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Justification of the Empirical Expression for Assessing the Noise Immunity of Quadrature Modulation Signals

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Abstract: *An approach to the substantiation of the empirical formula for calculating the bit error probability of quadrature modulation signals in terms of the average signal energy and the minimum Euclidean distance is considered. An analytical description of quadrature synthesis signals in the time and frequency continuum is presented. An approach to assessing the noise immunity of quadrature modulation signals from the standpoint of the indicator of the average signal energy and the Euclidean distance is considered. The equivalence of various well-known approaches to the analytical calculation of the bit error probability is shown. Graphic materials are presented, as well as simulation results. Empirically substantiated is a universal expression for assessing the noise immunity of receiving quadrature modulation signals, based on the differences in the average energy value and the value of the minimum Euclidean distance. Its generality with known expressions is shown.*

Keywords: *quadrature modulation signals, signal noise immunity, minimum Euclidean distance, bit error probability*

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Обоснование эмпирического выражения для оценки помехоустойчивости сигналов квадратурной модуляции

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Аннотация: *Рассмотрен подход к обоснованию эмпирической формулы для расчета вероятности битовой ошибки сигналов квадратурной модуляции по показателям средней энергии сигнала и минимального евклидова расстояния. Представлено аналитическое описание сигналов квадратурного синтеза во временном и частотном континууме. Рассмотрен подход к оценке помехоустойчивости сигналов квадратурной модуляции с позиций показателя средней энергии сигнала и евклидова расстояния. Показана эквивалентность различных известных подходов к аналитическому расчету вероятности битовой ошибки. Представлены графические материалы, а также результаты моделирования. Эмпирически* *обосновано универсальное выражение для оценки помехоустойчивости приема сигналов квадратурной модуляции, основанное на различиях величины средней энергии и значения минимального евклидова расстояния. Показана его общность с известными выражениями.*

Ключевые слова: *сигналы квадратурной модуляции, помехоустойчивость сигналов, минимальное евклидово расстояние, вероятность битовой ошибки*

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Introduction

Quadrature modulation (QAM) is widely used in standards of local area networks broadband access (LAN) IEEE 802.11, distributed under the commercial brand Wi-Fi [1–4]. The peculiarity of this type of modulation lies in the independent coding of the in-phase and quadrature channels by manipulating pulses, with their subsequent combination into a single signal structure [5–8].As a rule, the bit length of the M code selection for M-QAM signals is determined by the level of channel noise and reaches the value M = 32768 in ADSL modems [9].

The theory of formation and processing of signals of quadrature modulation is deeply developed and its methods are actively used in various areas of radio engineering and telecommunications [10–13].

At the same time, research continues in the field of synthesis of new signal structures formed by the quadrature method. And for the theoretical study of this direction, more general expressions are needed that allow one to evaluate their noise immunity based only on energy differences in relation to known signal structures [14, 15]. This will make it possible to determine the prospects of their application even at the stage of theoretical study.

Within the framework of this problem, this article presents an approach to justifying an empirical expression that allows estimating the probability of a bit error in a channel depending on the noise level by introducing a correction factor that takes into account the energy characteristics of the signal structure formed by quadrature synthesis.

Introduction to Quadrature Modulation

At its core, quadrature modulation is a symbiosis of amplitude manipulation in each of the channels, with a quadrature shift (the phase difference between the channels is π/2) between the channels [16]. This allows the resulting signal construction to be represented in the following form [17]:

$$s(t) = I(t)\cos(2\pi f_0 t) + Q(t)\cos\left(2\pi f_0 t + \frac{\pi}{2}\right), \quad (1)$$

where f_0 is the carrier frequency, and $I(t)$ and $Q(t)$ are manipulating information sequences.

In accordance with formula (1), the signals $I(t)$ and $Q(t)$ are formed from the original information bit sequence $u_m(t)$ by appropriate structuring (here m is the ordinal number of the information bit). As a result odd pulses $u_{2m-1}(t)$ manipulate the in-phase component, and even pulses $u_{2m}(t)$ manipulate the quadrature one [17, 18].

On Fig. 1 shows a typical quadrature modulator for synthesizing 4-QAM signals.

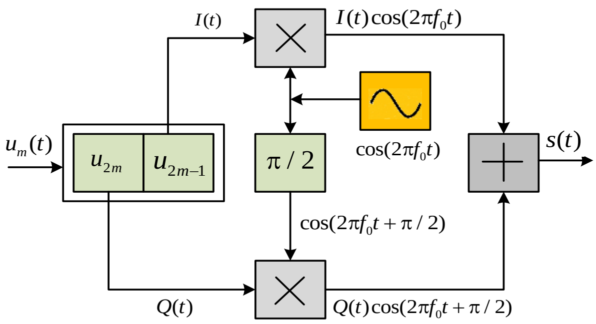

Fig. 1. Structure of a Standard 4-QAM Quadrature Signal Modulator

It should be noted that when dividing the information manipulating sequence $u_m(t)$ into an in-phase one, containing only odd pulses $u_{2m-1}(t)$, and a quadrature one, containing only even components $u_{2m}(t)$, the length of the pulses in these sequences doubles [19].

Quite often, the signals $I(t)$ and $Q(t)$ are directly associated with the manipulating sequence $u_m(t)$, which is not entirely true.

According to the structure of the modulator (see Fig. 1), the signal $s(t)$ must be high-frequency. But such an implementation is difficult for practical use, so the signals $I(t)$ and $Q(t)$ supplied to the multipliers already initially represent low-frequency keyed oscillations:

$$\begin{cases} I_n(t) = a_n \cos[\Omega_{2m-1} u_{2m-1}(t-(2m-1)T)]; \\ Q_n(t) = b_n \sin[\Omega_{2m} u_{2m}(t-2mT)], \end{cases} \quad (2)$$

where a_n and b_n are the amplitude values of the manipulation pulses; Ω is the full phase of the forming initial low-frequency oscillation; T is a clock interval, by means of which the manipulation speed is set.

In expression (2), the subscript n is introduced for clarity of the procedure for structuring the flows $I(t)$ and $Q(t)$, since the manipulating pulses are divided in the quadrature and in-phase channels into even and odd sequences.

The convenience of square modulation is determined not only at the stage of signal synthesis, but also at the stage of their processing in a coherent demodulator [18]. Thus, the resulting signal at the reception will be an additive mixture of the useful component $s(t)$ and channel noise $n(t)$ [20]:

$$z(t) = s(t) + n(t), \tag{3}$$

which goes to the demodulator (see Fig. 2).

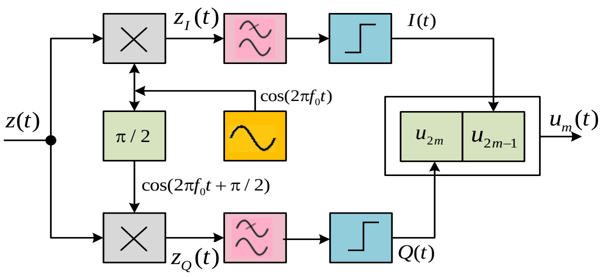

Fig. 2. Structure of a Standard 4-QAM Quadrature Signal Demodulator

When describing the processing procedures for quadrature modulation signals, some publications miss such an important point as the need to implement low-frequency filtering procedures in the in-phase and quadrature channels after removing the carrier wave.

In the demodulator, the removal of the carrier is carried out by multiplying the accepted implementation $z(t)$ (expression (3)), respectively, by the in-phase and quadrature components generated by the reference generator. To clarify this point, consider the implementation of this procedure in more detail using the example of an in-phase channel.

Analytically, the signal $z_I(t)$ can be represented as follows:

$$\begin{gathered} z_I(t) = z(t)\cos(2\pi f_0 t) = I(t)\cos(2\pi f_0 t) \times \\ \times \cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t)\cos(2\pi f_0 t). \end{gathered} \tag{4}$$

And, using the trigonometric transformation, we bring the expression (4) to the form:

$$\begin{gathered} z_I(t) = 0{,}5I(t)[1 + \cos(4\pi f_0 t)] - \\ -0{,}5Q(t)\sin(4\pi f_0 t) = 0{,}5I(t) + \\ +0{,}5[I(t)\cos(4\pi f_0 t) - Q(t)\sin(4\pi f_0 t)] \end{gathered} \tag{5}$$

Similarly carry out the removal of the carrier in the quadrature channel.

In the demodulator, the removal of the carrier is carried out by multiplying the accepted implementation $z(t)$ (expression (5)). Note that the carrier removal procedure does not yet provide the original keying sequence, since the signal $z_I(t)$ has a high-frequency component. For its localization, low-frequency filtering is used [21, 22].

Further, the filtered signals in each of the channels are fed to the forming devices, from where the pulse sequences (odd from the in-phase channel, and even from the quadrature channel) come to the output, where they are structured into the resulting information sequence $u_m(t)$. An important feature of quadrature modulation signals is that the total signal bandwidth $s(t)$ at the modulator output is similar to DSB (Double-Sideband) transmission signals [23, 24], which have a symmetrical spectrum with respect to the carrier. Note that the spectral redundancy of DSB signals potentially doubles the information capacity when using the quadrature method. Since the spectrum of signals formed in quadrature, unlike DSB signals, does not have a constant component at the carrier frequency [25], it is easy to restore the phase of the carrier oscillation with clock synchronization.

Thus, in order to preserve the independence of the signals $I(t)$ and $Q(t)$, hard clock synchronization must be provided at the reception when the carrier is removed. In the absence of synchronization of the transceiver equipment, a phase mismatch occurs between the oscillation of the demodulator reference oscillator and the carrier frequency of the received signal. As a result of such a mismatch, the effect of mutual penetration of the signal $I(t)$ into the quadrature channel, and the signal $Q(t)$ into the in-phase channel occurs, as a result of which crosstalk occurs [26–28]. In this context, the clock signal is called the "phase reference". In practice, synchronization in radio links using signals based on quadrature modulation is provided by additional transmission of a pilot signal [17].

In the interests of studying the spectral images of quadrature modulation signals, we transform expression (1) taking into account the equality:

$$\cos(2\pi f_0 t + \pi/2) = -\sin(2\pi f_0 t) \tag{6}$$

expression (6) and Euler's formulas to the form:

$$\begin{gathered} s(t) = I(t)\cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t) = \\ = 0{,}5\exp(j2\pi f_0 t)[I(t) + jQ(t)], \end{gathered} \tag{7}$$

where j is the sign of the complex representation.

And applying the Fourier transform to expression (7), we obtain the desired spectrum $F_s(f)$:

$$F_s(f) = 0{,}5\left[F_I(f - f_0) + \exp(j2\pi f_0)F_Q(f - f_0)\right], \tag{8}$$

here $F_I(f)$ and $F_Q(f)$ are the spectral representations of the signals $I(t)$ and $Q(t)$ after the execution 8 of the Fourier transform procedure.

Noise immunity of quadrature modulation signals

The noise immunity of any signal structure is determined by the energy of the signal symbol E [10, 15, 16]. Considering that with quadrature modulation, the signal symbol is formed on the basis of two components, then its energy of the n^{th} symbol will be determined as follows:

$$E_n = (a_n^2 + b_n^2)E_0 \,, \tag{9}$$

where a_n and b_n are the scaling amplitude coefficients of the in-phase and quadrature components of the shaping pulses; E_0 is the energy of the forming pulse.

Note that formula (9) fully characterizes only 4-QAM signals, in which a_n and b_n have the same values for any symbol, see Fig. 3.

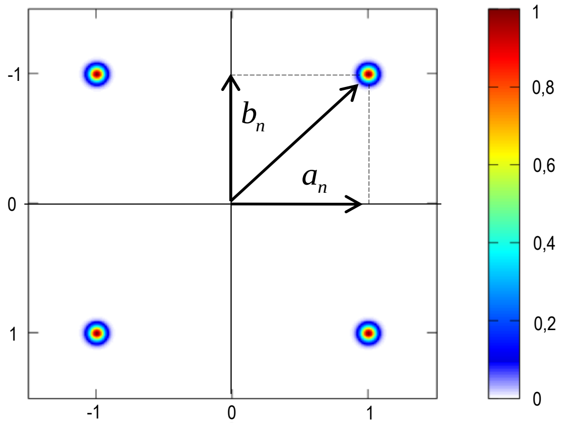

Fig. 3. 4-QAM Signal Constellation

However, things are more complicated for multi-position quadrature modulation signals with $n > 4$.

So, as an example, in Fig. 4 shows the signal constellation for 16-QAM, as well as the amplitudes A_n and A_k, which have different values, since they are formed by different values of a_n and b_n. Obviously, for a signal construction, one can only talk about the average energy E_Σ per N symbols.

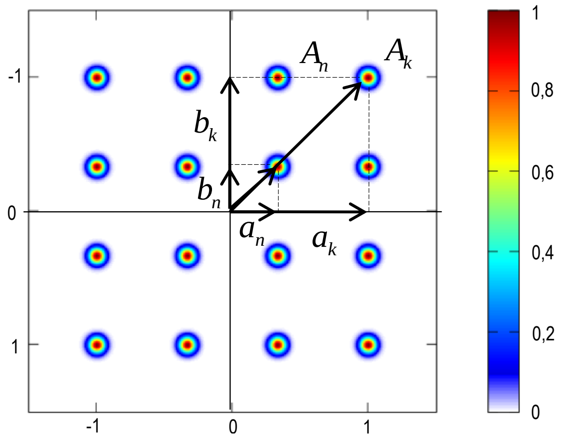

Fig. 4. 16-QAM Signal Constellation

$$E_\Sigma = \frac{1}{N} \sum_{n=1}^{N} (a_n^2 + b_n^2)\, E_0. \tag{10}$$

Formula (10) introduces the concept of the energy of the smallest impulse E_0, so the quantities a_n and b_n act as amplitude values. This is done so that expression (10) can be conveniently used for complex structures with dimensions $n > 4$.

Since the matrix of a_n and b_n values for 16-QAM is as follows:

$$\{a_k, b_k\} = \begin{bmatrix} (-3,3) & (-1,3) & (1,3) & (3,3) \\ (-3,1) & (-1,1) & (1,1) & (3,1) \\ (-3,-1) & (-1,-1) & (1,-1) & (3,-1) \\ (-3,-3) & (-1,-3) & (1,-3) & (3,-3) \end{bmatrix}, \tag{11}$$

then if we hypothetically assume that in the 16-QAM signal structure the order of symbol change is uniform, then we can calculate the average energy E_{16} in energy units of the smallest pulse E_0 (in this case, in relation to Fig. 4, this is the pulse formed by the amplitude values a_n and b_n).

The resulting value will be equal to $E_{16} = 10\ E_0$. Here and below, the subscript indicates the positional nature of the construction. To understand the considered approach, the energy E_4 for the 4-QAM signal structure, calculated in a similar way according to formula (11), will be $E_4 = 18\ E_0$.

That is, the average energy of the 4-QAM signal construct is 1.8 times higher than the average energy of the 16-QAM signal construct. By the way, for the 2-QAM design, the symbol energy will also be $E_2 = 18\ E_0$, which corresponds to the well-known fact about the equality of the noise immunity of QPSK and BPSK signals.

When assessing the noise immunity of quadrature modulation signals, the formula proposed in [16] is often used, which makes it possible to estimate the probability of a bit error depending on the signal-to-noise (hereinafter referred to as SNR) ratio $h^2 = E_b / N_0$, where E_b is the energy per bit, and N_0 is noise power spectral density:

$$P_b = \frac{2(1 - L^{-1})}{\log_2 L} Q\left[\sqrt{\left(\frac{3\log_2 L}{L^2 - 1}\right)\frac{2E_b}{N_0}}\right], \tag{12}$$

where L is the number of keying levels defined for the M-QAM signal as $L = \sqrt{M}$; E_b is the signal energy per bit; N_0 is the noise power spectral density: the Q-function is the Gaussian error integral:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{u^2}{2}\right) du, \tag{13}$$

However, formula (12) in its final form does not reveal the essence of the noise immunity of QAM signals. Therefore, in the interest of revealing the generality of signal structures formed on the basis of quadrature modulation to signals of phase and multiposition amplitude manipulation, we consider the probability of their detection at the reception using expression (13) .

Thus, the probability of reliable reception of the QAM signal is possible in the case of a positive decision to receive the signal in both in-phase and quadrature channels. Taking into account that the error probability of the L-level amplitude shift keying is determined in accordance with the formula presented in [29] (the validity of the formula is justified when encoding the levels with the Gray code):

$$P_s = \frac{2(\sqrt{M}-1)}{\sqrt{M}}\, Q\left[\sqrt{\frac{3E_s}{(M-1)N_0}}\right], \qquad (14)$$

then the probability of correct reception simultaneously in both channels of the quadrature demodulator will be determined as 6:

$$P_0 = (1 - P_s)^2. \qquad (15)$$

In formula (12), E_s is the energy per signal symbol.

Considering that the energy E_b is related to E_s by the following relationship [16, 30]:

$$E_s = E_b \log_2(M), \qquad (16)$$

the probability of a bit error of reception, taking into account formulas (14), (15) and (16), we write in the following form:

$$P_b = \frac{1 - \left[1 - \frac{2(\sqrt{M}-1)}{\sqrt{M}} Q\left(\sqrt{\frac{3E_b\log_2(M)}{(M-1)N_0}}\right)\right]^2}{\log_2 M}, \qquad (17)$$

where division by $\log_2 M$ is due to the fact that the value of P_b is related to the probability of a symbol error $P_c = 1 - P_0$ as follows $P_c = P_b \log_2 M$.

Formula (17) is a general expression for assessing the noise immunity of M-QAM signal structures. Therefore, for 4-QAM, i. e. for $M = 4$, we get:

$$P_b = Q\left(\sqrt{2}h\right)\left[1 - 0{,}5Q\left(\sqrt{2}h\right)\right]. \qquad (18)$$

Accordingly, for 16-QAM, i. e. for $M = 16$:

$$P_b = \frac{3}{4}Q\left(\sqrt{\frac{4}{5}}h\right)\left[1 - \frac{3}{4}Q\left(\sqrt{\frac{4}{5}}h\right)\right], \qquad (19)$$

where $h = \sqrt{E_b/N_0}$.

The analysis of the obtained results showed that the calculation results, according to formulas (18) and (19), completely coincide with the results obtained in accordance with (16), see Fig. 5.

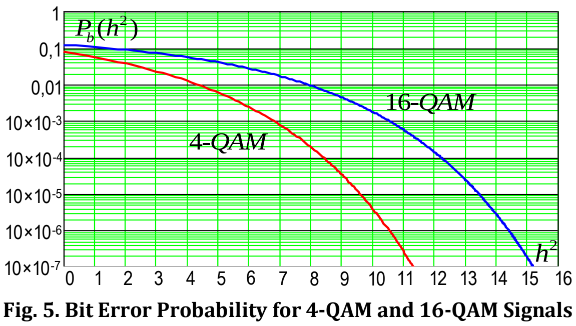

Fig. 5. Bit Error Probability for 4-QAM and 16-QAM Signals

In addition, the result (17) is similar to the calculations obtained in accordance with the well-known expression [17]:

$$P_b = Q\left(\sqrt{2}h\right). \qquad (20)$$

In [16], it is indicated that when encoding with a Gray code, the noise immunity of QPSK signals becomes equal to the noise immunity of BPSK signals. On Fig. 5 and further in the text along the abscissa of the SNR value in dB.

Justification of the calculated expression based on the empirical approach

The analytical complexity of expression (16) and the strict dependence on the value of the parameter M limit its practical application in experimental studies.

At the same time, another important indicator that determines the noise immunity of a signal structure is the minimum Euclidean distance (MED) Δ [31, 32], which can also be used to estimate the probability of a bit error. And then, given the equality of the signal energy, to assess the noise immunity, you can use formula (20) with a correction factor Y:

$$\tilde{P}_b = Q\left(\sqrt{2}hY\right). \qquad (21)$$

In turn, the coefficient Y will be equal to:

$$Y = \frac{[\Delta_{M_1}/\Delta_{M_2}]}{[E_{M_1}/E_{M_2}]},$$

here Δ_{M_1} is the value of the MEP of the reference signal structure, relative to which the comparison is carried out; Δ_{M_2} is the value of the MEP of the compared signal structure; E_{M_1} is the average energy of the reference signal structure against which the comparison is made; E_{M_2} is the average energy of the compared signal structure.

The MEP value can be calculated based on the logic of constructing the signal structure itself [33]. So for BPSK MEP is $\Delta_2 = 2\sqrt{2}$, for 4-QAM MEP is $\Delta_4 = 2$, for 16-QAM MEP is $\Delta_{16} = 2/3$. You can also calculate the values of the average energy. In particular, a value of 1.8 was previously obtained for 16-QAM. Then, taking into account the value of MEP $\Delta_{16} = 2/3$, it is possible to calculate the probability of a bit error using formula (21).

On Fig. 6 shows the results of calculating the bit error probability for a 16-QAM signal based on formulas (18) and (20).

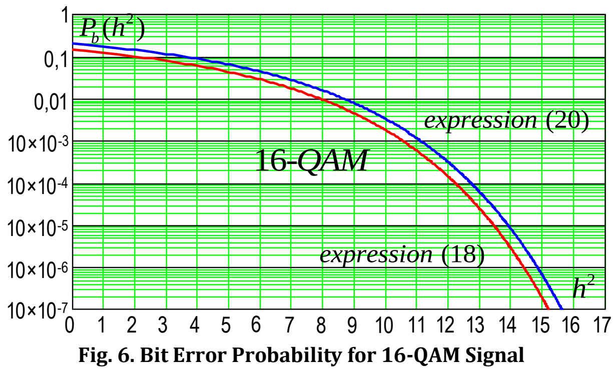

Fig. 6. Bit Error Probability for 16-QAM Signal

An analysis of the obtained results allows us to judge that the differences in the calculations do not exceed 0.5 dB over the entire range of SNR changes. In the course of substantiating the calculated expression, other signal structures formed by the quadrature method were also investigated. The results obtained have similar calculation errors, which indicates the generality of formula (21).

Conclusion

The validity of the proposed approach is based on the correspondence of the results of analytical modeling to well-known data. The convenience of the empirical formula (19) is that it allows using only the values of MEP and average energy in the synthesis of new signal structures to assess its noise immunity. This opens up the possibility of its application even at the stage of developing a hypothesis. For example, when synthesizing signal structures with transformed constellations obtained in [34], or for QAM signals built on the basis of various types of hexagonal arrays [35]. This is due to the fact that for such structures it is not applicable in the direct formulation of the analytical apparatus for assessing noise immunity.

Further research will be related to the development of an approach to increasing the spectral efficiency of signal structures formed by the quadrature synthesis method. Including using wavelet functions.

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