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INVESTIGATION OF NOISE IMMUNITY TELECOMMUNICATION SYSTEMS ACCORDING TO THE CRITERION ENERGY EFFICIENCY

Bayram Ibrahimov

*Department of Radio Engineering and Telecommunication, Azerbaijan Technical University
AZ1073, H. Javid ave. 25, Baku, Azerbaijan
i.bayram@mail.ru*

Methods for improving the characteristics of the reliability message transmission in multiservice telecommunication networks in the provision of multimedia services are analyzed. The noise immunity reception, effective methods modulation, paths transmission systems, indicators of information, frequency and energy efficiency of the system, methods of processing and receiving messages are considered. The problems of optimizing signal-code constructions according to the criterion of energy efficiency of a telecommunications system are studied. A new approach to the construction of methods for calculating the indicators of noise immunity of receiving messages is proposed, taking into account signal-code structures. The developed calculation method takes into account effective types of modulation, demodulator synthesis algorithms, signal processing methods, bandwidth, signal-to-noise ratio and energy efficiency indicators. On the basis of the calculation method, important analytical expressions were obtained that evaluate the characteristics of the noise immunity reception, taking into account the indicators energy efficiency, throughput per sample, the conditions for the indicators of the signal-to-noise ratio and the probability erroneous reception discrete signals.

Keywords: bandwidth, energy efficiency, modem, discrete signals, error probability, signal-to-noise ratio, signal-code structures

1. Introduction

At present, the task increasing the noise immunity multiservice telecommunication networks (MTN) based on modern technologies remains relevant, since the number users is constantly growing and the volume of transmitted useful and service traffic is increasing (Ibrahimov *et al.*, 2018).

One of the important indicators of the noise immunity functioning of a communication network based on the architectural concept of the next generation network (NGN) and future networks (FN) is the information, spectral and energy efficiency of the system, which ensures high reliability of message transmission (Bianco *et al.*, 2017).

To study the problem of noise immunity, one of the key positions is occupied by energy efficiency, that is, an indicator of how technical means use the energy of the transmitting subscriber and network terminals (Protopopov, 2013). The value energy efficiency is determined by the gain of the transmitting system, the characteristics of the radio signal propagation path, the properties of the receiving part, the intrinsic noise of the receiver, and the efficiency of the received signal processing system (Ibrahimov *et al.*, 2022). The energy efficiency indicator of the system characterizes the use of the channel in terms of power (Ibrahimov *et al.*, 2020).

One of the real ways to solve the problem increasing noise immunity in telecommunication systems is the widespread introduction mathematical modeling methods, among which the theory optimal reception discrete signals, effective modulation and coding schemes dominate (Ibrahimov *et al.*, 2020).

Numerous sources (Ibrahimov *et al.*, 2020; Burkov, 2023) consider some aspects related to the construction of an error-correcting receiver and the problem of demodulator synthesis. However, due to the variety of options for solving individual problems and the initial requirements for the systems being designed, it is very difficult to use these results when choosing the optimal modem construction option with efficient signal-code constructions (SCC) (Yu *et al.*, 2020). In addition, the vast majority of works (Jin *et al.*, 2023) are devoted to the study of the limiting capabilities of individual elements, and only a small number works considers the efficiency of the system for processing and receiving discrete signals as a whole (Chettri *et al.*, 2020).

In this case, message processing systems using discrete signals can be represented in the form of SCC. It is assumed that, considering signal-code constructions, it consists of an ensemble of signals and an error-correcting code (Ibrahimov *et al.*, 2020).

An optimization problem arises for studying noise immunity, taking into account SCC according to the criterion of energy efficiency telecommunication systems built in accordance with the concept of NGN

and FN (Ibrahimov *et al.*, 2020). Based on the study (Zeng *et al.*, 2017), it was found that the main obstacles in solving this problem is the lack of a sufficiently new approach to constructing a method for calculating the noise immunity indicators of signal reception and processing, which allow optimizing the characteristics communication quality (Ji *et al.*, 2018).

The purpose of this work is to develop a method for calculating the noise immunity characteristics signal reception using SCC according to the criterion of energy efficiency in telecommunication systems.

2. Statement of the problem and description of the new approach

The research (Ruixin *et al.*, 2020) showed that in telecommunication systems the necessary speed and reliability of transmission of discrete messages are achieved by certain costs of signal power P_S and channel bandwidth F_C . Therefore, it is necessary to comprehensively and jointly study both the information and frequency efficiency of the system, and the energy efficiency indicator (Deng *et al.*, 2019).

Information efficiency of the system – determines the degree of use of the bandwidth of the communication channel and is expressed as

$$\eta_{IE}(b_i) = [V_b(b_i) / C_{\max}] < 1, V_b(b_i) < C_{\max}, \quad (1)$$

where $\eta_{IE}(b_i)$ is the information efficiency of discrete binary signal transmission systems with an element b_i , $b_i = \{0, 1\}$, $V(b_i)$ is the binary element signaling bit rate b_i , $C_{\max}$ is the maximum value of the bandwidth of the communication channel.

Frequency efficiency is an indicator characterizing the use of the channel by frequency band and is found as follows:

$$\eta_{FE}(b_i) = [V_b(b_i) / F_C] < 1. \quad (2)$$

It is known (Ibrahimov *et al.*, 2018) that the energy efficiency in telecommunication systems is calculated by the following expression:

$$\eta_{FE}(b_i) = \frac{V(b_i)}{P_S / N_0} = \frac{R_k \cdot \log_2 m}{E_s / N_0}, \quad (3)$$

where $\eta_{EE}(b_i)$ is the energy efficiency of discrete binary signal transmission systems with an element b_i , $V(b_i)$ is the bit rate of discrete signals with a binary element b_i and is equal to

$$V(b_i) = R_k(1/T) \cdot \log_2 m,$$

where R_k is the code speed and equal $R_k = (k/n) < 1$, k , and n are the number of informational and common characters in the code word, respectively; m is the base of the code or the extent of the code alphabet; T is the duration of the multiposition signal (Jiaqi *et al.*, 2020).

Taking into account (1), (2) and (3), the energy efficiency discrete message transmission systems is expressed as:

$$\eta_{EE}(P_S, b_i) = 1/(E_b / N_0) = 1/h_b^2 = [SNR(P_S, E_b)]^{-1}, \quad (4)$$

where h_b^2 is the signal-to-noise ratio at the demodulator input and equal to

$$h_b^2 = E_b / N_0 = SNR(P_S, E_b),$$

where $SNR(P_S, E_b)$ is the signal-to-noise ratio with parameter P_S and E_b , E_b is the bit energy and determines the energy spent on the transmission of one bit of the message and is equal to $E_b = E_S / (R_k \cdot \log_2 m)$, E_S is the signal energy; N_0 is the one-sided (at positive frequencies) power spectral density of white noise and is equal to $N_0 = 0,5(NF \cdot G - 1) \cdot (h_0 \cdot f_0) \cdot (Vt / Hz)$, NF and G is the noise figure and signal gain of the amplifier in the demodulator, respectively; h_0, f_0 are the respectively the Planck coefficient and signal frequency (Fangyuan *et al.*, 2020).

Expressions (1), (2), (3) and (4) characterize the quality of communication and the coefficient of effective use of the channel in terms of signal power, taking into account the parameters N_0 and E_b .

3. Energy efficiency and the probability error analysis

Now, based on a new approach, we consider the energy efficiency of telecommunication systems, taking into account modulation methods, signal-to-noise ratio at the demodulator input, and the ability of an error-correcting code (Clerckx *et al.*, 2016). Given the last assumption, the minimum required is $SNR_m(P_S, E_b)$ expressed as follows:

$$SNR_m(P_S, E_b) = \frac{R_k^{-1}}{[G(k) \cdot p_{BER}(h)] \cdot \log_2 M} \cdot h^2, \quad (5)$$

where $G(k)$ is the parameter characterizing the reliability of the decoded message; h is the SNR for one count; $p_{BER}(h)$ is the bit error rate at the demodulator output; R_k is the a function that determines the relationship between the information and redundant parts of the code word, which is the code rate; M is the volume of the alphabet of the used signal (Clerckx *et al.*, 2020).

The proposed expression (5) is the minimum required signal-to-noise ratio $SNR(P_S, E_b)$ when receiving one bit of information with a given reliability $p_{BER}(h) \leq p_{BER}^{all.}(h)$ and characterizes the value of energy efficiency using SCC. which consists of an ensemble of signals and a correction code (Ibrahimov *et al.*, 2020 and Yuandong *et al.*, 2022).

The reception error probabilities, taking into account some important indicators such as the reliability of transmission and signal processing, multiposition phase shift keying (M-PSK), the signal-to-noise ratio, and the volume of the alphabet of the signal used, are expressed as follows (Qian *et al.*, 2021):

$$p_{BER}(h) = 2Q\left(\sqrt{2h^2} \sin \frac{\pi}{M}\right) \left[1 - Q\left(\sqrt{2h^2} \cos \frac{\pi}{M}\right)\right] + Q\left(\sqrt{2h^2} \cos \frac{\pi}{M}\right) - 2T\left(\sqrt{2h^2} \cos \frac{\pi}{M} \cdot \operatorname{tg} \frac{\pi}{M}\right), \quad (6)$$

where $T(h, a)$ is the tabulated Owen function with parameters h and a is expressed as (Ibrahimov *et al.*, 2020):

$$T(h, a) = \frac{1}{2\pi} \int_0^a \exp\left[-\frac{h^2}{2}(1+x^2)\right] \frac{1}{1+x^2} dx,$$

where a is the parameter of the Owen function using the correlation coefficient r is found as follows: $a = [(1-r)/(1+r)]^{0.5}$, $Q(x)$ based Gaussian function is the integral error probability and is equal to

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-0.5t^2) dt.$$

Expression (6) is one of the important indicators of the noise immunity reception when using energy efficiency, SCC and the volume of the alphabet used by the signal (Ibrahimov *et al.*, 2020).

To select an effective signal-code design for channel coding, it is necessary to build, based on the known characteristics of the channel, an encoder that sends input messages to the communication channel, which will be decoded by a noise-immune receiver with the maximum degree of system reliability. These are the conditions for the SCC and are found as follows (Islamov *et al.*, 2023):

$$S_{SCD}(b_i, k) = \frac{E_b}{T_b} (n - r) = V_b(b_i) \cdot E_b, \quad (7)$$

where T_b is the duration of the bit symbol and is equal to $T_b = (t_s \cdot m)/M$, E_b is the energy for the transmission of one bit in the communication channel; r is the number of check elements in the code combination.

To describe the new approach, it is necessary to analyze $SNR(P_S, E_b) = \Psi[C(h, m)]$ and $p_{BER}(h) = F[SNR(P_S, E_b)]$ dependence on the components included in (5), (6) and (7). Here $C(h, m)$ is the means the bandwidth per sample and has the unit of bits/sample. In this case, it is necessary to have relationships between h , R_k , m , $p_{BER}(h)$ and $G(k)$.

It should be noted that if the dependencies $p_{BER}(h) = F(E_b, R_k, M, N_0)$ are well studied (Ibrahimov *et al.*, 2020) and the number of types signals is limited, then enumeration of the characteristics of all known

codes is a very laborious task. Therefore, in this case, it is advisable to use the limiting dependencies between the correcting ability of the code and the relative number of redundant symbols, $R_k < 1$.

4. Research throughput per sample and message loss

Consider the most successful practical solutions. To do this, instead of the widely used boundaries obtained on the basis of combinatorial properties of code structures (Chettri *et al.*, 2020), we use boundary dependences for codes that are decoded using iteration methods (Ibrahimov *et al.*, 2020). Unfortunately, in the known literature there are no relations suitable for analysis (Ibrahimov *et al.*, 2022), so below we propose a formula that determines the information boundary of an ideal code.

Assume that, to a sequence independent equiprobable signal elements $p(b_i) = p(1) = p(0)$, received with some distortion under the influence of various noise sources, a certain number of the same elements are added to compensate for the lost message.

Let us assume that the quality of communication (Protopopov, 2013) and reception of each symbol is uniquely characterized by the bandwidth $C(h, m)$, then a necessary condition for compensating for distortions is the fulfillment of the inequality:

$$k[m - C(h, m)] \leq \delta_a \cdot C(h, m), \quad (8)$$

where k is the number information characters of the main message; δ_a is the number of characters added; $C(h, m)$ are the throughput per sample and has the dimension of bits/sample. Given the informative characteristics of the source $I(X, Y)$, the bandwidth of the communication channel is expressed as follows:

$$C(h, m) = \max_{p(x)} I(X, Y) / T = \max[V_b \cdot (1 - \frac{r}{n})]. \quad (9)$$

To study the quality of communication and reception, it is necessary to take into account the probability of distortion of discrete signals P_{sd} and the probability of losing a message P_{sl} . Taking into account the parameters of the error-correcting code, the probability of message distortion is determined as follows:

$$P_{sd} = \frac{P_{sl}}{P_r} \cdot R_k^{-1} = \frac{P_{sl}}{n} \cdot \frac{n - 2t}{1 - P_b}, \quad (10)$$

where t is the some integer, $t = 0, 5(d - 1)$, d is the minimum code distance for a given code and is equal to $d = \min_{x_i \neq x_j} \rho(x_i, x_j)$, P_b is the mean bit error and given the additive p_a upper bound is $E[P_b] = (d/n) \cdot p_a$, P_r is the probability receiving code combinations without the possibility of decoding it is expressed as $P_r = 1 - E[P_b]$.

Using the Bernstein's polynoma formula and based on the calculation method, the probability of receiving code messages can be estimated by the following expression, (Ibrahimov *et al.*, 2022):

$$P_b = \sum_{i=0}^t C_n^{n-i} \cdot (1 - P_{sd})^{n-i} \cdot P_{sd}^i, \quad (11)$$

where C_n^{n-i} is the binomial coefficient from n to $n - i$ and equals $C_n^i = \frac{n!}{i! \cdot (n - i)!}$, $n = k + r$, k , r are the number of information and verification code elements, respectively.

Expression (10) and (11) also characterizes the probability of an undetected error, taking into account the probability of signal distortion and the corrective ability of the error-correcting code. Figure 1 shows a graphical dependence of the probability distortion of discrete signals on the SNR at a given transmission rate.

Analysis of the graphic dependence shows that the increase $SNR(E_b, N_0)$ leads to a decrease in the probability of packet corruption $P_{un} \leq 10^{-2}$, meeting the requirements communication quality and the level

of noise immunity reception. Its noticeable change begins with the values $(E_b / N_0) \geq (4,5, \dots, 7,5) \text{ dB}$ at a given bit rate $V_{b1} = 100 \text{ Mbps}$, $V_{b2} = 125 \text{ Mbps}$.

Since the paths of receiving systems consist, as a rule, of sections K , the probability of loss on a composite system will be greater than the probability of losing a message on each of the sections separately:

$$P_{sl} \leq 1 - \prod_{j=1}^K (1 - p_j), \quad j = \overline{1, K}. \quad (12)$$

Let's assume that, $P_{sd} = 10^{-2}$, $G(m) = U(99, 75)$ and $R_k \rightarrow R_k^{\max} \rightarrow 0,76 \leq 3/4$, $p_j = 10^{-2}$, $V_b = 25 \text{ Mbps}$, to $P_{sl} \leq 10^{-8}, \dots, 10^{-9}$.

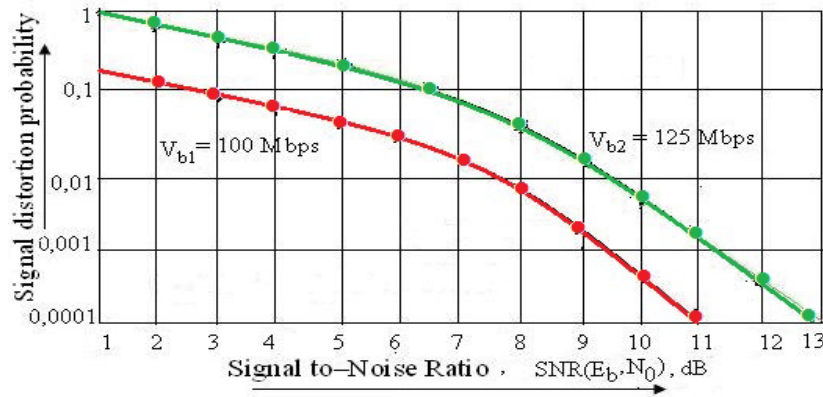


Figure 1. Graph of the dependence of the probability of packet distortion on the signal-to-noise ratio for a given communication channel speed

It can be seen from formulas (8), (9), (10) and (11) that minimizing the probability of message loss seriously reduces the throughput per one sample of the system. However, an increase in the probability of loss leads to an increase in retransmissions, as a result of which the load on the communication channels increases and the probability of failure when establishing a connection increases.

5. Condition analysis for signal-to-noise ratio indicators

In order to solve the problem, let's analyze the parameters included in the formula (8), (9), (10), (11) and (12). It follows from the last expression that the right side of inequality (8) corresponds to the value of the lost message and is equal to (Ibrahimov *et al.*, 2022 and Protopopov, 2013):

$$P_{sl} = [m - C(h, m)] \cdot (n - r). \quad (13)$$

Accordingly, the left part in (8) determines the amount of information needed to compensate for these losses:

$$I(\delta_a, m) = \delta_a \cdot C(h, m). \quad (14)$$

After some transformations and analysis in (8), (13) and (14), we obtain inequalities for estimating the boundary values of the throughput per one sample of the system:

$$C(h, m) \geq \frac{m}{k + \delta_a} \cdot (n - r). \quad (15)$$

From inequality (15) it follows that as the effect of interference increases, leading to a decrease in, it is necessary to increase $C(h, m)$, that is δ_a , to reduce the bit rate of the message.

The same condition takes place when choosing the code parameters $G(n, k, d)$, only instead of linking the code rate with the correcting ability, the number of additional elements will directly depend on the throughput. Taking into account relation (14), formula (4) can be rewritten in the following for

$$h_b^2 \geq [h^2 / C(h, m)]. \quad (16)$$

It follows from the last expression that the problem of optimization - minimization of the value is h_b reduced to minimizing the function (16) by a parameter for a given signal type.

6. Assessing the throughput of a communication channel

Based on the new approach and conditions for the indicators of the signal-to-noise ratio, the estimation throughput of the communication channel can be performed in two versions. These options are implemented depending on the digital signal processing method (Ibrahimov *et al.*, 2020).

1. The bandwidth value is determined using the informative characteristics of the source (Jin *et al.*, 2023) and is found as the maximum amount of information transmitted per unit of time. In this case, the calculation is made as follows:

$$C_{1.\max}(h, m) = \max_{p(U_s)} [H(U_n) - H_p(U_s, U_n)], \quad (17)$$

where $H_a(U_n)$ is the priori uncertainty, taking into account white Gaussian noise U_n (or the average amount of information in the absence of a signal); $H_p(U_s, U_n)$ are the posteriori uncertainty, taking into account white Gaussian noise U_n and the instantaneous value of the considered signal U_s (the average amount of information in the presence of a signal); $p(U_s)$ is the function describing the law of probability distribution of instantaneous values U_s .

It follows from (17) that the throughput is determined on the basis of the entropy approach and the calculation is made using the informative characteristics of the source.

2. In this case, depending on the signal processing method, the bandwidth value is determined as a function of the probability of an erroneous decision. In this case, the throughput is defined as

$$C_{2.\max}(h, m) = \log_2 m + p \log_2 \left(\frac{p}{m-1} \right) + (1-p) \log_2 (1-p), \quad (18)$$

where p is the likelihood of a wrong decision.

It can be seen from (18) that the throughput significantly depends on the probability of a symbol error in the communication channel and the size of the alphabet of the signal used.

7. Signal-code constructions according to the criterion of energy efficiency

It should be noted that, depending on the requirements for the characteristics of the communication channel under study and the limitations due to the features of the software and hardware implementation, the type of signal is selected. In the data (Deng *et al.*, 2019), the following types of signals in a channel with white Gaussian noise are considered:

- with a constant envelope;
- equidistant system of signals;
- signals with increased frequency efficiency.

Considering the above, consider the distribution of instantaneous noise values in two-dimensional space, which has the following form (Ibrahimov *et al.*, 2020 and Protopopov, 2013):

$$W_n(x, \sigma_n, y) = \frac{1}{(2\pi\sigma_n^2)^{0.5}} \exp\left(-\frac{x^2 + y^2}{2\sigma_n^2}\right), \quad (19)$$

where x and y are the coordinates of a point in a rectangular coordinate system; σ_n is the noise dispersion.

For signals that take discrete values M , the distribution law is determined by the following formula:

$$W_s(t, u) = \sum_{i=1}^M [\beta(1 - a_i) + \beta(u - b_i)], \quad i = 1, 2, \dots, M, \quad (20)$$

where M is the number of signal positions; a_i and b_i are the coordinates of the i -th signal position.

Based on formulas (19) and (20), we consider the joint distribution of signal and noise, which is defined as the sum of two independent random variables:

$$W_{sn}(u, \sigma_n) = \frac{1}{(2\pi\sigma_n^2)^{0.5}} \sum_{i=1}^M \exp\left[-\frac{(x-a_i)^2 + (y-b_i)^2}{2\sigma_n^2}\right], \quad i = 1, 2, \dots, M, \quad (21)$$

Expressions (21) describe the joint distribution of signal and noise in two-dimensional space. In addition, (21) in a particular case, describes the corresponding signals with a constant envelope, the coordinates a_i and b_i , equal $u \cos \varphi_i$ and $u \sin \varphi_i$ respectively, where u amplitude and φ_i signal phase. The phase of the signal in this case has a uniform distribution

$$w(\varphi) = \begin{cases} 1/2\pi, & -\pi \leq \varphi \leq \pi \\ 0, & |\varphi| > \pi \end{cases}. \quad (22)$$

The maximum value of the entropy of such a system of signals is achieved with a uniform distribution phase values $H_{\max}(\varphi) = \log w(\varphi)$, therefore, multiposition phase shift keying (M-PSK), is optimal under the given constraints (Ibrahimov *et al.*, 2020).

On the basis of the Communications Toolbox extension package and the standard Matlab environment, the calculation and simulation of communication systems with white Gaussian noise was carried out when calculating the communication channel bandwidth and indicators of signal-code design according to the criterion of energy efficiency.

Figure 2 shows the results of calculations of dependencies $\eta_{EE}(P_S, b_i) = F[SNR(P_S, E_b)]$ for M -PSK- n signals. Analysis of the graphic dependence shows that the increase $SNR(P_S, E_b)$ leads to increased energy efficiency $\eta_{EE}(P_S, b_i)$, meeting the requirements communication quality and the level of noise immunity of the processes of receiving and processing M-PSK signals. Its noticeable change begins with the values $SNR(P_S, E_b) \geq (8, \dots, 12)$ dB, at a given bit rate operation $V_b(b_i) = 125$ Mbps. In addition, the dependency graphs shown in Figure 2 clearly demonstrate the improvement in the level energy efficiency with an increase in $SNR(P_S, E_b)$ and modulation $n > 2$.

Comparative analysis shows that the minimum-optimal value of energy efficiency obtained here, tending to minus 1,5 dB at small values h , different in $\pi/2$ times the value obtained in (Jiaqi *et al.*, 2020) for the on-off signal M-PSK-2. This difference is due to the use of different signal processing methods (Ibrahimov *et al.*, 2020). In this case, it should be noted that formula (16) corresponds to a soft solution, while formula (17) corresponds to a hard solution with ideal coding.

An analysis was carried out for some variants communication systems that use multidimensional signal systems, which are considered in (Bianco *et al.*, 2017). However, in (Ruixin *et al.*, 2020) it is shown that the optimal value energy potential of the SCC is realized in the case of using equidistant signals.

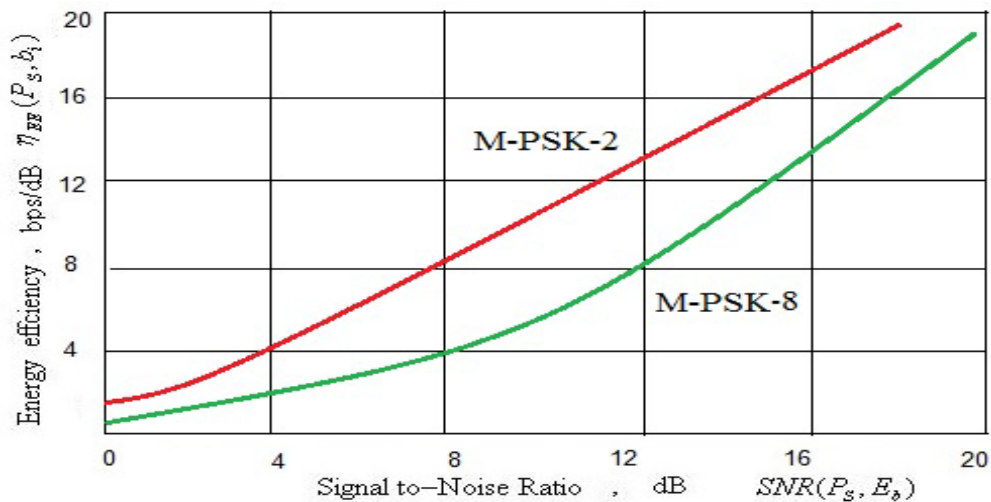


Figure 2. Dependence of energy efficiency on $SNR(P_S, E_b)$ when processing M-PSK signals

To analyze the probability of erroneous reception, Table 1 shows the results of calculating the ratio of the volume of the alphabet of the signal used and h_b .

Table 1. Estimated values m and h_b

m	3	4	5	6	7	8
h_b, dB	1,14	1,12	1,05	0,97	0,89	0,81

From Table 1 it follows that the energy efficiency dependence has a clear minimum, the position of which and the value depend on M .

8. Energy efficiency analysis based on signals of the form quadrature amplitude modulation

(Burkov, 2023) shows that quadrature amplitude modulation (QAM), is a type amplitude modulation of a signal, which is the sum of two carrier oscillations of the same frequency, but phase shifted relative to each other by $\pi/2$, each of which is modulated by amplitude with its modulating signal, at which both the phase and amplitude of the signal change, which allows you to increase the amount of information transmitted by one state - the signal count:

$$S(t) = I(t)\cos(2\pi f_0 t) + A(t)\sin(2\pi f_0 t),$$

where $I(t)$, $A(t)$ – respectively, modulating signals; f_0 – carrier frequency.

QAM signals are widely used in communication systems with minimal energy efficiency due to high efficiency, flexibility and $SNR(P_S, E_b)$.

In this case, when analyzing the properties QAM signals, classical constructions (Ibrahimov *et al.*, 2020) were considered, where telecommunication is widely used in modern digital systems. In this case, the bandwidth is calculated by formula (17), to construct the law of distribution sum of the signal and noise, the same method was used, where formulas (20) and (21) are shown.

In Figure 3 the dependence of the energy efficiency on $SNR(P_S, E_b)$ the processing signals of the QAM type is given.

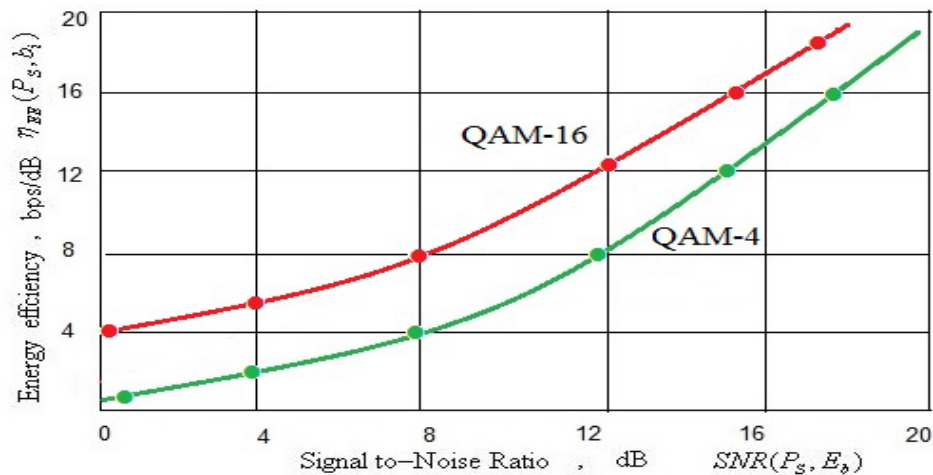


Figure 3. Dependence of the energy efficiency using signals of the QAM type on the Signal- to-Noise Rate

Analysis of the graphic dependence shows that with the improvement $SNR(P_S, E_b)$ increases the energy efficiency of the system $\eta_{EE}(P_S, b_i)$, meeting the requirements noise immunity of reception, when processing QAM-n signals ($n=4, 16$). In this case, a noticeable change begins with the values $SNR(P_S, E_b) \geq (4, \dots, 10) dB$ at a given bit rate operation $V_b(b_i) = 125 Mbps$. In addition, the dependency graphs shown in Figure 3 clearly demonstrate the improvement in the level of energy efficiency with an increase in $SNR(P_S, E_b)$ and modulation $n \geq 4$.

A comparative analysis according to the graphical dependence shows that the value of energy efficiency with QAM signals is noticeably inferior, by about $1,5 \div 2,5$ dB compared to systems with M-PSK signals.

9. Comparative analysis of the results of mathematical modeling

To assess the conformity of the obtained results with the characteristics of real receiver devices, mathematical modeling of the SCC was performed using the low-density parity check code (LDPC) code, which consists of the following important blocks (Clerckx *et al.*, 2020):

- pseudo-random on-off signal source, LDPC, which is a linear block error-correcting code suitable for error correction in large block sizes transmitted over very noisy communication channels;
- pseudo-random on-off signal source LDPC, which is a linear block error-correcting code suitable for error correction in large block sizes transmitted over very noisy communication channels;
- modem M-PSK-2, a communication channel simulator with constant parameters and additive white Gaussian noise, a carrier phase detection system and an LDPC code decoder. These codes are also known as Gallager codes (Islamov *et al.*, 2023 and Protopopov, 2013).

During the tests, the values of the signal-to-noise ratio at the demodulator input and the code rate were changed. The decoding result was estimated by the number of errors at the output of the decoder and the value of the syndrome. The decision on the correct decoding of this block was made in cases where there were no errors and the syndrome was equal to zero. The numerical results are shown in Table 2.

Table 2. Numerical values $SNR(P_S, E_b)$, dB and $\eta_{EE}(P_S, E_b)$, bps / dB

$SNR(P_S, E_b)$, dB	-2	0	2	4	6	8	10
$\eta_{EE}(P_S, E_b)$, bps / dB	0,12	0,86	2,45	4,0	6,0	8,0	10,0

Table 2 shows that the results mathematical modeling confirm the correctness of the recommendations obtained above regarding the relationship between the parameters of the signal-code design, as well as the possibility their practical implementation in telecommunication systems.

10. Conclusions and Recommendation

As a result of the study, a new approach was proposed to construct a method for calculating the indicators of noise immunity of reception under the influence interference sources, taking into account the characteristics of the energy efficiency of the communication system, the type of modulation keying, the coding coefficient and bit rates.

Based on the study of the calculation method, the conditions for the SCC, formulas for estimating the minimum required signal-to-noise ratio, the value of the bandwidth depending on the signal processing method are obtained. In addition, analytical expressions are obtained for calculating the probability erroneous signal reception.

A comparison various values of the maximum achievable energy efficiency telecommunication systems using the considered types of signals and ideal coding has been made. The results showed that the best results can be achieved using double phase keying, provided that a “soft” decision is applied.

The construction of a communication system with double phase shift keying, soft decision and LDPC code makes it possible to realize energy efficiency of the order of 0 dB. In this case, the mode corresponding to the optimal value of energy efficiency involves the use of a relatively low bit rate of message transmission.

A significant difference between the results mathematical modeling and the theoretical dependencies obtained in the study of a circuit with a rigid decision and the LDPC code requires further research and analysis.

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