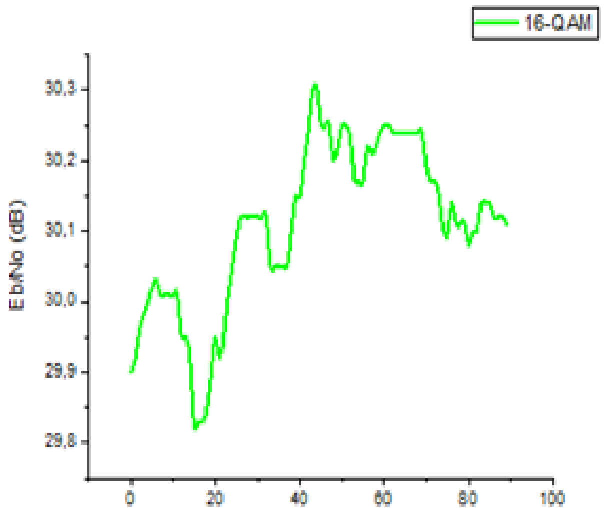

Fig.1.4. *Graph of "E_b / N_0" = f (φ) for 16-QAM*

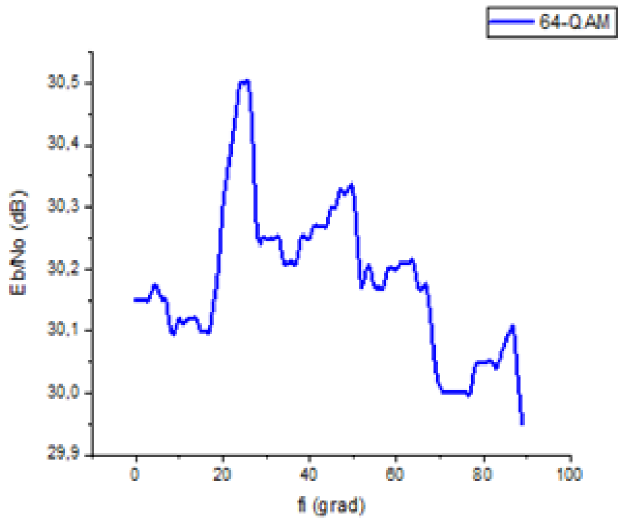

Fig.1.5. *Graph of "E_b / N_0" = f (φ) for 64-QAM*

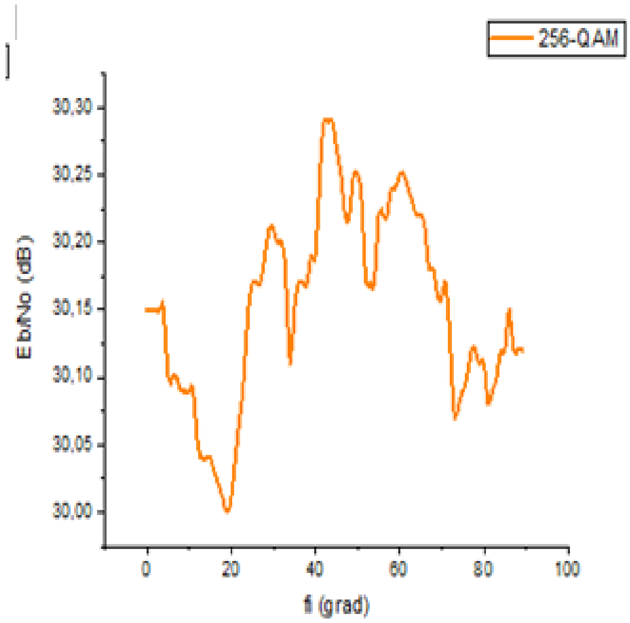

Fig.1.6. *Graph of "E_b / N_0" = f (φ) for 256-QAM*

From the graphs it can be seen that for each modulation several energy minima were found, for which the signal-to-noise ratio is less than for an un-turned signal constellation. The data on the detected energy minima are summarized in Table 1.2, and the main statistical information in Table 1.3.

Table 1.2. *Energetically favorable angles of rotation of the signal constellation*

Modulation Type	Angles of constellation, ^{0}	
	Recommended	Experimentally found angles
4-QAM	29	3, 29, 45, 82
16-QAM	16.8	16
64-QAM	8.6	9, 17, 75, 87.5
256-QAM	0.06	1, 7, 20, 74, 82

Table 1.3. *Statistical calculation data*

Modulation Type	$\frac{E_b}{N_0}$ min, dB	$\frac{E_b}{N_0}$ max, dB	$\sigma\left(\frac{E_b}{N_0}\right)$, dB	$\Delta\left(\frac{E_b}{N_0}\right)$, dB
4-QAM	29.4	29.95	0.1566	0.55
16-QAM	29.82	30.3	0.1184	0.48
64-QAM	29.95	30.5	0.1203	0.55
256-QAM	30	30,29	0.0714	0,29

3. Conclusion

In the program package MATLAB / SIMULINK, mathematical models of the subsystems "Transmitter", "Receiver" and "Model of recalculation of angles φ and φ ' " were developed. To investigate the effect of rotation of the signal constellation on the immunity system of transmission of digital information on the basis of the developed mathematical models of the subsystems is proposed mathematical model of the data transmission system with AWGN channel.

It can be seen from the graphs shown in Fig.1.3 – Fig.1.6 that for each modulation several energy minima were found for which the signal-to-noise ratio is less than for an un-rotated signal constellation.Based on the data presented in table 1.2 and table 1.3, we can draw the following conclusions:

• DVB-T2 recommended angles of rotation of the constellation received experimental confirmation.

• For all studied types of multi-point modulation, except for 16-QAM, besides the standard recommended by the standard, there are also other energetically favorable angles of rotation of the signal constellation. This opens up scope for further research on this topic.

• As M grows, the effect of turning the signal constellation decreases

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