International Conference on Problems of Logistics, Management and Operation in the East-West Transport Corridor (PLMO), October 27-29, 2021
http://conf.cyber.az

Research and Development of a Mathematical Model to Assess the Characteristics of the Noise Immunity of the Information Exchange System

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***Abstract*—A mathematical model is proposed for evaluating the noise immunity characteristics of a coherent modem reception in a message transmission system that functions under the influence of unintended interference sources. The developed mathematical model takes into account the demodulator synthesis algorithm, decoding methods, effective M-ary Phase Shift Keying modulations and Reed-Solomon codes in the modem. Integrated expressions are obtained that evaluate the noise immunity characteristics of a modem receive, taking into account the energy performance of the receiver.**

Keywords—communication networks, corporate networks, multiservice communication networks, communication channel, data transmission rate, coherent modem, telecommunication networks, mathematical model

I. INTRODUCTION

Currently, the development of corporate multiservice communication networks, provided that the volume of the transmitted useful and service flows of traffic packets is intensively growing, requires the creation of a noise-resistant message transmission system using a coherent modem that ensures high reliability of transmission. The most important task in the development of modern messaging systems in multiservice telecommunication networks is to constantly increase their noise immunity under the harmful effects of various sources of interference and linear distortions in the communication channel [1]. It is known [2, 3] that with an increase in the data transmission rate via an noise-tolerant coherent modem, intersymbol interference, which leads to a deterioration in the quality of communication, plays an increasingly important role in the quality of their reception. Based on the study [3, 4], it was found that the main obstacles to solving this problem are the lack of adequate mathematical models of digital signal processing in these systems, as well as effective numerical methods for analyzing and optimizing the reception noise immunity characteristics.

Thus, the urgency of the reception noise immunity problem lies in the need to increase the reliability of traffic packet message transmission and develop algorithms for calculating communication quality indicators, as well as optimize these message transmission systems.

II. PROBLEM STATEMENT

A messaging system using a coherent modem has the means to control the transmission and quality of communication in order to evaluate them in an interference environment. As a consequence, this helps the coherent modem adaptively take noise protection measures in real time to transmit documentary and voice traffic in order to minimize the effect of interference sources. As a result, the time delay of the transmitted packet streams of useful and service traffic is minimized, which increases the efficiency of multiservice telecommunication networks in the provision of multimedia services. Further, it should be noted that intentional interference is organized, and the sources of various interference are random [5]. Taking into account the components of the receive noise immunity vector $R_{ny}(t, k_{nm})$ at time t and taking into account the modem transmission coefficient k_{nm} when exposed, intentional interference is functionally described by the following dependence:

$$R_{ny}(t, k_{nm}) = W[P_{BER}, SNR(E_b, k_{nm}), V_b, N_{nn}(t)], \quad (1)$$

where, $N_{nn}(t)-$ is a function that takes into account intentional sources of interference at a time t; $SNR(E_b, N_0)-$ S signal-to-noise ratio (SNR, Signal Noise to Rate) taking into account the energy of the bit signal E_b and the spectral density of the interference power N_0, which characterizes the complex indicators of the communication quality when using a coherent modem. Expression (1) describes the essence of the new approach under consideration, taking into account complex indicators of communication quality in the messaging system, on the basis of which a mathematical model (MM) for estimating the noise immunity of a coherent modem reception is proposed [5].

Describes and implements the proposed mathematical model for evaluating the noise immunity characteristics of the reception of a coherent modem of a communication channel working with discrete binary signals. In this reception model, we assume that in the information signal $u(t,b_i)$, some parameter $b_i, 1 \le i \le n$ carries information, and therefore, is a random process. In the proposed scheme, it is required to efficiently distinguish this parameter from $S(t,b_i)$ in the time interval $[0,T_c]$:

$$S(t,b_i) = b_i \cdot u_0(t) + (1-b_i) \cdot u_1(t) + N_{nn}(t),\ 0 \le t \le T_c \quad (2)$$

Expression (2) allows us to analyze the implementation of binary signals in the time interval $[0,T_c]$ optimal [6], in the sense to reliably make decisions in favor of receiving $u_0(t)$ or $u_1(t)$. Thus, this scheme is an integral part of the task associated with noise-tolerant reception and processing of binary signals in a messaging system using a coherent modem.

III. PROBLEM SOLUTION

Now consider the description and construction of a mathematical model for evaluating the reception noise immunity. To solve this problem, an MM of reception noise immunity assessment has been proposed, which takes into account discrete signal reception methods, effective correction codes, and quadrature amplitude modulations in a message transmission system using a coherent modem. System-technical analysis showed [7, 8] that if the noise immunity depends on a number of random characteristics of the modem, then its quantitative measure may be the probability of disruption of the messaging systems. This probability is estimated by the average probability of erroneous reception of a discrete signal $E[P_{ош}]$ and is always a monotonic function of the signal-to-noise ratio at the receiver input:

$$E[P_{ош}] = F[SNR(E_b,k_{nm}),\ V_b], \quad (3)$$

where V_b − is the message bit rate.

The maximum value of the bandwidth of a coherent modem in a messaging system is determined as follows:

$$C_{\max}(E_b,V_b) = \Delta F_c \cdot \ell og_m[1 + SNR(E_b,k_{nm})], \quad (4)$$

where E_b- is the energy spent transmitting one bit of a discrete signal and is equal to

$$E_b = E_c / [R_k \cdot \ell og\, m],\ R_k = (k/n), \quad (5)$$

where R_k − is the speed of the Reed-Solomon code used and; ΔF_c − is the bandwidth occupied by the signal. From the expression (4) and (5) it can be seen that the main parameter that determines the maximum throughput and communication quality in the message transmission system are complex indicators of the signal-to-noise ratio and is found by the expression:

$$SNR(E_b,k_{nm}) = E_b \cdot V_b \cdot [\Delta F_c \cdot N_o]^{-1}, \quad (6)$$

Formula (6) characterizes the communication quality of a coherent modem and determines the ratio of signal power to interference power in a message transmission system. In addition, expression (6) is an energy indicator of the noise immunity of a reception and characterizes the use of a coherent modem in power. The condition in order to prevent a violation of the quality of communication in the message transmission system, taking into account the threshold signal / noise ratio q_{nop}, can be determined by the following inequality:

$$SNR(E_b,k_{nm}) \le q_{nop.} \le \min_{E_b}\{\alpha_{кр}[SNR(E_b,k_{nm})]\}, \quad (7)$$

where $q_{nop.}$ − is the threshold value of the signal-to-noise ratio and is the critical SIR with the help of the specified quality of the messaging system using a coherent modem:

$$q_{nop.} = \min_{E_b}\{\alpha_{кр}[SNR(E_b,k_{nm})]\}, \quad (8)$$

where α_{kp} − is a certain modem resource coefficient taking into account energy losses during processing of the received signal in a real transmission system compared to ideal reception conditions and is equal to $\alpha_{kp} \ge 1$.

To solve this problem, a MM has been developed for evaluating reception noise immunity in a messaging system using a coherent modem, a mathematical formulation that describes the following objective functions:

$$Q_P = W\{Arg \max_{E_b,k_{nm}} R_{ny}[SNR(E_b,k_{nm})]\}, \quad (9)$$

under the following restrictions

$$C_{\max}(E_b,V_b) \ge C_{\max}^{треб.}(E_b,V_b),\ P_{BER} \le P_{BER}^{треб.},$$
$$SNR(E_b,k_{nm}) \ge SNR(E_b,k_{nm}), \quad (10)$$

Expressions (9) and (10) determine the essence of the proposed new approach, with the help of which the MM of reception noise immunity estimates is constructed, taking into account indicators of communication quality, energy efficiency, modulation and coding methods. In addition, (9) and (10) are a simple analytical record of the noise immunity function of a message transmission system using a modem in assessing their quality of operation. Considering the above stated tasks, we consider the study and estimation of the probability of bit errors in the reception of discrete signals. Based on the model for evaluating the noise immunity of a reception and in accordance with the Neumann-Pearson criterion, the probability of receiving a discrete signal at the output of the DM and the indicators of the total power of intentional noise at the input of the receiver are taken as a characteristic of the noise immunity of the modem.

As a result of research [3], a formula was proposed for estimating the probability of receiving a discrete signal at the output of the demodulator:

$$P_n = 1 - \sum_{i=1}^{t} C_N^{N-i} \cdot (1 - P_{un})^{N-i} P_{un}^{i}, \quad (11)$$

where P_{un} – is the probability of distortion of the message packet traffic when it is transmitted through the transmission system;

C_N^{N-i} – is a binomial coefficient from N to $N-i$, t – the correcting ability of the Reed-Solomon code and taking into account the length of the code sequence N and the code speed is expressed as

$$t = 0{,}5N \cdot (1 - R_k) = 0{,}5(k + r)(1 - R_k) \quad (12)$$

where R_k – is the speed of the Reed-Solomon code and is equal to $R_k = (k/N) < 1$ Here the polynomial $GF(N,k,d) = GF(32,\ 24, 4)$ was used, where $d_{\min} \geq (2t + \sigma + 1)$ called the minimum code distance, $\sigma = \sigma_{ou}$ – is the number of errors in the packet.

The total interference power p_{mn} at the receiver input is determined by the bandwidth occupied by the signal ΔF_c, the interference ΔF_n and the spectral density of the average external interference power N_n as follows [6]:

$$p_{mn} = \eta_{cn}(F) \cdot N_n \cdot \Delta F_n, \quad (13)$$

where $\eta_{cn}(F)$ – is the coefficient of matching the interference and signal in frequency and is equal to

$$\eta_{cn}(F) = [(\Delta F_n) + (\Delta F_c)] / \Delta F_c, \quad (14)$$

Given (13) and (14), and also taking into account that

$$[E_b / N_{mn}] = [P_c / P_{mn}], \quad (15)$$

then it is possible to determine the probability of a bit error for a coherent modem:

$$P_{BER} = \frac{1}{2} erfc\left[\frac{k}{N} \cdot \frac{E_b}{N_{mn}} \cdot k_{nm}\right]^{0,5}, \text{ at M=2}, \quad (16)$$

where $erfc(x)$ – is an additional integral of the error function and is equal to: $erfc(x) = (2/\sqrt{\pi})\int_x^{\infty} \exp(-t^2)dt$, where k and N – are the characteristics of the Reed-Solomon error-correcting code (k – is the number of information bits in the packet).

The essence of using this method is that the graphical dependence is built according to the analytical formulas (14) using the BERTool environment.

As a result, the following numerical values were obtained: $SNR(E_b, k_{nm}) = [2,...,24]dB$, $V_b \leq (155,...,135)Mbs$, 2-PSK modulation scheme, $N = 32$, $d = 4$, $k = 24$, $R_k = 0{,}75$ reed-Solomon coding, and dependency P curves were plotted. As a result of the study, an approach to constructing an MM estimate of the noise immunity level of a coherent modem reception under the influence of unintended interference sources was proposed, taking into account the modem's energy performance, type of modulation manipulation, coding coefficient and bit rates. In the system of transmitting and receiving messages at the physical and channel level, a modulation scheme of the M-ary phase modulation M-PSK (M-ary Phase Shift Keying) type and Reed – Solomon code (RS) with polynomial $GF(N,k,d)$, N,k,d – RS code parameters are used. In the system, the reed-Solomon codes used are among the cyclic codes with direct correction of error packets, described by a polynomial

$$GF(p^m) = GF(N,k,d), \ d = N - k + 1 \quad (17)$$

System-technical analysis showed [3] that if the noise immunity depends on a number of random characteristics of the receiver, then its quantitative measure may be the probability of system malfunction. This probability is estimated by the average probability of erroneous reception of $E[P_{ou}]$:

$$E[P_{ou}] = F\{R_k, SNR[(E_b, k_E(V_b)],\ M, V_b\}, \quad (18)$$

where R_k – is the speed of the Reed-Solomon code;

$SNR(E_b, k_{nm})$ – signal-to-noise ratio taking into account the energy of the bit signal E_b and the energy transfer coefficient k and is equal to

$$k_E(V_b) = (E_b / E_{in}) \leq 1, \quad (19)$$

where E_{in} – is the energy of the bit signal at the input of the SF.

Considering the above, as well as (17) and (19), the mathematical formulation of the problem of the proposed MM assessment of noise immunity indicators in the telecommunication system is described by the following objective functions:

$$K_n(E) = W\{Arg \min_{h_c} E[P_{ou}(h_c^2)]\}, \quad (20)$$

under the following restrictions

$$C_{\max} \geq C_{\max.доп.},\ P_{BER} \leq P_{BER}, \quad \eta_{SЭ}(\Delta F_c) \geq \eta_{CЭ.доп.}(\Delta F_c), \quad (21)$$

where $C_{\max}$ – is the maximum bandwidth of telecommunication systems in the provision of multimedia services; Probability of bit errors (BER, Bit Error Rate);

$\eta_{SЭ}(\Delta F_c)$ – is the spectral efficiency of telecommunication systems with incoherent reception, which characterizes the efficiency of using the bandwidth ΔF_c occupied by a binary signal; $C_{\max.don.}$, $P_{BER.don.}$, $\eta_{CЭ.don.}(\Delta F_c)$ –, respectively, the permissible value of the maximum throughput, the probability of bit errors and the spectral efficiency of telecommunication systems. In the structure, the demodulator (DM), the matched filter (SF), the amplitude detector (HELL) and the threshold device (PU) act as the optimal receiver. In the receiver, the receiver solves the problems of coordinated filtering and controls the number of correctly received bit elements. In addition, the circuit consists of a low-pass filter (LPF) block that cuts off high-frequency components, an electronic key that closes at time $t = T_c$. Further, after comparing the threshold value $\Pi(u_{1,0})$ of the PU, a decision is made in favor of hypotheses H_0, and H_1. Using the likelihood criterion, the threshold level is determined as follows:

$$\Pi(u_{1,0}) \underset{H_0}{\overset{H_1}{\gtrless}} \Pi(S) = \frac{p(u_1)}{p(u_0)}, \tag{22}$$

In the case of equally probable signals, we have $\Pi_0 = 1$, and then the expressions for the relationship likelihood will take the form:

$$\ell n I_0(2S_1 / N_0) - \ell n I_0(2S_0 / N_0) \underset{H_0}{\overset{H_1}{\gtrless}} \frac{E_1 - E_0}{N_0}, \tag{23}$$

Expressions (22) and (23) determine the structure of the optimal binary signal receiver with an unknown initial phase for incoherent reception. The binary signal at the output of the PF and SS represents, in fact, the energy of the discrete signal: {see P (0, 1)}

$$E_{0,1} = \int_0^{T_c} u_{0,1}^2(t)\, dt = E \tag{24}$$

At time T_c, we give a comparison with the threshold $S(\Pi_0)$. Usually, in such cases, a threshold close to $(E/2) = S(\Pi_0)$. As a result of the study of MM, we consider the estimates of the average probability of an error in the reception of discrete signals. On the basis of the reception noise immunity estimation model with the likelihood criterion (23) and (24), a formula is proposed for estimating the probability of receiving a code packet at the output of a matched filter:

$$P_n(N, t_k) = 1 - \sum_{i=1}^{t_k} C_N^{N-i} \cdot (1 - P_{un})^{N-i} P_{un}^i, \tag{25}$$

where P_{un} – is the probability of distortion of the packet message when it is transmitted through the system; C_N^{N-i} – is a binomial coefficient from N to $N-i$;

t_k – is the correcting ability of the R-S code and taking into account the length of the code sequence N and the code rate is expressed as

$$t_k = 0{,}5N \cdot (1 - R_k) = 0{,}5(k + r)(1 - R_k), \tag{26}$$

where R_k – is the P-C code rate and is equal to $R_k = (k/N) < 1$. Here the polynomial $GF(N,k,d) = GF(127, 64, 7)$ was used, where $d_{\min} \geq (2t + \sigma + 1)$ – is called the minimum code distance, $\sigma = \sigma_{ош}$ – is the number of errors in the packet, k – is the number of information bits in the packet. Expressions (26) allows you to calculate the probability of packet loss on the recipient side, caused by various data distortions due to insufficient corrective ability of the code:

$$P_{nn}(t_k < t_{k.mp.}) = (k/N) \cdot P_{un} \cdot P_n(N, t_k), \tag{27}$$

When using the modulation scheme $M - PSK$, the total power of intentional interference at the input of the receiver is adopted as a characteristic of noise immunity. The total interference power P_{cmn} at the input of the DM is determined by the bandwidth occupied by the signal ΔF_c and the interference ΔF_n and the spectral density of the average external interference power N_{cn} as follows:

$$P_{cmn} = \eta_{cn}(F) \cdot N_{cn} \cdot \Delta F_n + P_{ш}, \tag{28}$$

where $\eta_{cn}(F)$ – is the coefficient of matching noise and signal in frequency and is equal to

$$\eta_{cn}(F) = [(\Delta F_n) + (\Delta F_c)] / \Delta F_c, \tag{29}$$

Taking into account (28) and (29), the signal-to-noise ratio will have a complex form:

$$SNR(P_c / P_{cmn}) = E[B_c, P_{cmn}, \eta_{cn}(F), N_{cn}], \tag{30}$$

where B_c – is the base of the complex receiving signal and taking into account the duration of the T_b bit is

$$B_c = T_b \cdot \Delta F_c = (1/V_b) \cdot \Delta F_c, \tag{31}$$

Given (27), ..., (31) and taking into account that

$$[E_b / N_{cmn}] = [P_c / P_{cmn}],$$

we determine the probability of a bit error for the system $M - PSK$ with $M = 2$ from the relation:

$$P_{BER} = \frac{1}{2} erfc\left(\frac{h_c}{\sqrt{2}}\right) = \frac{1}{2} erfc\left[R_k \cdot \frac{E_{in}}{N_{cmn}} \cdot k_E(V_b)\right], \tag{32}$$

where $erfc(x) = 1 - erf(x)$ – is the residual error function and is equal to

$$erfc(x) = 2(\pi)^{-0,5}\int_x^{\infty}\exp(-\delta^2)\,d\delta \cdot$$

Using a graphical environment, BERTool calculates and builds BER graphs for a given range of $SNR(E_b, N_0)$. Based on the model, summarized in the form of noise immunity characteristics P_{BER}, taking into account the modulation scheme M-PSK and code R-S will take the following form:

$$P_{BER} = (\frac{2}{\ell og_2 M})\cdot Q\left[2\ell og_2\frac{k_E(V_b)}{(k+r)}\cdot k\cdot\frac{E_{in}}{N_{cmn}}\cdot\sin^2(\pi/M)\right]^{0,5}, \quad (33)$$

where $Q(x)-$ is the Gaussian error integral and is equal to $Q(x) = 0,5[1 - erf(x/\sqrt{2})]$.

For the modulation scheme $M-PSK$ and the R-S code with correction of error packets, the average error probability can be expressed as follows:

$$E[P_{ou}] = \frac{1}{N}\sum_{\sigma_{ou}=t+1}^{N}\sigma_{ou}\cdot C_N^{\sigma_{ou}}\cdot(P_{BER})^{\sigma_{ou}}\cdot(1-P_{BER})^{N-\sigma_{ou}}, \quad (34)$$

Expressions (33) and (34) determine the noise immunity for incoherent reception, taking into account the indicators P_{BER}, the parameters of the P-C code, and the modulation $M-PSK$ under the influence of interference. Thus, the analysis and development of a model and methods for calculating the noise immunity indicators of transmission system paths, processing and receiving traffic packet messages based on the development of the architectural concepts of NGN and FN requires the study of individual and complex indicators of the reliability of the system in corporate communication networks.

CONCLUSION

The proposed MM takes into account indicators of communication quality, spectral efficiency, a modulation and coding scheme when providing multimedia services to users. Based on the study, it was found that the use of an M-PSK type modulation scheme and a Reed - Solomon code optimizes the process of transmitting packet messages, minimizes the bit error rate for a given signal / noise ratio, and restores lost packets without additional re-requests using lengths of code and information sequences. Based on the study of the model, the results obtained allow us to achieve improved accuracy in evaluating the noise immunity characteristics of the reception and improve the quality of the receiver with incoherent reception.

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