**УДК 621.396.969.1**

## FEATURES OF CODE REDUNDANCY FORMATION IN INFORMATION TRANSMISSION CHANNELS

**DOI 10 36994 / 2788- 5518- 2022-02-04-01**

***Juliy Boiko,*** *Dr.habil., Prof. Khmelnytskyi National University, Khmelnytskyi, Ukraine. boiko_julius@ ukr.net*

***Anatoly Semenko,*** *Dr.habil.,Prof. Open University of Human Development "Ukraine" , Kyiv, Ukraine.setel@ukr.net*

***Ilya Pyatin,*** *Ph.D., Ass. Prof. Khmelnytskyi Polytechnic Professional College by Lviv Polytechnic National University, Khmelnytskyi, Ukraine. ilkhmel@ukr.net*

***Abstract:*** *The article presents studies of procedures for generating error-correcting codes for various telecommunication technologies. The article is focused on evaluating and identifying mechanisms for adding redundancy to signal-code structures in secure information channels. An important focus of this article is the proposed comparison of the formats of error-correcting codes, the structure of code structures, generator polynomials, code words, and generator matrices. The researches including the analysis of the specifics of inclusion of redundancy in the code structure are given, the general mathematical models of constructive synthesis of error-correcting codes are described. The result is achieved by analyzing convolutional codes, Reed-Solomon codes, turbo codes (TC) and polar codes, which are currently widely used for 5G mobile technology. The verification of the effectiveness of signal-code structures of noise-correcting codes was carried out by the method of mathematical modelling for various telecommunication channels by determining the energy gain of coding (EGC). The performance of the codes was evaluated by establishing a comparison of the coding energy gain for the basic constructions of the codes taken into consideration. It is shown that error-correcting coding is associated with the addition of redundancy. This introduction of redundancy leads to the possibility of eliminating errors in decoding and the resulting error probability at the output of the decoder is reduced compared to uncoded transmission of information in communication channels. The results a study the energy efficiency of turbo codes, convolutional codes, polar codes, low-density parity-check codes, and Reed-Solomon codes are presented. The EGC was about 6 dB. It has been found that enlarging block size of TC, which is decoded, entails appearing of "saturation" effect. For the researched SCC based on TC the values of EGC reached 2 dB for BER level – 10E-4. The possibilities of eliminating the saturation effect of turbo codes using concatenated coding are evaluated. It is assumed that the results proposed in the article will be useful in choosing coding schemes in modern information networks.*

***Key words:*** *telecommunication, encoder, information, error correction, redundancy*

## ОСОБЛИВОСТІ ФОРМУВАННЯ КОДОВОЇ НАДЛИШКОВОСТІ У КАНАЛАХ ПЕРЕДАЧІ ІНФОРМАЦІЇ

***Бойко Ю.М.**, д.т.н., проф. Хмельницький національний університет, Хмельницький, Україна. boiko_julius@ ukr.net*

***Семенко А.І.**, д.т.н.,проф. Відкритий міжнародний університет розвитку людини «Україна»,Київ, Україна. setel@ukr.net*

***П'ятін І.С.,** к.т.н.,доц. Хмельницький політехнічний фаховий коледж Національного університету «Львівська політехніка», Хмельницький, Україна. ilkhmel@ukr.net*

***Анотація:*** *В статті представлені дослідження процедур формування кодів з виправлення помилок для різних телекомунікаційних технологій. Стаття зосереджена на оцінці та ідентифікації механізмів додавання надлишковості до сигнально-кодових структур у захищених інформаційних каналах. Наведені дослідження включають аналіз специфіки додавання надлишковості в структуру коду, описано загальні математичні моделі конструктивного синтезу кодів з виправленням помилок. Результат досягається шляхом аналізу згорткових кодів, кодів Ріда-Соломона, турбо-кодів і полярних кодів, які зараз широко використовуються для мобільних технологій 5G. Перевірку ефективності сигнально-кодових конструкцій завадостійких кодів проведено методом математичного моделювання для різних*

*телекомунікаційних каналів шляхом визначення енергетичного виграшу кодування.*
***Ключові слова:*** *телекомунікації, кодер, інформація, виправлення помилок, надлишковість*

## Introduction

The rapid development of telecommunication technologies at the present stage, the introduction of communication standards the fourth (4G) and fifth generations (5G) [1, 2], the development of satellite communications, telemetry systems, etc., poses quite specific tasks for researchers related to ensuring the necessary quality indicators of digital information transmission channels. The important task of ensuring reliable transmission of digital data over different communication channels is more relevant than ever. The solution of this problem lies in the plane of application noise-correcting coding in such channels [3].

It should be noted that the development of telecommunication technologies, the emergence of new digital standards contributes to an increase in the speed of transmission and the volume of transmitted data, and their volume is increasing every year. Naturally, the requirements for the applied codes and methods for their encoding and decoding are increasing. Thus, modern coding systems, in addition to high resistance to interference and reliability in error correction, must have extremely high speeds in data processing [4]. The development of coding theory allows us to state that an effective direction in the construction of decoder circuits is the direction associated with the use of a significant number of high-speed elements of microelectronics. In this case, it is expedient to refuse from long feedback channels, which directly affect the reduction in the rate of data transmission advancement. In addition, the implementation of decoding schemes should, if possible, avoid the situation when the number of calculations per decoded symbol turns out to be a random variable, and more complex decoder schemes should be built to perform efficient decoding [5].

Coding theory is an applied science [3, 5]. It is integrated into the tasks being solved, including means of telecommunications, radar, measuring, computing and control equipment. In this case, the fact of the possibility of applying the obtained results, their competitiveness in comparison with non-coded methods of error protection is of great importance. Practical achievements of coding theory are now well known [6]. However, the most widely used at the present stage of development of telecommunication technologies are such coding methods as convolutional codes (CC), Reed-Solomon codes (RS), turbo codes (TC), low-density parity codes (LDPC) [1], polar codes (PC), which became the basis for the deployment of 5G mobile telecommunications [7-10].

Application of spectrally effective modulation methods, effective coding methods, in particular signal coding construction (SCC), creates preconditions to research basic parameters of signal processing systems, telecommunication systems and optimize data decoding algorithms. The actual problem here is in finding noise immunity for modulation methods, benefits from coding, energy gain, symbol error probability benefits for receiver, acceptable code redundancy, complexity and rate of codec and synchronizing received signals. Conception of improving noise immunity in telecommunication systems, that belong to 4th and 5th generations [10, 11] and are used in conditions of high noise and hindrances becomes actual for communication systems developers, especially when data transmission standards are rapidly rising and taking into account the world trends and requirements to operation of data processing devices [12].

Noise-immune coding is necessarily associated with the introduction of symbol redundancy, which, in the case of a constant information source rate, leads to a decrease in the duration of the symbols and, for a constant transmitter power, to a decrease in the energy that falls on one symbol. It should be noted that in this case the probability of error increases. However, due to error correction during decoding, the resulting error probability at the output of the decoder will be less than in the case of uncoded transmission of information. An important indicator of coding efficiency is the energy gain resulting from coding (EGC) [4], which is generally determined through the difference between the signal-to-noise ratios in the case of uncoded and coded transmission, provided that the same bit error probability in the channel is provided.

Thus, the proposed article presents the problem of analyzing the principles of the formation of redundancy in error-correcting codes. For analysis, the above codes are taken - convolutional, Reed-Solomon, turbo codes and polar codes. As a result of the analysis, it is necessary to obtain generalized principles for constructing codes, as well as comparative characteristics of codes for different degrees of redundancy. The subject of the research of the article is the methods and means ensuring the noise immunity telecommunication systems of information transmission based on the definition the structure of the code structure. The paper describes a set of scientifically based theoretical provisions, as well as practical recommendations and proposals for the development of mechanisms for a formalized description of a methodology for increasing the efficiency of coding / decoding in telecommunication information transmission systems.

**Theoretical Description**

Error Correction Codes (ECC) are a sequence of numbers generated by special algorithms to detect and correct errors in data transmitted over noisy channels. Error correction codes identify corrupted bits and their location.

Let's start with convolutional codes.

In convolutional codes, the input bits are not divided into blocks, but are transmitted as bit streams, which are convolved into the original bits based on the logic function of the encoder. Also, in convolutional codes, the source stream depends not only on the current input bits, but also on the previous input bits stored in memory.

To generate a convolutional code (CC), information is sequentially passed through a linear shift register with a finite number of states. The shift register consists of (bit) stages and logic function generators. The convolutional code can be represented as (*n, k, K*), where:

- *k* - the number of bits shifted in the encoder at one time. Usually, *k* = 1;
- *n* - the number of encoder output bits corresponding to *k* information bits:
- *K* is the number of states of the shift register;
- Code rate, $R_c = k/n$;
- the sequence of input bits is transmitted to the encoder sequentially, starting from the last bit of the block.

Convolution code generation example is presented in fig. 1. Consider a convolutional encoder with *k*=1, *n*=2 and *K*=3. Code rate: $R_c = k/n = 1/2$.

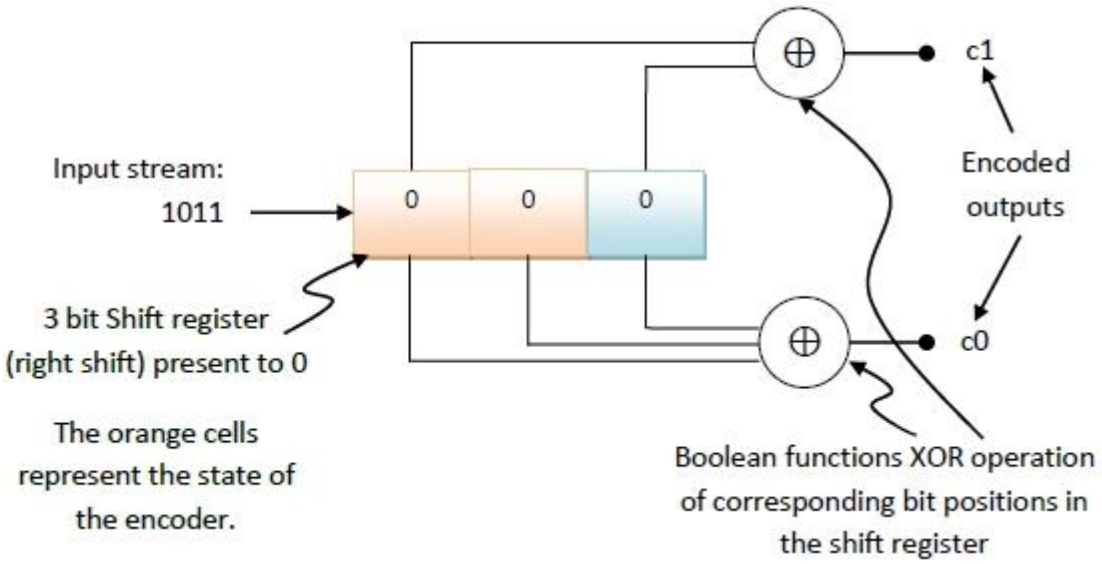
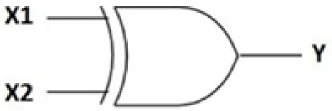



Fig. 1. Convolution code generation

The value of the bits at the output of the convolutional encoder is calculated by the logical function "exclusive OR" (modulo 2 additions, XOR), which has the following graphic symbol and truth table 1:

For the XOR function, a unit at the output of a logic element appears when only one is active at one input. If there are two or more units at the input, or zero at all inputs, then the output will be zero. The change in the state of the registers and the signal at the outputs of the encoder, depending on the input information sequence, is shown in table 2.

Table 1. Truth table




| INPUT X1 | INPUT X2 | OUTPUT Y |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 1 | 0 |

Table2.

Changing the state of the registers and the signal at the outputs of the encoder depending on the input information sequence

| SHIFT REGISTER STATUS | OUTPUT C1 | OUTPUT C0 |
|---|---|---|
| $b1 \ \ b2 \ \ b3$ | $b1 \oplus b3$ | $b1 \oplus b2 \oplus b3$ |
| 0 0 0 | 0 | 0 |
| 1 0 0 | 1 | 1 |
| 1 1 0 | 1 | 0 |
| 0 1 1 | 1 | 0 |
| 1 0 1 | 0 | 0 |

That is, if the input sequence is: 1 0 1 1

The output will be the sequence: 0 0 1 0 1 0 1 1.

Now let's consider how redundancy is formed in Reed-Solomon codes.

Unlike coding with “soft decision” used for convolution codes (CC), the output of decoder RS is “hard”, so decoder acts on alphabets symbol that is used in coding. Noteworthy is that decoder RS creates undistorted sequence in the output if received sequence of symbols differ from the real word by t symbols maximally [5]. Decoder automatically detects information on number of errors. In forward error correction system, the RS code (255, 239) will be used that is highly effective in the packet error medium. The code construction consists of: code word length $n$=255 bytes; number of information symbols in data block $k$=239 bytes; number of errors fixed in code word $t=(n-k)/2=8$; number of errors detected in code word $2 \cdot t=16$. Fig. 2 represents RS code (255, 239) construction.

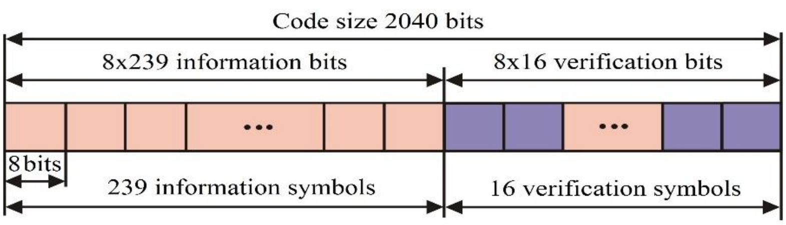



Fig. 2. Reed-Solomon code (255, 239) construction

In error correction scheme codec processes data block (information bytes 1...239) and calculates verification symbols (bytes 240...255), fig. 3.

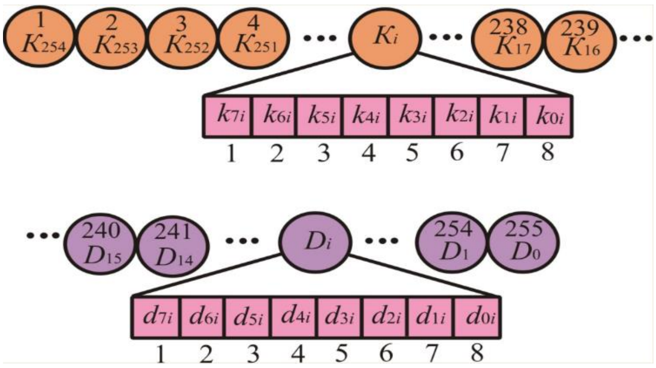



Fig. 3. Code word construction for coding with noise immunity and error correction

Bytes that belong to code word x are represented as:

$$x + 16(j - 1), j = 1 \ldots 255 \,. \tag{1}$$

The generator polynomial is represented as:

$$G(z) = \prod_{i=0}^{15}(z - \alpha^i), \tag{2}$$

where $\alpha$ – root of binary primitive polynomial of type: $x^8 + x^4 + x^3 + x^2 + 1$ .
The code word construction will be represented by polynomial as:

$$Y(z) = K(z) + D(z) \tag{3}$$

that is a summation of information and verification bytes, Fig. 4.
Information bytes will be represented by the polynomial:

$$K(z) = K_{254} \cdot z^{254} + K_{253} \cdot z^{253} + \ldots + K_{16} \cdot z^{16} \,, \tag{4}$$

where $K_j (j = 16 \ldots 254)$ – information byte given by element of the Galois field GF(256), then $K_j = k_{7j} \cdot \alpha^7 + k_{6j} \cdot \alpha^6 + \ldots + k_{1j} \cdot \alpha^1 + k_{0j}$.

Such construction is described by: bit $k_{7j}$ – most significant bit, and $k_{0j}$ – least significant bit; byte $K_{254}$ – corresponds to first byte in code word, and $K_{16}$ – 239.

The pairing verification bytes are represented as:

$$D(z) = D_{15j} \cdot z^{15} + D_{14} \cdot z^{14} + \ldots + D_1 \cdot z^1 + D_0 \tag{5}$$

where $D_j$ ($j$ =0…15 – verification byte given by element of the Galois field GF($2^8$) and $D_j = d_{7j} \cdot \alpha^7 + d_{6j} \cdot \alpha^6 + \ldots + d_{1j} \cdot \alpha^1 + d_{0j}$.

Bit $d_{7j}$ is most significant bit, $d_{0j}$ – least significant bit of pairing verification byte. Byte corresponds to byte 240 of under-feed which is responsible for coding with forward error correction (FEC) and byte $R_0$ corresponds to byte 255.

The verification bytes $D(z)$ will be calculated as:

$$D(z) = K(z) \, mod \, Y\,(z), \tag{6}$$

where $mod$ – module calculated by generator polynomial $Y(z)$ with elements of GF($2^8$). Each element in Galois field GF($2^8$) will be determined by primitive polynomial: $x^8 + \mathrm{x}^4 + \mathrm{x}^3 + \mathrm{x}^2 + 1$ . Hemming distance of RS code (255, 239) – $d_{min}$ [5].

In error correction mode code can correct up to 8 errors of symbols in code word FEC and can detect up to 16 errors of symbols in code word FEC on error detection mode [1].

Coding is performed with reverse Fourier transform:

$$c_j^{/} = C(z^j) \quad , \tag{7}$$

where $z$=2 – primitive element of the field.

Conditions to be considered are: forming SCC requires identification which elements are informational and which are verifying (redundant). Mention was made that number of redundant symbols should be twice higher than the number of error symbols which should be renewed. If the double error is to be corrected ($t$ = 2 – error multiplicity), then four verification symbols should be used correspondently.

Decoding is conducted by the formula:

$$c_j = C^{/}(z^{-j}) \quad (8$$

Counting redundant symbols is sufficient to verify if information is not distorted. If their number equals zero then errors are absent. To correct an error, first of all, the position of error symbol should be defined. This requires calculation of error locator's polynomial whose roots will point to error positions. The locator polynomial is represented by matrix as: $L$ = [1, $l_1$, $l_2$, ... $l_t$].

Matrix and vector-column will be formed, which is required for calculation of error locators L. This process is formalized as:

$$G = \begin{pmatrix} S_{t-1} & \dots & S_1 & S_0 \\ & \dots & & \\ S_{2t-2} & & S_t & S_{t-1} \end{pmatrix}, \qquad \begin{pmatrix} l_1 \\ \dots \\ l_t \end{pmatrix} = G^{-1} \cdot J,$$
$$J = \begin{pmatrix} S_{t-2} \\ \dots \\ S_{2t-2} \end{pmatrix}. \tag{9}$$

The reverse matrix $G^{-1}$ will be calculated taking into account calculation rules in the Galois field. Summarizing error vector with distorted code sequence will result in correct coded sequence whose decoding will deliver correct information symbols.

Coder presents digital machine where all operations are performed in the Galois field by module of primitive polynomial. The information in byte form is incoming to codec's input. Information symbols are going to codec's output with no delay in case of switches P1 and P2 are in position 1. After k information symbols come, codec's input switches off, P1 and P2 are in position 2 and $n-k$ verification symbols, which are contained in the shift registers (fig. 4), are coming to the output.

The represented coder scheme is specific in having N registers. In the scheme the principle of block interleaving is used, which can be described by matrix of X rows and Y columns. In this case data is read by columns in transmitter and by the rows in the receiver. Parameter Y equals to the length of code word in block code. The advantage is obtained by: since RS code coding gives block length multiple of X·Y, the scheme is obtained, in which register cleaning process is absent.

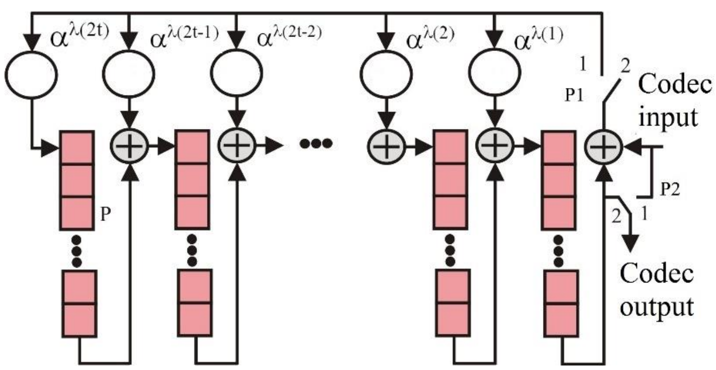



Fig. 4. RS coder scheme with interleaving data: R – shift register; P - switches; α – Galois field

element

Such scheme redundancy, which is due to presence of interleaver, will be zero. Scheme of such coder cyclically processes input information sequence in form of bytes.

The general structure of the frame used in channel coding is shown in fig. 5.

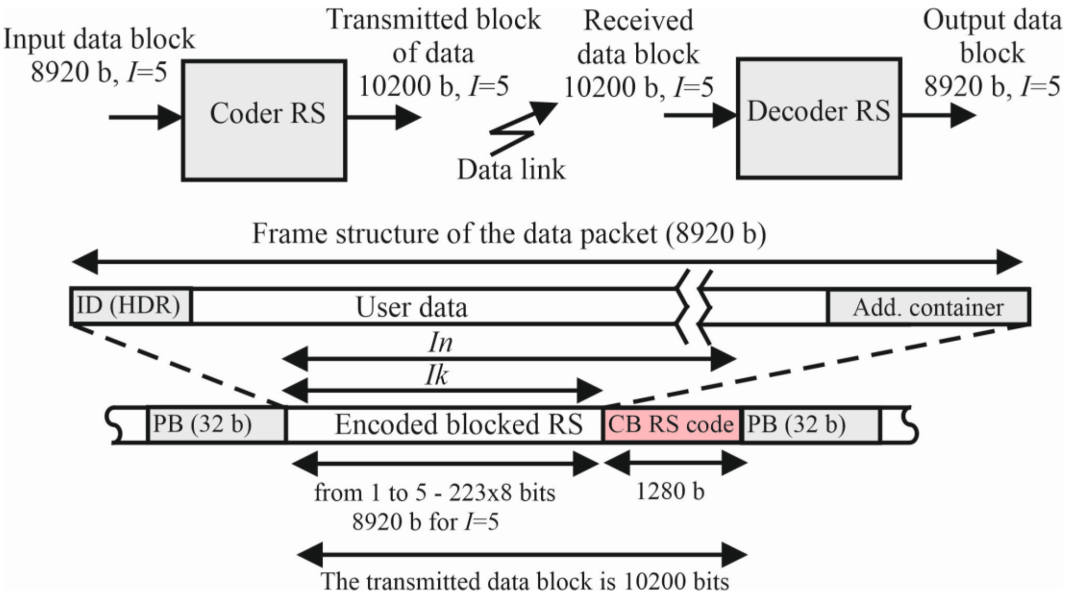



Fig. 5. Frame structure of a data packet for transmitting information by the RS code: ID - the name of the input frame data (header); PB - check bits; CB - synchronization control bits, *I*=5 - interleaver length

Let us now consider the principles of redundancy formation in the design of TC.

The code word is represented by 16-bit construction of Hemming block code (16, 11). Such code contains 11 information bits and 5 verification ones, fig. 6.

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IB | IB | IB | IB | IB | IB | IB | IB | IB | IB | IB | VB | VB | VB | VB | VB |

Fig. 6. Code word to build turbo-code: IB – information bits; VB – verification bits

Fig. 7 demonstrates results of building TC as two-dimensional construction 16x16 bits. The turbo-code synthesis is represented by the following sequence. The matrix is formed whose base is made of 11 input bits: matrix 16x11 and verification bits.

Noteworthy is that in matrix cells, shown in Fig. 6, various codes can be used: Hemming, Golay and others. Vertical blocks in code word can be built with Golay code, and horizontal ones – with Hemming code for an instance. Then we obviously obtain two-dimensional turbo-code.

Fig. 8 demonstrates process of building turbo-code as three-dimensional construction. To correct productivity of turbo-code decoder considered in the decoder is offered to be improved by including scaling block. The idea is that outer information is multiplied by the specified scale before it is put again in the input of component decoder through the scheme of iterative decoder.

Fig. 9 shows the simulation scheme of decoder construction described above. Simulation is conducted within the research framework of telecommunication system for transmitting data with turbo-coding.

The scheme can be divided into APP-decoder, interleaving blocks, scaling sub-system – Scaling. The logarithmic ratio of likelihood functions for each information symbol $u_l$ is represented as:

$$G(u_l) = ln\left[\frac{p(u_l=+1)}{p(u_l=-1)}\right] \cdot k_{\text{м}1} \,, \quad (10)$$

where $p(u_l = n)$ – event probability $u_l = n$ and $u_l = n$ .

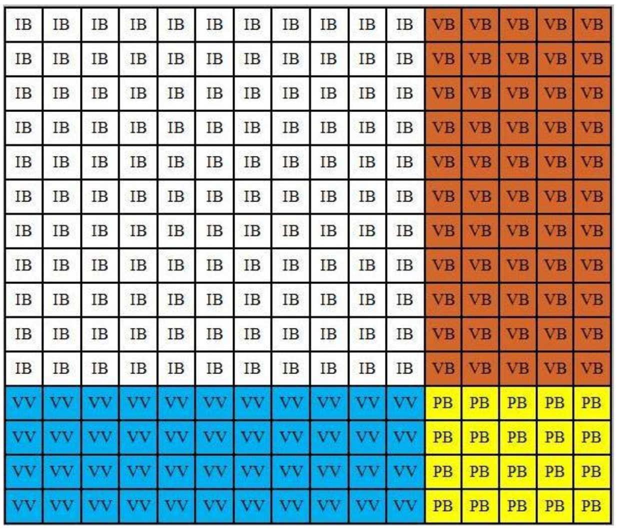


Fig. 7. Code word for building two-dimensional turbo-code: VV – vertical verification bits; PB – pre-implementation verification bits

Decoder SISO1 (Inner Decoder) on the base of information received from transmission channel assesses information bits with account for scale. Then outer information is formed from made assessment $G(u_k^{/}|\overline{y})$ with account for scale by excluding a priori information and systematic symbols received from the channel. This process is formalized as:

$$G_{зв}^{/}(u_l) = G(u_l^{/}|\overline{y}) - G_a y_{ls} - G(u_l), \quad (11$$

where for discrete Gaussian channel without memory (AWGN) member $G_a = 2/\sigma^2$ will determine channel reliability, and $\sigma^2$ – noise dispersion.

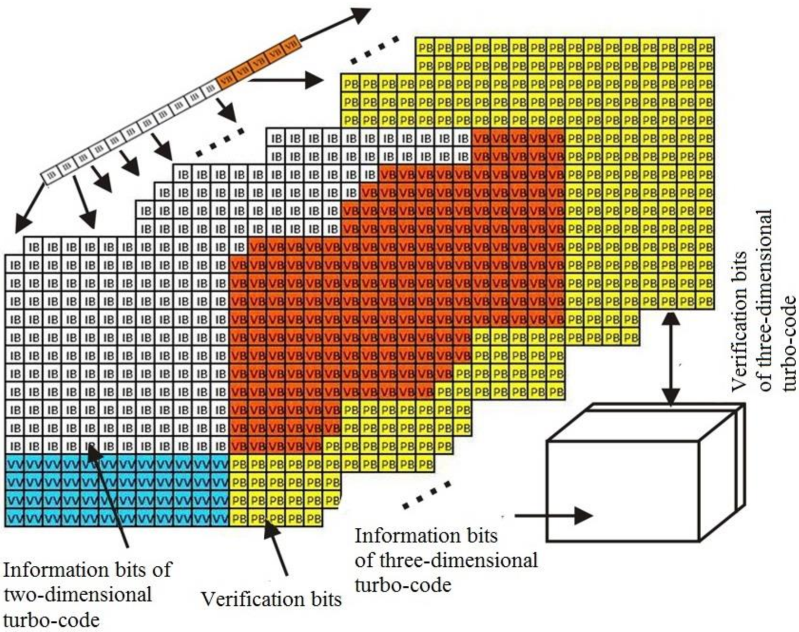



Fig. 8. Code word for building three-dimensional turbo-code: VB – verification bits of three-dimensional realization

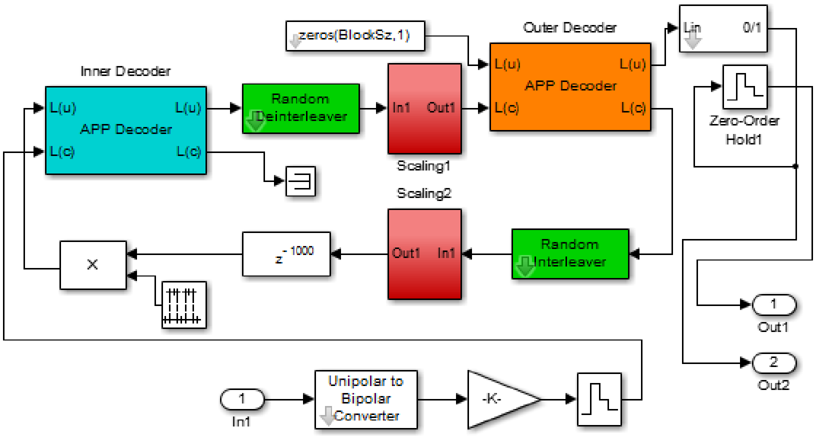



Fig. 9. The frame of subsystem simulation scheme for turbo-code decoder

Second SISO2 (Outer Decoder) uses received information (a priori) for self-assessment with account for scale $k_{M2}$.

For Gaussian channel, in which noise has zero mean value and dispersion $\sigma^2$, when a priori probability is replaced for probability density function, the following expression will be obtained:

$$\Lambda(\hat{d}_k) = \pi_k \exp\left(\frac{2x_k}{\sigma^2}\right) \frac{\sum_m \alpha_k^m \exp\left(\frac{y_k v_k^{i,m}}{\sigma^2}\right) \beta_{k+1}^{f(1,m)}}{\sum_m \alpha_k^m \exp\left(\frac{y_k v_k^{0,m}}{\sigma^2}\right) \beta_{k+1}^{f(0,m)}} = \pi_k \exp\left(\frac{2x_k}{\sigma^2}\right) \pi_k^e \quad , \tag{12}$$

where $\pi_k = \pi_k^l / \pi_k^0$ – will be input ratio of a priori probabilities (a priori likelihood), and $\pi_k^e$ – outer output likelihood received in a moment $k$ – correction (correction member) of coding, which changes input priori information of data bits. In turbo-code such correction members pass from one decoder to another in order to improve ratio of likelihood functions for each information bit and in such way to minimize decoding error probability. Thus, decoding process is followed by using equation (12) to obtain several iterations $\Lambda(\hat{d}_k)$. Outer likelihood $\pi_k^e$ obtained from concrete iteration substitutes a priori likelihood $\pi_{k+1}$ for the next iteration.

TS and convolutional codes are typical for use in 4G telecommunications. Consider the principles of redundancy formation for the code that is typical for 5G [9].

Consider a polar code encoder with *N*=4 bits input. The polar code of this data vector is calculated by the expression: $x_1^N = u_1^N G_N$. Here $x_1^N$, is a code vector containing *N* bits. $G_N$ is a generator matrix and is calculated by the expression: $G_N = B_N F^{\otimes n}$. *F* is the Kronecker matrix. The matrix $B_N$ is calculated using the following expression: $B_N = R_N(I_2 \otimes B_{N/2})$. $R_N$ is the permutation operator. $I_2$ - information array. A polar encoder of a 4-bit long data vector is shown in the Fig. 10 below.

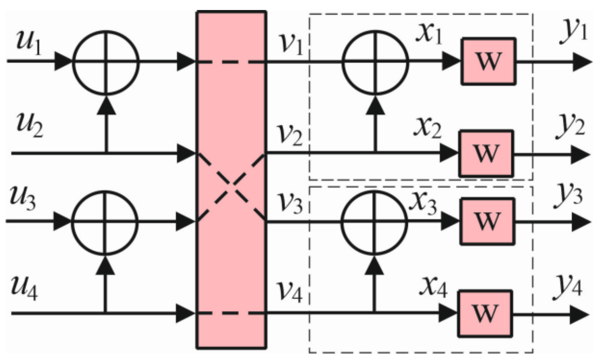



Fig. 10. Polar coding scheme

Consider an example of how a polar encoder works without moving. Let: $K$=132 – informational message length; $E$=256 is the length of the rate-matched output block [13].

Next comes the construction of the polar encoder. The MATLAB function returns an $N$-bit vector ($N$=256) as the original data, where the K elements in the original data will be 0 (the location of the information bits. $K$=132), and the $N$-$K$ elements in the original data will be 1 (frozen bits). positions $N$–$K$=124). $E$ is the length of the output at the agreed rate, and $N_{MAX}$ is the maximum value of $n$ (9 or 10). The code rate is defined as $K/E$.

As a result of constructing the encoder, indexes of the location of frozen bits and parity bits are determined.

Next, the generator matrix $G$ is defined as the nth order of the products of the Kronecker matrix [13], $n$=8:

.

$$G = \begin{vmatrix} 1 & 0 \\ 1 & 1 \end{vmatrix} \quad . \tag{13}$$

As a result, the matrix $G$ will have dimensions of 256×256 elements.

For polar coding, the mod 2 product operation of the generator matrix and the input data array is performed.

Below we present the MATLAB program code designed to generate polar codes.

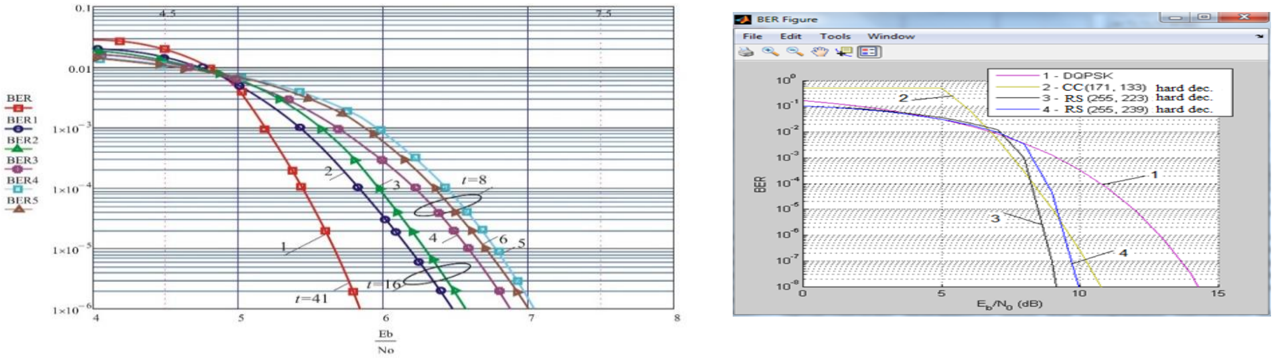
MATLAB code for polar encoding CRC-Aided Polar.

```
K = 132;            % Message length
E = 256;            % Rate matched output length 256
in = randi([0 1],K,1);               % Generate random message
nMax = 10;       % maximum n value for N
iIL = false;     % input interleaving
out1 = nrPolarEncode(in,E,nMax,iIL);            % Polar encode
% Get frozen bit indices and parity-check bit locations
   [F,qPC] = nr5g.internal.polar.construct(K,E,nMax);
   N = length(F);
   nPC = length(qPC);
      inIntr = in;
   % Generate u
   u = zeros(N,1);     % doubles only
      % CRC-Aided Polar (CA-Polar)
      u(F==0) = inIntr;   % Set information bits (interleaved)
   % Get G, nth Kronecker power of kernel
   n = log2(N);
   ak0 = [1 0; 1 1];   % Arikan's kernel
   allG = cell(n,1);   % Initialize cells
   for i = 1:n
      allG{i} = zeros(2^i,2^i);
   end
   allG{1} = ak0;      % Assign cells
   for i = 1:n-1
      allG{i+1} = kron(allG{i},ak0);
   end
   G = allG{n};
   % Encode using matrix multiplication
   outd = mod(u'*G,2)';
   out = cast(outd,class(in));
```

**Estimation of Encoding Gain**

This section presents the experimental results of performance evaluation of various error-correcting codes. The noise immunity was evaluated by determining the energetic coding gain, the method for obtaining which is described above in the text of the article. This assessment is rather arbitrary. First of all, as described in the article, a certain signal-code constructing (SCC) finds application in a certain telecommunication technology for solving specific buildings. In this case, the structure of the error-correcting code, the requirements for its noise immunity, the main indicators: code rate, redundancy, degree of interleaving, degree of puncturing, and others, will differ significantly. However, the invariance with respect to certain parameters of the SCC will make it possible to obtain a certain, general graph of noise immunity. Such a graph will make it possible to assess in general the possibilities of the codes taken for consideration in terms of energy efficiency, approaching the Shannon boundary. This is the essence of the results presented in this section.

Fig. 11 shows the dependencies of BER on the corrective ability of RS codes. In particular, the simulation results make it possible to establish that the code RS (255, 173) has the best performance in the case of *t*=41.




a b

Fig. 11. Dependencies for assessing the noise immunity of RS codes: a - 1 - (255, 173); 2- (157, 125) 3 - (255, 223), 4 - (97, 81), 5 - (255, 239); 6 - (204, 188); b - to determine the energy gain of coding

Unlike the "soft" decisions used for convolutional codes, the output of the RS decoder is "hard" so that the decoder acts on the character of the alphabet that is used in the encoding. It is important to note here that the RS code decoder creates an undistorted sequence at the output if the sequence of received symbols differs from the real word by no more than t symbols, which was shown in [4]. In this case, the decoder automatically sets the information about the number of errors.

On Fig. 12 and Fig. 13 shows the results of the study of noise immunity for concatenated codes according to the SCC: RS(255, 223)+CC and RS(255, 239)+CC and convolutional codes.

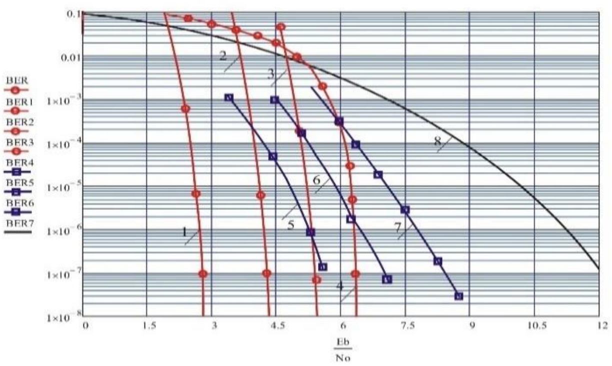



Fig.12. Plots of BER from $(E_b/N_0)$ for convolutional and concatenated code at different coding rates at: *t*=16: 1 - RS+CC(255, 223), *R*=1/2 ; 2- RS+CC(255, 223), *R*=3/4, 3- RS+CC(255, 223), *R*=7/8; 4 - RS(255, 223); 5 – CC *R*=1/2; 6- CC *R*=3/4; 7- CC, *R*=7/8; 8- uncoded QPSK

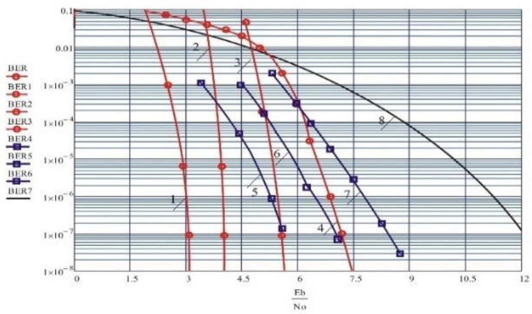



Fig.13. Plots of BER from $(E_b/N_0)$ for convolutional and concatenated code at different coding rates at: *t*=8: 1 - RS+CC(255, 239), *R*=1/2 ; 2 - RS+CC(255, 239), *R*=3/4, 3- RS+CC(255, 239), *R*=7/8; 4 - RS(255, 239); 5 – CC *R*=1/2; 6 - ЗК, *R*=3/4; 7 - CC *R*=7/8; 8 - uncoded QPSK

The results of the study allow us to establish that the efficiency of using concatenated codes is higher than when using RS codes separately (compare, for example, Fig. 12, 1 and Fig. 12, 5, the energy gain is almost 3.2 dB (BER=10E-7).

Let's consider how the number of iterations affects the decoding efficiency and noise immunity of turbo codes. Used turbo code: TC $(7, 5)_8$ with rate $R$=1/2 with puncturing (perforated code), frame length for interleaving $l$=400 bits. Decoding was performed according to the log-MAY algorithm. On fig. Fig. 14 shows the dependence of the error probability on that obtained in the simulation. The axes are, respectively, the bit error probability (BER), the signal-to-noise ratio in dB, and the number of iterations during decoding. The simulation result is a surface formed by sections, each of which determines the dependence of the bit error probability on a fixed number of iterations. An analysis of the graph allows us to establish the following: code characteristics and noise immunity improve with an increase in the number of iterations, however, after the seventh iteration, this improvement is rather insignificant. We use the proposed modified SCC: RS (255, 223) + TC ($l$ = 16384 bits; 15 iterations) + DQPSK and present noise immunity graphs. Decoding was performed using the log-MAP algorithm (fig. 15).

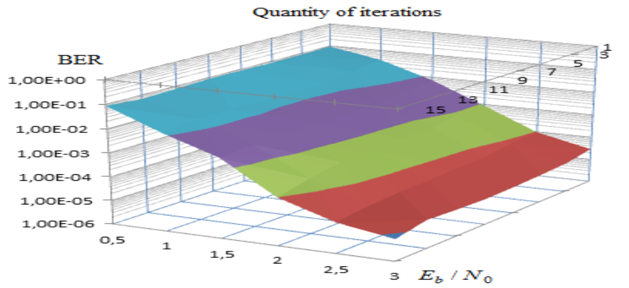



Fig.14. Dependences of noise immunity for the proposed TC on the number of iterations

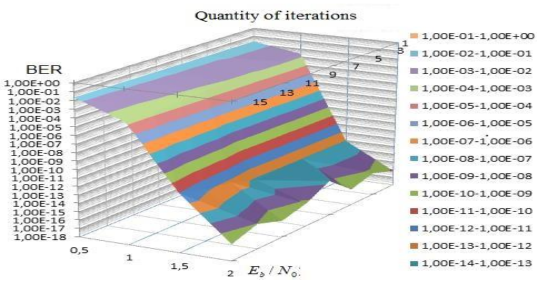



Fig.15. Noise immunity dependences for the offered SCC in case of changing iteration quantity in TC

The offered scheme has removed TC saturation effect for the offered codes and allowed to obtain EGC at the level of 3.1 dB (BER=10E-8)

In order to compare the codes described above in the article, we determined the performance of the RS, CC, LDPC (Low-density parity-check code) [9], TC and polar codes. Mathematical modeling used SCC with QPSK, code rate 2/3,fig.16.

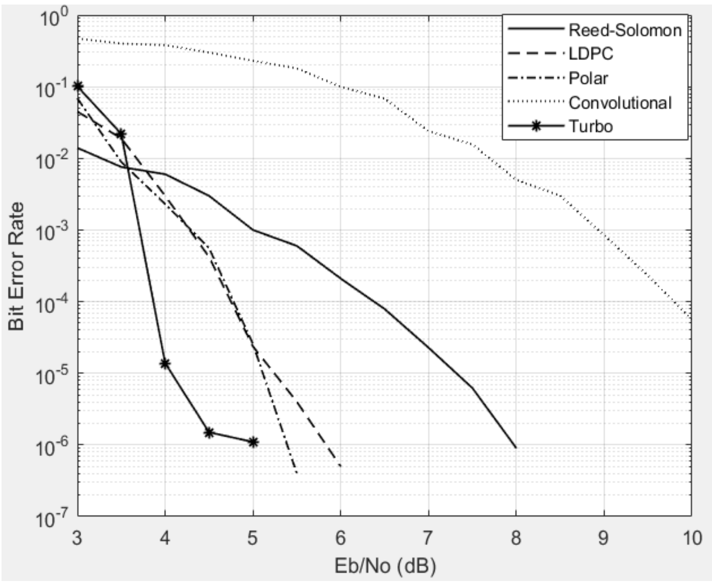



Fig.16. Noise Immunity Graph to Compare Energy Efficiency of CC, TC, RS, Polar Code and LDPC

**Conclusions**

The conditions for increasing the spectral and energy efficiency when establishing the evaluation requirements for digital telecommunications transmission systems are determined. The analysis noise-immune coding algorithms in telecommunication systems of information transmission is carried out. The features the implementation of noise-immune coding algorithms

in telecommunication channels information transmission with digital modulation types are considered. The features of the use error-correcting codes in digital telecommunication systems for information transmission are determined. Practical recommendations are given on the structure, redundancy and form of SCC in solving the problem increasing the noise immunity of information transmission under conditions of a real interference complex.

***Література***

1. Пятін І., Бойко Ю. Порівняння продуктивності завадостійких кодів на основі програмного HDL моделювання для захищених інформаційних технологій. *Інфокомунікаційні та комп’ютерні технології*, 2022. № 1(03). С. 43-68.
2. Bioglio V., Condo C., Land I. Design of Polar Codes in 5G New Radio. *IEEE Communications Surveys & Tutorials*, 2020. P. 1.
3. Dumas J-G., Roch J-L., Tannier E., Varrette S. Error Detection and Correction. Foundations of Coding: Compression, Encryption, Error Correction. Wiley, 2015. P.209-276.
4. Boiko, J., Pyatin, I., Eromenko, O., Stepanov, M. Method of the adaptive decoding of self-orthogonal codes in telecommunication. *Indonesian Journal of Electrical Engineering and Computer Science*. 2020. №19(3), P. 1287-1296.
5. Kim H. Error Correction Codes. Wireless Communications Systems Design. Wiley, 2015, P.123-207.
6. Berkman L., Turovsky O., Kyrpach L., Varfolomeeva O., Dmytrenko V., Pokotylo O. Analyzing the code structures of multidimensional signals for a continuous information transmission channel. *Eastern-European Journal of Enterprise Technologies*, 2021.Vol. 5, № 9. P. 70–81.
7. Семенко А.І., Кушнір М. Я., Бокла Н. І. Синтез широкосмугової телекомунікаційної системи з підвищеною конфіденційністю передачі інформації шляхом використання псевдовипадкових послідовностей на основі хаосу. *Вісник університету «Україна». Серія: інформатика, обчислювальна техніка та кібернетика*, 2020. №1(24). С.65-75.
8. Бірюков, М., Семенко, А., Тріска, Н. Принципи узгодження цифрових потоків транспортних телекомунікаційних мереж. *Інфокомунікаційні та комп’ютерні технології*, 2021. № 2(02). С. 64-80.
9. Boiko, J., Pyatin, I., & Eromenko, O. Design and Evaluation of the Efficiency of Channel Coding LDPC Codes for 5G Information Technology. *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*, 2021. № 9(4), P. 867-879.
10. Бойко, Ю., П’ятін, І., Карпова, Л., Пархомей, І. Transmission of control information in 5G broadband telecommunication systems. *Адаптивні системи автоматичного управління*, 2021. №1(38), С. 82-95.
11. Luo F. Deep Learning Techniques for Decoding Polar Codes. *Machine Learning for Future Wireless Communications*. 2020., P.287-301.
12. Bae J., Abotabl A., Lin H., Song K., Lee J. An overview of channel coding for 5G NR cellular communications *APSIPA Transactions on Signal and Information Processing*. 2019, No. 8, E17.
13. Arikan E. Systematic Polar Coding. *IEEE Communications Letters*. 2011. Vol. 15, No. 8. P. 860-862.

***References***

1. Pyatin, I., Boiko, J. (Porivniannia produktyvnosti zavadostiikykh kodiv na osnovi prohramnoho HDL modeliuvannia dlia zakhyshchenykh informatsiinykh tekhnolohiiю [Comparison the performance of error-control code based on software HDL modeling for information security technologies]. *Infocommunication and computer technologies*, 2022).*1*(03), s.43-68.
2. Bioglio V., Condo C., Land I.) Design of Polar Codes in 5G New Radio. *IEEE Communications Surveys & Tutorials*.2020, P. 1.
3. Dumas J-G., Roch J-L., Tannier E., Varrette S. Error Detection and Correction. Foundations of Coding: Compression, Encryption, Error Correction. Wiley, 2015. pp.209-276.
4. Boiko, J., Pyatin, I., Eromenko, O., Stepanov, M). Method of the adaptive decoding of self-orthogonal codes in telecommunication. *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS).* .2020. *19*(3), pp. 1287-1296.
5. Kim H. (2015). Error Correction Codes. Wireless Communications Systems Design. Wiley, P.123-207.
6. Berkman L., Turovsky O., Kyrpach L., Varfolomeeva O., Dmytrenko V., Pokotylo O. (2021). Analyzing the code structures of multidimensional signals for a continuous information transmission channel. *Eastern-European Journal of Enterprise Technologies*. *5*(9), P. 70–81.
7. Semenko A.I., Kushnir M. Ya., Bokla N. I. Sintez shirokosmugovoyi telekomunkacjnoyi sistemi z pidvishenoyu konfidencijnistyu peredachi informaciyi shlyahom vikoristannya psevdovipadkovih poslidovnostej na osnovi haosu. *Visnik universitetu «Ukrayina».*[Synthesis of a broadband telecommunication system with increased information transmission confidentiality by using pseudo-random sequences based on chaos].. *Visnyk Visnyk universytetu «Ukrain», Seriya: informatika, obchislyuvalna tehnika ta kibernetika*. 2020. *1*(24), s.65-75 .
8. Biriukov, M., Semenko, A., Triska, NPryntsypy uzghodzhennia tsyfrovykh potokiv transportnykh telekomunikatsiinykh merezh. Принципи узгодження цифрових потоків транспортних телекомунікаційних мереж.[lignment of the transport network digital streams]. *Infocommunication and computer technologies* . 2021,. *2*(02), s. 64-80.
9. Boiko, J., Pyatin, I., Eromenko O. Pryntsypy uzghodzhennia tsyfrovykh potokiv transportnykh

telekomunikatsiinykh merezh. [Design and Evaluation of the Efficiency of Channel Coding LDPC Codes for 5G Information Technology. *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*. 2021. *9*(4), pp. 867-879.
10. Boiko J., Piatin I., Karpova L., Parkhomey I. (2021). Transmission of control information in 5G broadband telecommunication systems. *Adaptivni sistemi avtomatičnogo upravlinnâ*. 2021*. 1*(38), pp. 82-95.
11. Luo F. (Deep Learning Techniques for Decoding Polar Codes. *Machine Learning for Future Wireless Communications.* 2020. pp.287-301.
12. Bae J., Abotabl A., Lin H., Song K., Lee J. An overview of channel coding for 5G NR cellular communications *APSIPA Transactions on Signal and Information Processing*. 2019. 8, E17.
13. Arikan E. Systematic Polar Coding*. IEEE Communications Letters*. *15*(8), 2011. pp. 860-862.