CONFERENCES AND SYMPOSIA

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ON 80th ANNIVERSARY OF VICTORY IN GREAT PATRIOTIC WAR

Academician V.A. Kotelnikov's works (1932–1946) — the basis of research fields in encryption, cryptography, and potential noise immunity *

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Contents

Abstract. We consider the scientific and applied research work of Academician V.A. Kotelnikov in the pre-war and wartime periods (1932–1946) focused on the development and creation of encrypted telephone communication systems, the creation of cryptographically secure equipment based on research in the sampling of speech signals, and the development of a theory of potential noise immunity when transmitting information through noisy channels.

Keywords: encryption, cryptography, noise immunity

Vladimir Aleksandrovich Kotelnikov

1. Introduction

The contribution of a generation of Soviet scientists and engineers to the Victory over fascism in the Great Patriotic War cannot be overestimated. Academician of the USSR Academy of Sciences Vladimir Aleksandrovich Kotelnikov, an outstanding scientist, organizer, teacher, and public figure, occupies a worthy place in this regard. His scientific works enriched world science and became a classic foundation for the creation and development of new scientific fields [1].

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V.A. Kotelnikov is considered one of the founders of the theory and practical applications of statistical radio engineering, radio physics, cryptography, computer science, radar astronomy, and large-scale space exploration [1–3]. The results obtained in the creation and development of these areas are still relevant and in demand for solving modern problems of digital signal processing, organizing reliable and high-speed information transmission over noisy radio lines using adaptive transmission/reception methods, and developing domestic cryptography.

Among the wide range of his scientific and applied achievements, a special place is occupied by the areas of development and creation of encrypted communication systems [3], the creation of cryptographically secure equipment based on research on the sampling of speech signals [4, 5], and the creation of a theory of potential noise immunity in the transmission of information over noisy channels [6], completed in the pre-war and wartime period (1932–1946).

Worth noting are the parallel developments of foreign scientists in similar areas, particularly the research of the American mathematician K. Shannon (1916–2001) [7]. K. Shannon studied the issues of the theoretical security of cryptographic ciphers and the creation of a theory of the capacity of noisy transmission channels. Based on the results of his research, a classified report, "Mathematical Theory of Cryptography," was presented in 1946. In 1948, his book, *Mathematical Theory of Communication* [8], was published, which presented the main results of V.A. Kotelnikov, rediscovered with a significant time delay, in terms of representing analog signals in discrete form and optimal signal processing during transmission over noisy channels.

This article reviews the scientific and applied studies of V.A. Kotelnikov in the above areas, which have formed the foundations for various fields of modern science.

2. Key milestones in creative biography of V.A. Kotelnikov

V.A. Kotelnikov was born in 1908 in Kazan. His grandfather, Petr Ivanovich Kotelnikov (1809–1879), was a mathematician and professor at Kazan University. His father, Aleksandr Petrovich Kotelnikov (1865–1944), was a mathematician, a specialist in mechanics, and also a professor at Kazan University [3].

V.A. Kotelnikov's creative career began in 1927. After completing his first year at the Bauman Moscow State Technical University, he worked at the Nizhny Novgorod Radio Laboratory. This was a time when radio engineering was in its infancy and under development.

In 1930, he graduated from the Moscow Power Engineering Institute (MPEI), received a diploma in electrical engineering (specializing in radio engineering), and was assigned to the Research Institute of Communications of the Red Army. Then, he studied in graduate school at MPEI (1931–1933), while simultaneously working at the Research Institute of Communications of the People's Commissariat of Communications. During this period, he analyzed the problem of 'flat' signal fading in the course of multi-path propagation along shortwave (HF) radio lines.

In 1932, he completed his fundamental work, "On the transmission capacity of the 'ether' and wire in electrical communications" (Kotelnikov's Sampling Theorem).

In 1938, V.A. Kotelnikov was awarded the degree of Candidate of Technical Sciences without defending his dissertation. In 1946, he defended his doctoral dissertation on potential noise immunity in signal transmission over noisy channels, which gave rise to a new scientific field: statistical radio engineering.

In 1953, he was elected a full member of the USSR Academy of Sciences, bypassing the Corresponding Member degree.

From 1954 to 1987, V.A. Kotelnikov served as Director of the Institute of Radio Engineering and Electronics of the USSR Academy of Sciences, remaining its Honorary Director until his death.

Below is a more detailed overview of V.A. Kotelnikov's scientific works, which represent the basis for the theoretical development and technical implementation of information systems for various purposes, such as modern terrestrial and satellite-based mobile communication systems. The core components of these information systems include speech encryption, cryptographic transformation of the information flow, and signal reception with noise-induced distortions taken into account, using optimal processing to ensure potential noise immunity.

3. Analog speech encryption

The original problem of analog speech encryption was solved during the development and technical implementation of the Moscow–Khabarovsk HF radio link (1936–1941), which involves multipath signal propagation due to reflection from the near-Earth ionosphere and Earth's surface. Figure 1 shows an example of dual-path signal propagation from the output of a transmitting device (TD) along an HF radio link.

A realization of $\hat{s}(t)$ is input into the receiver device (RD) in the form of a sum of l signal copies

$$s(A_i, t_i, t) = A_i \cos\big(2\pi f(t + t_i) + \varphi(t)\big)$$

with different amplitudes A_i and time delays t_i (possibly from $l = 2\ldots6$ propagation paths)

$$\hat{s}(t) = \sum_{i=1}^{l} s(A_i, t_i, t)\,, \qquad (1)$$

where f, $\varphi(t)$ are the carrier frequency and phase of the transmitted signals.

Due to the destructive addition of speech signals $s(A_i, t_i, t)$ with a frequency band in the range of (0.3...3 kHz), 'flat' (frequency–nonselective) fading of the signal amplitudes $\hat{s}(t)$ is observed, reducing the reliability of telephone conversations on these channels [9, 10].

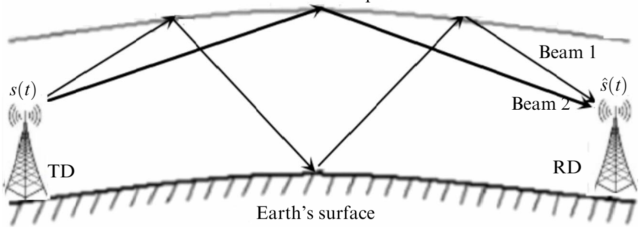

Figure 1. Diagram of two-beam (beam 1, beam 2) signal propagation along HF ionospheric radio line (TD — transmitting device, RD — receiving device).

The analysis of transmission channels of this type performed by V.A. Kotelnikov was noted above. To compensate for the distorting influence of a multipath channel, a method was developed based on the diversity of p receiving antennas (RD) for the temporal decorrelation of signals $\hat{s}_p(t)$ and their combination when forming the processed realization upon reception, e.g., selecting a signal from the set of $\hat{s}_p(t)$ with the maximum amplitude [9–13].

Simultaneously, during the development and creation of this information system, the problem of encryption of telephone speech for protection from unauthorized eavesdropping was solved, which for V.A. Kotelnikov was a new applied area. Encryption of analog voice information was achieved using special devices called scramblers. The approach known at the time to creating devices of this type was based on the inversion of the frequency spectrum $S(f)$ of the speech signal with additional modulation of the carrier at a high frequency f_t [3]. This approach and the corresponding equipment could not provide the required protection of the content of intercepted communications.

Under the hard wartime conditions, a fundamentally new frequency–time (mosaic)-type telephone scrambler (the Sobol P device) was developed and tested in V.A. Kotelnikov's laboratory. Figure 2 shows its functional diagram. The Sobol P encryption device performs frequency-inversion transformation of the speech signal $s(t)$ (mutual displacement of the low and high frequencies of the signal relative to the central frequency f_0), representing the transformed signal in time segments no less than 100 ms long, randomly permuting them, and additionally modulating the resulting signal with a high frequency f_t in the range of 10.6–38.4 kHz (HF modulation). The receiving device performs a sequence of inverse operations.

In 1942, prototypes of the Sobol P encryption device were put into service. For the technical means of that time, decrypting a two-dimensional (frequency-time) information flow was an extremely difficult task. A report was submitted to the German high command on the impossibility of eavesdropping and deciphering encrypted voice telephone messages [3].

The Sobol P encryption equipment was used for communication between the Supreme Command Headquarters and the USSR delegation during the signing of Germany's capitulation in May 1945 [3]. The Sobol P analog encryption devices were used for a long time on the Moscow–Helsinki, Moscow–Paris, and Moscow–Vienna lines during negotiations to conclude peace treaties after the end of World War II. Evidence of the high quality of this equipment is the fact that, due to the impossibility of eavesdropping on telephone conversations, a method of destroying them by creating interference in the transmission channels was used [3].

For their work on the creation and improvement of the Sobol P equipment, the team of authors was awarded the Stalin Prize of the first degree (1943); in 1946, V.A. Kotelnikov was awarded a second Stalin Prize of the first degree [3].

4. Discrete speech encryption

With the development of signal processing technology (speech spectrum analyzers, etc.), further improvements in the efficiency of speech encryption were required. To advance this approach, V.A. Kotelnikov formulated a fundamentally new approach, discrete speech encryption.

The essence of the proposed approach to discrete speech encryption is the use of telegraph-type transmission, including [2, 3]:

— analog-to-digital conversion of the speech signal, i.e., sampling of the analog speech signal using a sampling theorem, quantization, and encoding of discrete samples;

— cryptographic encoding of digital samples of the speech signal.

Figure 3 shows a block diagram of the discrete speech encryption method proposed by V.A. Kotelnikov (1941).

The n-bit analog-to-digital conversion (ADC) block in the transmitting device performs the sampling of speech signals in accordance with the Kotelnikov sampling theorem, quantization of discrete samples into 2^n levels, and their encoding [13]. Each of the n binary digits of the ADC is summed in the $GF(2)$ field with binary symbols of the cryptographic sequence [14, 15], with the resulting binary symbols fed to the modulator of signals $\hat{s}(t)$ transmitted over the channel. In the receiving device, computational operations inverse to the operations of the transmitting device are performed, and the output of the digital-to-analog converter (DAC) $\hat{s}(t)$ is the output of a discrete speech encryption system [13].

Analysis of the Kotelnikov sampling theorem. The ADC block implements the digital representation of analog signals $s(t)$ with a limited frequency band W by the Kotelnikov approximation series $\hat{s}(t)$ with time samples $s(i\Delta t)$ with a sampling frequency $f_s \geqslant 2W$ (sampling period $\Delta t \leqslant 1/2W$) [10, 13],

$$\hat{s}(t) = \sum_{i=-\infty}^{\infty} s(i\Delta t)\,\mathrm{sinc}\left(\frac{\pi(t - i\Delta t)}{\Delta t}\right), \tag{2}$$

where $\mathrm{sinc}\,(x) = \sin\,(x)/x$.

The literature notes the following features of the approximation series (2):

— slow convergence of the series [16];

— representation of signals $\hat{s}(t)$, by summing discrete samples with weighting coefficients, included in the class of ill-conditioned problems [17];

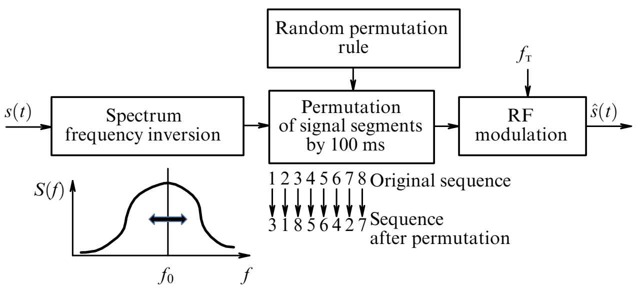

Figure 2. Functional diagram of Sobol P analog encryption system.

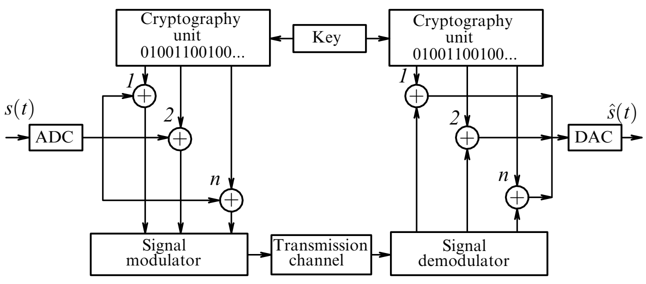

Figure 3. Block diagram for discrete encryption of speech signal.

— approximate calculation of signals $\hat{s}(t)$ due to the limited duration of signals $s(t)$ [16];

— convergence of the approximation series in the Euclidean metric L_2 [18, 19].

Despite these features, the Kotelnikov series is the basis of digital signal processing and one of the main foundations of digital technology, intensively developed in recent decades [13, 20].

Vocoder theory. The required information flow rate from the output of a discrete encoder, implemented in accordance with the block diagram in Fig. 3, is quite high, which is a limiting condition for its technical implementation. A significant reduction in the required flow rate of a discrete encoder (by an order of magnitude or more) with practically equivalent transmission quality is achieved by using a vocoder — a device for compressing the frequency band of a speech signal [20]. The research and development of the vocoder were initiated by V.A. Kotelnikov in 1941, but, with the beginning of the war, work on improving the vocoder was suspended and resumed only in 1948 [3]. The initial information rate of the discrete encoder, designed with the participation of V.A. Kotelnikov, was 64 kbit per second; with the inclusion of the vocoder, the required information rate decreased to 4.8 kbit per second [3].

The basis of modern vocoder theory is the CELP (Code Exited Linear Prediction) model based on the autoregressive relation [21–23]

$$\hat{s}(n) = \sum_{i=1}^{N} a_i s(n-i) + qw(n)\,. \tag{3}$$

The value of a discrete sample $\hat{s}(n)$ of a speech signal is calculated using the previous N samples $s(n-i)$ with weighting coefficients a_i, and the current value of the fundamental tone $w(n)$ with amplitude q (recommended value $N = 10$, sampling frequency of 10 kHz [21]).

A feature of the vocal apparatus is the practical stationarity of the statistical characteristics of the random process of the speech signal $s(n)$ for time intervals up to 10–40 ms. Using this property, computational procedures for estimating the weighting coefficients $\mathbf{a}$ and the amplitude of the fundamental tone q have been developed [22, 23].

Only quantized and coded values of the vector of weighting coefficients $\mathbf{a}$ and the characteristics of the fundamental tone are transmitted to the input of the receiving device, which makes it possible to significantly reduce the required frequency band of the transmission channel W' in relation to the original frequency band W.

Criteria for cryptographic encryption strength. At the same time, the problem of cryptographic coding was considered by the American mathematician K. Shannon. His research on this topic was presented in the report "A Mathematical Theory of Cryptography" (1946) and published in an article (1948) [8].

Based on the results of research carried out by V.A. Kotelnikov and K. Shannon, the following criteria for the cryptographic strength of discrete encryption have been defined:

(a) the cryptographic block key is known only to legitimate users;

(b) the key length is not less than the message length;

(c) the key is generated randomly;

(d) the key is used in one-time pad mode.

When these criteria are met, the transmitted and encrypted messages are statistically independent. The main problem in implementing cryptographic systems with keys in one-time pad mode is meeting criterion (a). One promising approach to solving this problem is based on quantum computing methods, which are currently being intensively researched and developed [24, 25].

For the efficient operation of information systems for various purposes, including communication systems with analog and discrete speech encryption, decisions are required regarding the selection of signals $s(t)$ and their processing upon reception, taking into account the distorting influence of physical transmission channels [26]. Below are the results of V.A. Kotelnikov's research into these areas.

5. Theory of potential noise immunity

By the fall of 1946, V.A. Kotelnikov had prepared a dissertation for the degree of Doctor of Science titled "Theory of potential noise immunity." In 1956, the text of the dissertation was published as a book [6]. This work gave rise to the scientific field of statistical radio engineering, which includes the theory of testing statistical hypotheses regarding the reception and discrimination of digital signals with various types of manipulation (phase, frequency) and the theory of estimating signal parameters (frequency, initial phase, amplitude, detection time, etc.) [9, 11, 12, 16, 19, 26, 27]. The approach used to solve the complex of problems under consideration, based on the application of methods of probability theory and mathematical statistics, was completely new for researchers and engineers of that time; there is a single reference in the published book [6].

The field of statistical radio engineering is related to the theory of discrete message transmission (the general block diagram is shown in Fig. 3) regarding the use and analysis of digital signals $s(t)$ and the determination of algorithms for processing realizations from the output of the transmission channel, leading to the optimal choice of solutions taking into account statistical quality criteria [26].

The general formulation of the problem of potential noise immunity is as follows: for the realization $x(t)$ from the output of the transmission channel, given by the formula

$$x(t) = \mu s(\boldsymbol{\lambda}, t) + n(t)\,, \quad t \in [0, T]\,, \tag{4}$$

it is necessary to determine the mapping rule $x(t) \to s(\boldsymbol{\lambda}_0, t)$ that minimizes the distorting effect of the additive noise $n(t)$ [6, 26]. Here, μ is the channel transmission coefficient, assumed to be known; $\boldsymbol{\lambda}$ is the information vector. For discrete message transmission systems using an ensemble of digital signals $s(\lambda_i, t)$ with a volume M, the values of the elements of the information vector are discrete, $i = 1, 2, \ldots, M$. For signals with continuous information parameters, the corresponding elements of the vector $\boldsymbol{\lambda}$ are part of the subsets L of the Euclidean space [6, 26].

Reception of signals in discrete message transmission systems represents a test of statistical hypotheses [19, 26]. In this case, under the condition of equal probability of transmitting signals $s(\lambda_i, t)$, the optimal reception rule implementing the statistical criterion of minimum Bayesian risk is formulated as follows: a signal $s(\lambda_m, t)$ is present if the following condition [26] is satisfied for all $j \neq m$:

$$\int_0^T V_{mj}(t) x(t)\,\mathrm{d}t \geqslant \frac{1}{2}\int_0^T V_{mj}(t)\big[s(\lambda_m, t) + s(\lambda_j, t)\big]\,\mathrm{d}t\,, \tag{5}$$

where $V_{mj}(t)$ is the solution of the inhomogeneous linear integral equation

$$\int_0^T B(t-u)\,V_{mj}(u)\,\mathrm{d}u = s(\lambda_m, t) - s(\lambda_j, t)\,, \quad t \in [0, T]\,, \quad (6)$$

where $B(t)$ is the correlation function of additive channel noise.

Condition (5) is equivalent to calculating the posterior probabilities $\Pr\left(s(\lambda_i|x(t))\right)$, $i = 1, 2, \ldots, M$ and choosing the maximum value for λ_m.

The dissertation considers the model transmission channel with additive white Gaussian noise (AWGN) $n(t)$ with a one-sided spectral density N_0. This model is not free of shortcomings; in particular, the noise correlation function is represented by a generalized delta function $B(t) = (N_0/2)\delta(t)$ [26], i.e., the noise power is unlimited. At the same time, the proposed model has been accepted by the scientific community as a basic one and is intensively used in the analysis of information systems for various purposes (communication systems, navigation, radar, etc.) [16, 19, 26, 27].

For the AWGN channel model, the solution to the integral equation (6) has the form $V_{mj}(t) = (2/N_0)[s(\lambda_m, t) - s(\lambda_j, t)]$. In this case, condition (5) is reduced to the following form [6, 26]:

$$\int_0^T \left[\mu s(\lambda_j, t) - x(t)\right]^2 \mathrm{d}t \geqslant \int_0^T \left[\mu s(\lambda_m, t) - x(t)\right]^2 \mathrm{d}t\,. \quad (7)$$

Figure 4 shows the block diagram of algorithm (7) for optimal reception (discrimination) of equally probable discrete signals $s(\lambda_j, t)$, $j = 1, 2, \ldots, M$ for an AWGN channel. A decision is made regarding the transmitted signal with parameter λ_m, under the condition of the minimum Euclidean distance between $\mu s(\lambda_m, t)$ and $x(t)$.

V.A. Kotelnikov considered a generalization of the model of stationary additive Gaussian noise with a frequency-dependent spectral power density $N(f)$ ('colored' noise) and with the corresponding correlation function $B(t)$ [6]. In this case, it is proposed to use the optimal reception algorithm (7) with the inclusion of a whitening (inverse) filter to implement $x(t)$ at the input of the decision device. The development of this approach is a computational algorithm for processing the input realization $x(t)$, specified by relations (5) based on the solution of the inhomogeneous linear integral equation (6).

Consideration of 'colored' noise in the dissertation work formed the basis of an independent research direction in the development of models for a number of more complex transmission channels with frequency-selective fading properties and with dispersion properties (ionospheric, atmospheric, sonar transmission channels) [10, 16, 19, 26, 28].

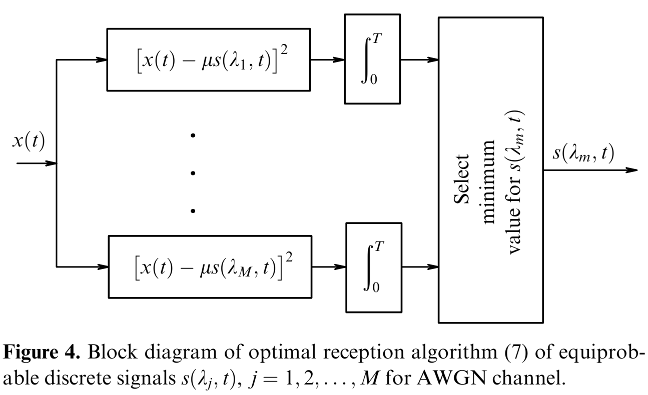

Figure 4. Block diagram of optimal reception algorithm (7) of equiprobable discrete signals $s(\lambda_j, t)$, $j = 1, 2, \ldots, M$ for AWGN channel.

Estimates of the continuous parameters of the m-dimensional vector $\boldsymbol{\lambda}$ of signals $s(\boldsymbol{\lambda}, t)$ using the maximum likelihood criterion are given as solutions to the system of equations [26]

$$\int_0^T \frac{\partial}{\partial \lambda_i} V(\boldsymbol{\lambda}, t)\left[x(t) - s(\boldsymbol{\lambda}, t)\right] \mathrm{d}t = 0\,, \quad i = 1, \ldots, m\,, \quad (8)$$

where $V(\boldsymbol{\lambda}, t)$ is the solution of the inhomogeneous linear integral equation

$$\int_0^T B(t, u)\,V(\boldsymbol{\lambda}, u)\,\mathrm{d}u = s(\boldsymbol{\lambda}, t)\,, \quad t \in [0, T]\,. \quad (9)$$

For the AWGN channel model considered in V.A. Kotelnikov's dissertation, the solution is $V(\boldsymbol{\lambda}, t) = (2/N_0)s(\boldsymbol{\lambda}, t)$, and system of equations (8) is simplified:

$$\int_0^T \frac{\partial}{\partial \lambda_i} s(\boldsymbol{\lambda}, t)\left[x(t) - s(\boldsymbol{\lambda}, t)\right] \mathrm{d}t = 0\,, \quad i = 1, \ldots, m\,. \quad (10)$$

In V.A. Kotelnikov's dissertation, an analysis of the transmission of discrete messages over a channel with additive white Gaussian noise was performed using a number of signals. In particular, for ensembles of orthogonal signals with volume M, an expression was proven for the probability of erroneous reception P_{err} when using algorithm (7) [6],

$$P_{\mathrm{err}} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{x^2}{2}\right) \times \left[1 - F\left(x + \sqrt{2E_{\mathrm{b}} \log_2 M/N_0}\right)\right]^{M-1} \mathrm{d}x\,, \quad (11)$$

where

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left(-\frac{y^2}{2}\right) \mathrm{d}y\,,$$

and E_{b} is the signal energy per bit.

Figure 5 shows the dependences of the error probability P_{err} on the ratio E_{b}/N_0, calculated using relation (11) for ensembles of orthogonal signals with volumes $M = 8$ (curve

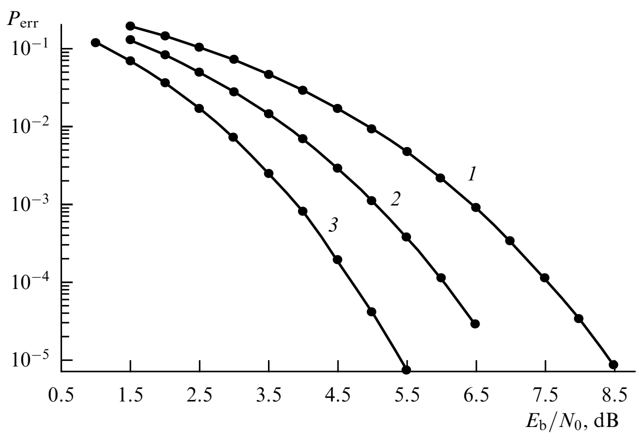

Figure 5. Dependences of error probability P_{err} on ratio E_{b}/N_0 for ensembles of orthogonal signals with volumes $M = 8$ (curve *1*), $M = 32$ (curve *2*), $M = 256$ (curve *3*).

1), $M = 32$ (curve *2*), and $M = 256$ (curve *3*). It is evident that the probability P_{err} is a monotonically decreasing function of M at a constant E_{b}/N_0 value.

A remarkable property of the signals under consideration with increasing volume M is the threshold effect relative to P_{err} [27],

$$\underset{M\to\infty}{P_{\mathrm{err}}} = \begin{cases} 1\,, & \dfrac{E_{\mathrm{b}}}{N_0} < \ln 2\,, \\ 0\,, & \dfrac{E_{\mathrm{b}}}{N_0} > \ln 2\,, \end{cases} \tag{12}$$

i.e., the use of ensembles of orthogonal signals ensures error-free transmission under the condition $M \to \infty$ and the limitation $E_{\mathrm{b}}/N_0 > \ln 2$, while an unlimited channel frequency band is required [27].

The limit relation (12) is of particular importance for information theory, which determines the Shannon capacity C and the possibility of organizing error-free transmission with an information rate reaching C [7, 8],

$$C = W \log_2 \left(1 + \frac{S}{N_0 W}\right) [\text{bit s}^{-1}]\,, \tag{13}$$

S being the signal power and W being the channel frequency band.

It should be noted that Shannon's paper provides no constructive recommendations on the signal choice, the use of which ensures the achievement of probabilistic-energy characteristics determined by the channel capacity C.

In proving the relation regarding the capacity C (13), K. Shannon (1948) rediscovered the sampling theorem (16 years later than V.A. Kotelnikov did) and the basic principles of V.A. Kotelnikov's theory of potential noise immunity.

As the frequency band W increases, expression (13) takes the form

$$\underset{W\to\infty}{C} = \frac{E_{\mathrm{b}}}{N_0 \ln 2}\,; \tag{14}$$

it determines the minimum value of signal-to-noise ratio $E_{\mathrm{b}}/N_0 > \ln 2$, at which error-free transmission of information is theoretically possible without restrictions on the signals used with frequency band W.

The threshold effects with respect to the signal-to-noise parameter defined by relations (12) and (14) are identical. At the same time, in V.A. Kotelnikov's work, a specific class of signals is proposed that theoretically make error-free transmission of information possible over channels with a marginal signal-to-noise ratio. Thus, in developing the theory of potential noise immunity, V.A. Kotelnikov took the initial steps toward creating the information theory, subsequently developed by K. Shannon [8, 9]. The currently developed approach to error-correcting coding, used in the development of discrete message transmission systems with characteristics close to the throughput capacity of transmission channels, is based on applying methods from the theory of potential noise immunity [9, 10, 16, 19].

6. Conclusion

V.A.Kotelnikov's scientific and applied work on analog and discrete speech encryption, the development of domestic cryptography, and the creation of the potential noise immunity theory made a significant contribution to the Victory, form the basis of many scientific fields, and are in demand by the modern scientific community.

For his scientific achievements, V.A. Kotelnikov received 31 state awards, including two State Prizes (Stalin Prizes of the 1st degree). It is remarkable that minor planet No. 2726 is named after him, and the name "Vladimir Kotelnikov" has been assigned to a degaussing vessel of the Russian Navy.

The Eduard Rein International Science Foundation (Germany) awarded V.A. Kotelnikov in 1999 for the first proof of the sampling theorem (known in English-language scientific literature as the Whittaker–Kotelnikov–Shannon theorem) in the context of communications technologies. This demonstrates respect and international recognition of Vladimir Aleksandrovich's contribution to science.

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