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Coding Methods and Permutation Decoding in the Systems for Network Processing of Data

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ABSTRACT

Introduction
A distinctive feature of current network technologies is that the quality of service is guaranteed. This requirement fully covers wireless sensor networks (WSN) that represent ad hoc network structures. Launching telecommunication services using similar structures resulted in inventing a concept of Internet of things, Tactile Internet, flying networks that collectively define the major directions of developing the 5th generation networks. Since WSN technologies predominantly use a system of radio channels and self-contained power sources, it is indispensable to improve their energy performance applying means based on noise-immune codes with elements of cognitive processing of data.

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Materials and methods
The algorithm reported here is based on applying properties of equivalent codes (EC) and new technology for fast transformations of reference standard matrices of binary and non-binary equivalent codes (EC), corresponding to probable tuples of permutations, adopted to process code combinations.

Results
A concept for numerators of rows and columns of generating matrix of error-correcting linear block code (LBC) shall be introduced. A proof is presented that the structure of interleaved LBC generating matrix in a systematic form corresponds to various transformations of parent LBC matrix when numerators of parent matrix rows and columns are permutated. It is shown that parent matrix with classical layout of rows and columns constitutes a reference standard that produces EC generating matrix corresponding to the specified permutation of numerators, when fast matrix transformations (FMT) suggested in the study are used. Validity of the suggested FMT for binary and non-binary LBC is proved. Here, a change in series of numerators for each code combination obtained by a receiver depends on soft decisions formed by a receiver for binary (non-binary) symbols of code vector. To save computing resources of WSN elements for generating soft decisions, it is recommended to use erasure communication channel. Registration of all code vector symbols terminates with their sorting (permutation) in a descending order of their soft decision values. From this an EC vector is formed. A subsequent comparison of the received vector of the main and EC code enables to calculate a vector of errors active within communication channel during transmitting source code combination. When tuples of symbols permutations are repeated, it is recommended to utilize cognitive approach to form EC matrices.

Discussion
An assessment of the degree of reducing complexity of decoder implementation through applying FMT system and introducing cognitive map for storing samples of reference standard matrices into decoder structure is given.

Conclusion
A complex algorithm has been developed for permutation decoding (PD) of binary and non-binary redundant codes involving a system of making soft decisions of symbols, their ranking, forming EC using FMT procedure and identifying vector of errors therefrom. Estimation of energy gain of a code (EGC) is made.

Key words**:** soft decision of symbol, permutation decoding, cognitive map of decoder.

INTRODUCTION

Practical application of various robotic stations, self-contained machineries, development of conceptual bases of Internet of things, and Tactile Internet, using radio channels for control system, intrinsically requires application of the means to protect control commands and processed information from effect of destructive factors that use redundant codes [1, 2, 3]. Thus, a problem of reducing cycle time needed for controlling elements of WSN structure remains relevant for multiple modern and future control systems. It creates a vital necessity for using short block noise-immune codes more adapted to the systems of packet data transmission and tasks of synchronizing not-long control signals. Therefore, error protection system should involve all potential of redundancy incorporated into code with minimum expenses for organizing computation process that is of particular importance for off-line mobile tools, for example, those from flying networks. It is known that capabilities of codes to correct errors within Hamming distance are employed to the fullest only when soft methods of processing data are used [4]. As a result, it provides energy gain of a code and an increase in a distance of remote control with mobile tools that indirectly facilitates solving immediate problems of electromagnetic compatibility. PD tools shall further develop soft methods of processing data based on hidden methods of transforming generating EC matrices and establish principles of cognitive organization of algorithms for functioning of block redundant code decoders [5, 6, 7].

Communication systems address two important problems: acceptable improvement of spectral efficiency and reduction of energy spent in the process of transmitting a unit of information volume under specified requirements to its reception integrity. The first task shall be accomplished through applying complex types of modulation or signal-code sequences that is typical of stationary network structures. The second one shall be solved using noise-immune coding means with binary type modulation extensively used in mobile networks.

MATERIALS AND METHODS

To correctly solve a problem of permutation decoding requires proving a number of concepts of general theory of communication that allow to find boundaries defining conditions of method applicability, for example, under a particular signal-noise ratio. Furthermore, it is necessary to work out a method for fast matrix transformations in the system of binary Galois fields with a specific degree of extension.

These computations will allow to significantly reduce complexity of implementing decoders through introducing cognitive methods of processing received data. Basically, these approaches to the problem raised will enable PD procedure to go from theoretical studies to their intense practical use in the modern WSN with not only binary type modulations, but in the systems of exchanging data with complex types of signal transformation as well.

RESULTS

Present-day telecommunication systems opt for a value of EGC obtained through applying in them noise-immune coding as a criterion of efficiency. It is known that EGC in the channel with Gaussian noise upon condition that ratio $E_b / N_0 \to \infty$, where E_b is an energy of signal for a bit, N_0 – spectrum density of Gaussian noise, shall be estimated according to formula $D_h = 10\lg(R(t+1))$ dB in case of hard decisions and implementation of algorithm for correcting t errors. When using algorithms for correcting erases, EGC is estimated by formula $D_s = 10\lg(Rd_{\min})$ dB, where $d_{\min}$ – Hamming distance [1]. Ratio $R = k/n$ in these formulas is a relative speed of a code, where k is the number of information symbols in a code vector of n length. This means that with $E_b / N_0 \to \infty$ and corrections of erases, EGC becomes twice as much as when processing hard decisions since parameter $d_{\min} = 2t+1$, therefore maximum gain is about 3dB. The above ratios show that irredundant coding with $n = k$, $t = 0$, and $d_{\min} = 1$ in the systems in question shall not principally provide any energy gain at all.

Assessment of possibility for decoding both block, and convolution binary codes beyond boundaries defined by Hamming distance is important in terms of applying these codes in a composition as consecutive or parallel connections of codecs.

There are methods of decoding noise-immune codes that use maximum of redundancy introduced and ensure minimum number of probable errors for a bit p_b. It means that code is capable to erase more errors (erases) than it is possible when using Hamming distance. Here a formula $D_m = 10\lg\left(k\left(1 - R + 1/n\right)\right)$ dB [1] can serve as asymptotic estimation of energy gain from using block binary code.

It is supposed that $d_{\min} = n - k + 1$ and it corresponds to properties of maximum decoded codes, for example, codes of Reed-Solomon (RS) unambiguously attain value D_m, but it can't be stated for the known not maximum decoded binary codes [9, 10]. For binary codes, condition $D_h < D_s$ is met without limitations, however, condition $D_s < D_m$ is met only for possible permutations of symbols of code combinations.

When decoding binary codes, value D_m may be reached using cluster approach [1, 3, 6, 12]. The method is based on the principle of decomposing space $\{\Omega\}$ of permitted code vectors from algebraic group into the lists with their unique numbers characterizing each list. Number of cluster (list) is defined with pre-specified similarly-named positions of set $\{\Omega\}$ elements. These numbers are the same within certain list. To correctly define the cluster number, soft decisions of symbols

(SDS) with the highest estimations need to hold specified positions. This condition is strongly negative; it increases risks of wrong identification of a list, and, hence, increases risks of probable error decoding of vector $P_{cluster}$.

No compliance with this rule is required for PD procedure. Therefore:

$$P_{permut} < P_{cluster} < P_{soft} < P_{algebraic}. \quad (1)$$

When implementing classical PD algorithms, computations shall be made according to the steps described below in detail:

Step 1. Fix hard decisions of code vector V_{av} received from channel with errors, supporting each of them with value of SRS λ_i.

Step 2. Rank SRSvalues and respective bits in a descending order so that the most reliable λ_i are high-order positioned (to the left) having in mind left-side positioning of a unit matrix $\mathbf{E}$ in generating matrices of systematic codes.

Step 3. Based on step 2, bijection of $f: V_{av} \to V_p$ type and respective permutation (commutative) matrix $\mathbf{K}$, where V_p is an interleaved vector.

Step 4. Pursuant to the results of taking step 3, left k of the most reliable classes shall be sorted out in vector V_p, and their numerators shall be memorized as a new information vector V'_{inf}.

Step 5. Multiply numerator of columns of source code $\mathbf{G}$ generating matrix by matrix $\mathbf{K}$ for permutation of matrix $\mathbf{G}$ columns according to step 2 and obtain code $\mathbf{G}_\mathrm{p}$ permutation matrix.

Step 6. Sort out the first k columns in matrix $\mathbf{G}_\mathrm{p}$, obtain square matrix $\mathbf{Q}_{\mathbf{k}\times\mathbf{k}}$, and calculate a determinant of this matrix Δ. Proceed to step 7, if $\Delta \neq 0$. Refuse to decode, if $\Delta = 0$, proceed to step 2 and make new permutations, having interchanged column with numerator k and column with numerator $k+1$. Here, matrix $\mathbf{K}$ is properly transformed. This step takes extra time; therefore, it is advisable to represent the combination in the form of erasing.

Step 7. Calculate matrix of minors $\mathbf{M_Q}$ for matrix $\mathbf{Q}_{\mathbf{k}\times\mathbf{k}}$;

Step 8. Find inverse matrix $\mathbf{Q}^{-1}_{\mathbf{k}\times\mathbf{k}}$ according to results of steps 6 and 7.

Step 9. Transform matrix $\mathbf{G}_\mathrm{p}$ into systematic form $\mathbf{G}^\mathbf{s}_\mathbf{p}$ according to vales of matrix $\mathbf{Q}^{-1}_{\mathbf{k}\times\mathbf{k}}$.

Step 10. Multiply vector of length k from step 4 V'_{inf} by matrix $\mathbf{G}^\mathbf{s}_\mathbf{p}$ and calculate vector of equivalent code V_{eq}.

Step 11. Multiply vector V_{eq} by $\mathbf{K}^\mathbf{T}$, having made bijection $f: V_p \to V_{av}$, and obtain interleaved vector V^p_{eq}.

Step 12. Adding vectors $V_{av} \oplus V^p_{eq} = V_e$ bit-wise, obtain vector of errors active in the communication channel during recording hard decisions of vector V_{av}.

Analysis of classical algorithm shows that efficiency of decoder is considerably decreased when taking steps 6-9, where matrix computations are made. The main deficiency of algorithm is in necessity to take the above steps even if there is a repetition of certain permutations of numerators V_{av} during processing data.

It makes sense to memorize permutations of the main code generating matrix $\mathbf{G}$ columns that do not result in matrix $\mathbf{Q}_{\mathbf{k}\times\mathbf{k}}$ degeneration, and retain the structure of transformed matrix $\mathbf{G}^\mathbf{s}_\mathbf{p}$, corresponding to a certain permutation of matrix $\mathbf{Q}_{\mathbf{k}\times\mathbf{k}}$, in decoder's memory. Such a solution allows to "train" decoder in advance to identify repeated permutations, and through expanding the decoder's memory to fulfil its cognitive functions, making a cognitive map of permutations of matrix $\mathbf{G}$ columns that ensure positive or negative result of decoding obtained.

There are three modes in the above process: mode of prompt exchange of data with simultaneous filling-in a cognitive map of decoder, mode of training and preliminary mode of filling-in a cognitive map of decoder from the system of peripheral computing devices.

In the first case, no essential difference from classical scheme is observed in decoder's functioning, however, the results of processing matrices $\mathbf{G}_{\mathbf{p}}^{\mathbf{s}}$ are entered into a decoder's cognitive map.

In the second case, with no immediate functioning decoder artificially generates stochastic sequences V_{av}. If vectors V_p didn't appear when algorithm was implemented previously, new data are entered into a decoder's cognitive map.

In the third case, decoder's cognitive map is made using peripheral computing devices and is entered into decoder's memory when it is implemented in the receiver processing unit. There is no future need for taking more complex computing steps 6-9 of classic algorithm. Cognitive decoder map enables to substantially reduce time period for computing process of decoding and speed up their processing that facilitates retention of capacity of WSN off-line elements.

Decoder cognitive map principle

Cognitive principles applied in telecommunication technologies are considered in works [12, 13]. Cognitive model of technical system functioning is based on a procedure for training, which suggests that various external environment factors and their respective attributes would develop due to reaction of system sensors (sensor plane) to external conditions. Generally speaking, a consecutive processing of sensor information takes place with its further recompilation and acceptance of "successful" hypotheses and rejection of "ineffectual" alternatives thereof based on successful attempts of their use [14]. In this connection, well-known principles of constructing adaptive systems suggest that these functions are partially fulfilled in a reduced form since adaptation constitutes only an element of a perceptual cycle involving scheme of training like a major element of cognitive structure. Therefore, introducing adaptive system of operators for comparing current situation with preset thresholds into algorithm may be interpreted as a solution to the problem according to the externally specified pattern. The above steps are covered in cognitive systems more extensively and interpreted as capability for differentiating external factors of functional disadaptation that result in failures of technical system operation as a whole.

Analysis of state-of-the-art methods for creating devices of noise-immune coding shows that an overwhelming majority of them are basically created for particular systems of communication with previously and rather fully studied statistics of errors flow as an external training element. However, such opportunity arises when using rather effective PD algorithms, since for data tuple it is possible to indicate a finite set of permutation scenarios of combination symbols, find and save for them prepared solutions that may be stored in decoder's memory, without computing them again when certain permutations are repeated [6, 7, 8]. Computation and selection of SRS are important components of PD being a basis of a procedure for sorting symbols of the received combination and organizing their further permutations, and thus, shall properly correspond to the current state of the communication channel used. Both application of complex types of modulation, and logistics of recovering data storages raise an issue about utilizing PD algorithms for non-binary redundant codes [15]. Some information about this approach is available from work [17, 18]. At the same time, it's not necessarily clear from the known sources of information, how to apply cognitive procedures for searching most probable vectors of interleaved non-binary codes, how, using properties of permutation matrices, to reduce volume of stored data obtained due to decoder's training.

PD principle shall be examined using an example of processing combinations of Hamming code (7,4,3) with a generating matrix of the following type:

$$\mathbf{G}=\begin{pmatrix}1&0&0&0&1&0&1\\0&1&0&0&1&1&1\\0&0&1&0&1&1&0\\0&0&0&1&0&1&1\end{pmatrix}. \qquad (2)$$

Numerator of columns 1 2 3 4 5 6 7

Matrix columns shall be numbered in a canonical way from left to right using numerator of columns. Here, there is a permanent certain column of matrix $\mathbf{G}$ for each number of a numerator. Generator of data, working in the training mode, creates in a random manner sets of nonrecurrent $k=4$ columns (numbers) of matrix $\mathbf{G}$, which will coincide with the most reliable symbols of vector V_{av} during decoding at the 4th step of algorithm of decoder's current operation.

Let these sequences be denoted by z_i. There might be $\binom{n}{k}=\binom{7}{4}=35$ sequences formed for this code.Based on each such sequence z_i columns from generating matrix of code $\mathbf{G}$ are drawn, exactly corresponding to z_i taken bearing in mind numerators of columns. As a result, matrix $\mathbf{Q_{k\times k}}$ is created. If after verifying whether matrix $\mathbf{Q_{k\times k}}$ is degenerated,determinant of this matrix $\Delta \neq 0$, such tuple of numbers z_i is entered into database of positive decisions, and further matrix $\mathbf{G_p^s}$ is computed using basic algorithm, which (matrix) is also entered into database and for this code will always correspond to unique sequence z_i. If similar sequence of symbol numbers appears in the course of the decoder's current operation, no computation of matrix $\mathbf{G_p^s}$ will be required for this combination of numerators that ensures gain in time resource since matrix is drawn ready-made from data base.

With negative result when $\Delta=0$, value of sequence z_i is written to data base of negative decisions. 28 combinations (80%) meet $\Delta \neq 0$ condition and only 7 values (20%) meet $\Delta=0$ condition out of 35 various groupings of numbers for combinations of the code under study. For fast searching sequences z_i in cognitive map data base, they should be written in a canonical form. Base values of z_i according to the first condition when $\Delta \neq 0$ are given in table 1.

Table 1

Base of ranked combinations of numbers of positive decisions

1234	1236	1237	1245	1246	1256	1257
1267	1345	1346	1347	1356	1357	1457
1467	1567	2345	2347	2356	2357	2367
2456	2457	2467	3456	3467	3567	4567

Base values of z_i when $\Delta=0$ are given in table 2.

Table 2

Base of ranked combinations of negative decisions

1235	1247	1367	1456	2346	2567	3457

Bringing tables of decoder's cognitive map into a canonical form enabled to significantly reduce requirements to memory of a decoder and decrease time for searching the required element of a map. Without such a procedure, a decoder's memory will have to store $N=C_n^k \times k! \times (n-k)!$

samples of matrices $\mathbf{G_p^s}$. $N \approx 69\,kbit$ of memory will be required for the example in question, however, for Bose-Chaudhuri-Hocquenghem code (15,5,7) only $N \approx 93 \cdot 10^7$ Mbit of memory will be needed that is not quite reasonable.

Fast matrix transformations in equivalent code system

To minimize requirements to the volume of memory, quite effective method for calculating various matrices $\mathbf{G_p^s}$ as per a certain reference standard was found. Let only one sample of some reference standard matrix $\mathbf{G}_{Z_i}$ .correspond to each ordered set Z_i from table 1. Since $\Delta \neq 0$ is defined for these sets, any permutations of matrix $\mathbf{Q_{k \times k}}$ columns definitely assure derivation of matrix $\mathbf{E}$. Therefore, the structure of generating matrix $\mathbf{G_p^s}$ will be defined only with elements from the remaining and ordered $(n-k)$ positions. It opens up a possibility for fast matrix transformations of equivalent codes with simple software and hardware implementation. Let set $Z_i' = 4752613$ be formed. Ordered set $Z_i = 2457$ is in the list of positive decisions. Ordered numerators of columns 136 may take up the remaining positions of permutation generating matrix. A sample of reference standard matrix G_{Z_i} is stored in decoder's memory according to formula (2)

$$\mathbf{G}_{2457136} = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{pmatrix}. \quad (3)$$

5th column in matrix (3) corresponds to numerator 1, 6th column corresponds to numerator 3, and the last column corresponds to numerator 7. General numbering of reference standard matrix rows and columns is given in Fig. 1.

$\mathbf{G}_{2457136} = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{pmatrix}$	2 4 5 7
1 3 6	

Figure 1 – Reference standard matrix sample, number 2457 136

When deriving generating matrix $\mathbf{G}_{4752613}$ for set 4752 613, permutation of rows of the last three columns of the reference standard matrix in sequence 4752 will suffice with further permutation of the obtained columns with retained sequence 136 according to sequence 613.

$$\mathbf{G}_{4752613} \Rightarrow \begin{matrix} 1 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 3 & 6 \end{matrix} \Rightarrow \begin{matrix} 0 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \\ 6 & 1 & 3 \end{matrix} \Rightarrow \mathbf{G^s}_{4752613} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 \end{pmatrix},$$

that, considering structure of matrix (2), is identical to transformation

$$\mathbf{G}_{4752613}=\begin{pmatrix}0&1&1&0&0&1&0\\0&1&1&1&1&0&0\\0&0&1&0&1&0&1\\1&1&0&0&1&0&0\end{pmatrix}=\mathbf{G}^{\mathbf{s}}_{4752613}=\begin{pmatrix}1&0&0&0&0&1&1\\0&1&0&0&1&1&1\\0&0&1&0&1&0&1\\0&0&0&1&1&1&0\end{pmatrix}.$$

Thus, complex matrix computations typical of 6-9 steps of classical algorithm are replaced with common sorting of rows and columns of a matrix for verifying appropriate sorting of the received SRS in the received code vector. Only 28 samples of generating equivalent code matrices should be stored in decoder's cognitive map under new conditions, instead of 4032 analogues thereof with no system of matrix transformations. It will require only 784 bits, and about 0.3Mbit of memory for code (15,5,7). Taking into account rational organization of memory in certain WSN devices, more economical organization of computing process is possible. If values of permutated numerators from table 2 are stored in decoder's cognitive map, possible PD may be performed since there is no such permutation in a specific implementation from the stated list.

Increased speed of processing data in the modern computing devices and plenty of opportunities opened up for storing data therein create new possibilities to develop ideal systems for exchanging data and provide favourable environments for improving such systems through introducing cognitive functions. General theoretical concepts of PD using elements of cognitive processing data with respect to a procedure for computing vectors of noise-immune group codes are given in works [5 – 7]. The structure of PD algorithms enables to fully implement redundancy introduced into a code and effectively utilize cognitive function of decoder training in identifying pattern of a specific permutation using such data for fast drawing generating matrix of equivalent code that corresponds to this pattern from a decoder's memory. PD functions are most fully fulfilled in a strict model of erasure communication channel, for example, while restoring storages of data, when exact parameters of the storage lost are known. During channel processing of redundant-code protected data, soft methods of processing thereof, quite well designed for binary codes, are in use on a real-time basis [1,7]. However, processing of non-binary symbols and computing reliable SRS values for them remains relevant so far.

Volume of cognitive map can be considerably reduced, because data contained in tables 1 and 2 are of cyclical nature. For example, table 2 might contain 1235 as a source number. With a cyclic shift, this number is followed by 2346, and 3457, 1456, 2567, 1367, 1247, and 1235, subsequently. The last number indicates that the cycle is repeated. Similarly, four cycles might be specified for table 1 numbers. It suggests that the volume of data on a decoder's cognitive map can be reduced to only five combinations.

Methods for making soft decisions based on erasure communication channel

PD is characterized with a need for transforming generating matrix $\mathbf{G}$ of the main redundant code into permutation matrix of equivalent code $\mathbf{G}_{\mathrm{p}}$. This transformation is made according to the structure of permutation matrix $\mathbf{K}$ [1, 15]. Matrix $\mathbf{K}$ is formed through SRS sorting in a descending order of their absolute values. It is comfortable to present SRS as an integer expression, that in terms of energy code efficiency (EGC) falls slightly short (only 0.2 dB) of real EGC assessments, however, facilitating an increase in a speed of computing process [6, 15, 18, 19]. Analytical form for calculating SRS integer expressions using binary type modulations is as follows:

$$\lambda_i(z)=\left\lfloor\left|\frac{\lambda_{max}}{\rho M_z}\times z\right|\right\rfloor, \tag{3}$$

where λ_{max} – maximum value of SRS adopted for this system, $M_z=\pm\sqrt{E_b}$ – mathematical expectation of values of the received signals, ρ – erase interval (usually $0\le\rho<1$), and z – value of received signal having an impact of interfering factors in mind [9]. It is comfortable to assess reliability of non-binary symbol in field $GF(2^n)$ by cumulative value λ_i, where $i=\overline{1,n}$, in likelihood factor $K_{cr} = \sum_{i=1}^{n}\lambda_i \Big/ \sum_{i=1}^{n}\lambda_{max}$ format; here $0 \le K_{cr} \le 1$. Rate F of various parameter K_{cr} assessments when using various degrees of binary field extension n is different. Analysis of the results of simulation modelling of independent error flow channel for various signal-noise ratios E_b/N_0 has shown that rate F for values K_{cr} in terms of various assessments strongly depends on parameter E_b/N_0 and is not monotonous that causes difficulties when identifying the best assessments. Hence, an application of a cognitive procedure is made expedient for defining a likelihood coefficient according to histograms known to decoder and typical for various values of signal-noise ratios. To collect and replenish statistical data about changes in parameter K_{cr} is a problem that relates to a cognitive level of the first data processing stage for a specific direction of communication targeted at performing best assessments of PD system in a flexible manner. Therefore, it is rational to enter K_{cr} values distribution histograms into a special decoder's cognitive map to precisely determine the best SRS values.

Permutation decoding of non-binary codes

A procedure for permutation of non-binary code matrix $\mathbf{G}$ columns based on chosen K_{cr} do not present any computing challenges with respect to binary codes, however, it is more difficult to take the next step of transforming matrix $\mathbf{G}_{\mathrm{p}}$ into a systematic form, since it requires computing an inverse matrix, matrix of minors and finding an inverse matrix based thereupon with further transformation of $\mathbf{G}_{\mathrm{p}} \Rightarrow \mathbf{G}_{\mathrm{s}}$ type. Such computations for each received combination make permutation decoding extremely ineffective when addressing problems of enhancing data adequacy in the real time control systems [15]. To reduce complexity of $\mathbf{G}_{\mathrm{p}} \Rightarrow \mathbf{G}_{\mathrm{s}}$ type computing process in many ways, it is suggested that a system of reference standard matrices $\mathbf{G}_{\mathrm{eqi}}$ would be created, each of which will correspond to *i*-th set of permutations of the numbers of reliable symbols of the received code vectors. Transformation of matrix $\mathbf{G}_{\mathrm{eqi}}$ sample for any other permutation out of the respective set of numbers $\mathbf{G}_{\mathrm{eqi}}$ shall be made using method of fast matrix transformations (FMT), generally described below.

Specified transformations are linear, however, not all permutations of symbols of code combinations for binary block codes produce an equivalent code. Such codes are not decodable to the maximum, therefore, some permutations do not provide nondegeneracy of matrices $\mathbf{G}_{\mathrm{p}}$. It doesn't concern system of non-binary codes. In any case, when reliable symbols are drawn from the received vector k, numbers of these symbols may be distributed as $k!$ permutations. The rest $(n-k)$ numbers may similarly be distributed as $(n-k)!$ permutations. All possible combinations of permutations out of $k!$ and permutations out of $(n-k)!$ Constitute a set of equivalent codes for a certain group of symbols. There will totally be $\binom{n}{k}$ groups in the code to be used, hence, application of a system of reference standard matrices together with FMT reduces the volume of decoder's memory by $k! \times (n-k)!$ times.

Let non-binary Reed-Solomon code with (7,3,5) parameters be used in the data exchange system. Matrix $\mathbf{G}$ of this code in a systematic form is as follows

$$\mathbf{G} = \begin{Vmatrix} \alpha^0 & 0 & 0 & \alpha^4 & \alpha^0 & \alpha^4 & \alpha^5 \\ 0 & \alpha^0 & 0 & \alpha^2 & \alpha^0 & \alpha^6 & \alpha^6 \\ 0 & 0 & \alpha^0 & \alpha^3 & \alpha^0 & \alpha^1 & \alpha^3 \end{Vmatrix}, \qquad (4)$$

from now on α – a primitive element of field $GF(2^3)$; matrix columns are numerated from left to right in a standard way.

Let symbols with numbers (2 4 5) be reliable symbols in some received code vector of RS code, and less reliable symbols are arranged in a sequence of (6 7 1 3) type in a descending order of K_{cr} values. Then, it follows from expression (2)

$$\mathbf{G}_{\text{p}} = \begin{Vmatrix} 0 & \alpha^4 & \alpha^0 & \alpha^4 & \alpha^5 & \alpha^0 & 0 \\ \alpha^0 & \alpha^2 & \alpha^0 & \alpha^6 & \alpha^6 & 0 & 0 \\ 0 & \alpha^3 & \alpha^0 & \alpha^1 & \alpha^3 & 0 & \alpha^0 \end{Vmatrix}. \quad (5)$$

To make transformation of $\mathbf{G}_{\text{p}} \Rightarrow \mathbf{G}_{\text{s}}$ type, a pattern of key matrix $\mathbf{Q}$ of $k \times k$ dimension is sorted out in expression (5) that includes the first k columns. Then, an inverse matrix for $\mathbf{Q}$ is actually a key matrix, definitely indicating what actions with matrix $\mathbf{G}_{\text{p}}$ rows need to be taken to transform it into a systematic form since $\mathbf{Q} \times \mathbf{Q}^{-1} = \mathbf{E}$ $\mathbf{Q} \times Q^{-1} = \mathbf{E}$. For the example in question $\mathbf{Q}_{3\times3} = \begin{Vmatrix} 0 & \alpha^4 & \alpha^0 \\ \alpha^0 & \alpha^2 & \alpha^0 \\ 0 & \alpha^3 & \alpha^0 \end{Vmatrix}$, and determinant of this matrix $det_{\mathbf{Q}} = \alpha^6$ and inverse matrix shall be of $\mathbf{Q}^{-1}_{3\times3} = \begin{Vmatrix} \alpha^6 & \alpha^0 & \alpha^2 \\ \alpha^1 & 0 & \alpha^1 \\ \alpha^4 & 0 & \alpha^5 \end{Vmatrix}$ form. $\mathbf{Q} \times \mathbf{Q}^{-1} = \mathbf{E}$ verification confirms that a unit matrix is derived, hence, the structure of matrix $\mathbf{Q}^{-1}_{3\times3}$, is a key for transformation $\mathbf{G}_{\text{p}} \Rightarrow \mathbf{G}_{\text{s}}$ [5].

To obtain the first row of matrix in a procedure $\mathbf{G}_{\text{p}} \Rightarrow \mathbf{G}_{\text{s}}$, the first row of matrix $\mathbf{G}_{\text{p}}$ shall be sequentially multiplied by α^6 (element x_{11} in matrix $\mathbf{Q}^{-1}_{3\times3}$), the second row of matrix $\mathbf{G}_{\text{p}}$ shall be multiplied by α^0 (element x_{12} in matrix $\mathbf{Q}^{-1}_{3\times3}$), then, the third row in matrix $\mathbf{G}_{\text{p}}$ shall be multiplied by element α^2 and add the obtained results according to the rule of adding degrees of primitive element α in field $GF(2^3)$. Similar actions taken with other elements of the second and third rows of matrix $\mathbf{Q}^{-1}_{3\times3}$ produce permutation matrix of a code in a systematic form.

$$\mathbf{G_p} \Rightarrow \mathbf{G_s} = \begin{Vmatrix} \alpha^0 & 0 & 0 & \alpha^6 & \alpha^2 & \alpha^6 & \alpha^2 \\ 0 & \alpha^0 & 0 & \alpha^3 & \alpha^3 & \alpha^1 & \alpha^1 \\ 0 & 0 & \alpha^0 & \alpha^5 & \alpha^4 & \alpha^4 & \alpha^5 \end{Vmatrix}. \quad (6)$$

During operational processing of data, there are high chances that a set of reliable symbols of code combination of (2 4 5) type non-binary code may be repeated. To save decoder's computing resource in future, it is wise to store the calculated expression (6) in its memory and use it when making permutations of elements (2 4 5). Matrix with strictly increasing sequence of column numbers is called canonical, and the matrix as such is a reference standard one. It is comfortable in terms of fast searching of required reference standard matrix in the list of such matrices. Each reference pattern is stored in memory in a tabulated form, as shown in Fig.1, and in such a case, there is no any need for storing a systematic part of a matrix.

$$\begin{matrix} \alpha^6 & \alpha^2 & \alpha^6 & \alpha^2 & 2 \\ \alpha^3 & \alpha^3 & \alpha^1 & \alpha^1 & 4 \\ \alpha^5 & \alpha^4 & \alpha^4 & \alpha^5 & 5 \\ 6 & 7 & 1 & 3 & \end{matrix}$$

Figure 1 – Structure of reference standard matrix in a canonical form according to a system of reliable symbols

Following principles of cognitive data processing, decoder, for instance, having received a tuple of values K_{cr} in (5 2 4) form for the first k reliable symbols of the received combination and remaining $(n-k)$ less reliable symbols in (3 7 1 6) form creates matrix $\mathbf{G}_\mathrm{p}$, based on reference standard matrix structure as shown below.

$$\mathbf{G}_\mathrm{p} \Rightarrow \mathbf{G}_\mathrm{s} = \begin{Vmatrix} \alpha^0 & 0 & 0 & \alpha^5 & \alpha^4 & \alpha^4 & \alpha^5 \\ 0 & \alpha^0 & 0 & \alpha^2 & \alpha^2 & \alpha^6 & \alpha^6 \\ 0 & 0 & \alpha^0 & \alpha^1 & \alpha^3 & \alpha^1 & \alpha^3 \end{Vmatrix}. \quad (7)$$

Studies have shown that when retaining numbers of positions of reliable k and not-reliable$(n-k)$ symbols in permutations, in the first case matrix (4) rows should be permutated, in the second case permutation of the matrix columns should be made.

Organization of cognitive non-binary code decoder map

Non-binary codes in data management complexes may be used independently or as a part of product codes (cascade structures) at the external stage of decoding [4, 9]. Then error statistics needs to be included in histograms of a decoder's cognitive map at the stage of forming soft decisions.

An example of RS codes can show that permutation decoding of such codes reduces decoder's computing complexity since there are constant structures formed during the computing process of decoding typical for the whole cycle of the device operation. These structures principally involve fixed positions of polynomials of syndromes $g(x_c)$, the only polynomial of error locators $L(x)$ and a system of equations for searching values of erased positions. In total it allows to make 28-40% less arithmetical operations to obtain the final result in extended Galois field as compared to classic methods of decoding [3, 4, 9]. Application of cognitive procedures brings extra advantage in minimizing computing complexity. It was shown above that the total number of reference standard matrices in permutation decoder of RS code reaches value $\binom{n}{k}$. It is not considered in this statement that such codes are cyclical, however, this property has never been taken into account when forming decoder's cognitive map. It was revealed during studies that cyclic property of code combinations allows to minimize requirements to decoder's memory volume by n times. For example, for RS code PC (7, 3, 5) it will be required to use only 5 instead of 35 reference standard matrices. Key data of such combinations are presented in table 3.

Table 3
Key data of decoder's cognitive map, SRS example (7, 3, 5)

Sets of numbers of reliable symbols for RS code combinations with homogeneous generating matrices				
$\mathbf{G}_\mathrm{s}^1 = \mathbf{G}$	$\mathbf{G}_\mathrm{s}^2$	$\mathbf{G}_\mathrm{s}^3$	$\mathbf{G}_\mathrm{s}^4$	$\mathbf{G}_\mathrm{s}^5$
123	124	125	126	135
234	235	236	237	246

345	346	347	341 → 134	357
456	457	451 → 145	245	461 → 146
567	561 → 156	256	356	257
671 → 167	267	367	467	361 → 136
712 → 127	371 → 137	471 → 147	571 → 157	247

In the above table, transition in shift cycle of $X \to Y$ type means conversion of the number with the maximum value in the adopted system of symbols to the least value as per $mod(2^n - 1)$. Analysis of data shows that original generating matrix of code $\mathbf{G}$ corresponds to cyclic shifts of consecutive symbol, for example, 1 2 3. Here, it is important to ensure compliance with the two rules of transforming parent reference standard matrices.

Rule 1. For any reference standard matrices cyclical transition of position 7 to position 1 corresponds to cyclical shift of rows of a reference standard matrix bottom-up for one step. For example, expression (4) matrix computed for combination of reliable symbols with numbers (2 4 5), will exactly be equivalent to matrices of $\mathbf{G}_s^4$ type for combinations of numbers of (3 5 6) and (4 6 7) type symbols. When transitioning through position 7, expression (4) for numbers (1 5 7) takes the following form

$$\mathbf{G_S} = \begin{Vmatrix} \alpha^0 & 0 & 0 & \alpha^5 & \alpha^4 & \alpha^4 & \alpha^5 \\ 0 & \alpha^0 & 0 & \alpha^6 & \alpha^2 & \alpha^6 & \alpha^2 \\ 0 & 0 & \alpha^0 & \alpha^3 & \alpha^3 & \alpha^1 & \alpha^1 \end{Vmatrix}. \quad (8)$$

Rule 2. Difference between maximum value of bound on the right and bound on the left defines the number of shifts of columns in a reference standard matrix towards selected direction of a cycle. For example, when transitioning from set (3 4 7) to the set of bounds (1 4 5), which has two ones of difference between bounds 7 and 5, it is necessary to shift columns of parent matrix $\mathbf{G}_s^3$ towards cycle two steps to the right and observe rule 1, as shown below.

Matrix for a set of bounds (3 4 7):

$$\mathbf{G_S} = \begin{Vmatrix} \alpha^0 & 0 & 0 & \alpha^2 & \alpha^2 & \alpha^0 & \alpha^6 \\ 0 & \alpha^0 & 0 & \alpha^5 & \alpha^4 & \alpha^0 & \alpha^5 \\ 0 & 0 & \alpha^0 & \alpha^1 & \alpha^3 & \alpha^0 & \alpha^3 \end{Vmatrix},$$

for set (1 4 5) it takes a form as follows:

$$\mathbf{G_S} = \begin{Vmatrix} \alpha^0 & 0 & 0 & \alpha^0 & \alpha^3 & \alpha^1 & \alpha^3 \\ 0 & \alpha^0 & 0 & \alpha^0 & \alpha^6 & \alpha^2 & \alpha^2 \\ 0 & 0 & \alpha^0 & \alpha^0 & \alpha^5 & \alpha^5 & \alpha^4 \end{Vmatrix}.$$

The rules stated are required to regulate decoder’s cognitive map in conditions of limitations on volume of its memory, and for fast searching of the required reference standard matrices it is advisable to place their numbers in lexicographical order.

Permutation decoding in a system of storing and restoring data

Actual tendency for constant and intense growth of generated and processed information volumes dictates a need for organizing long-term storage of data through rational use of network resources. To perform the above task, various devices for storing data are utilized. Major requirements to data storages involve: volume suitable to place user data, accessibility of data, reliability of their storing, and systems of effective restoration of data in case of losing certain storages.

Buildup of volume suitable for storing data, and improving their accessibility for end-user are achieved through integrating certain information storing devices into systems for storing data (SSD), and distributed systems for storing data (DSSD) as their particular case. To ensure guaranteed reliability of storage, SSD use both newly developed technologies for storing devices, and various methods for redundant storing based on mechanisms of correcting coding. When SSD scales are continually on the rise, an acute problem of transporting large volumes of data is raised between topologically distant elements of a particular system for storing. It is necessary to carry out such a procedure in cases of partial damage or total loss of the entire devices for storing data with further restoration of their content in memory of newly arrived storing devices. Solving the problem is mostly relevant in systems with DSSD, where distances between specific devices for storing might be quite large.

Computation of code vectors in extended Galois fields with a specified degree of extension definitely increases complexity of implementing PD procedure, however, if applied in data restoration systems, it has a number of advantages, advisable to be utilized in the subject area in question. Classical algorithm for decoding RS codes when correcting random errors is usually performed in three steps [20-23]. The first stage using Berlekamp-Massey algorithm (BMA) involves searching error locators, the second uses Chien procedure for computing polynomial of syndrome $S(x)$ and polynomial of error locators $L(x)$ and its derivative, and the last stage involves regeneration of received vector [4], using the product of the above polynomials and error locator polynomial derivative based on Forney algorithm. When correcting channel errors, the stated parameters are transformed while processing each received vector of RS code. If lost data storage is restored using classical algorithm, there is no need for BMA (position of lost storage is always known), hence, value of polynomial $L(x)$ needs to be computed once; however, polynomial $S(x)$ has to be determined for each block of data, received from backing stores. The major drawback of such approach lies in possible distortion of data coming through network resources into data restoration center. Impact of this factor puts in question ignoring BMA that is rather complex since there are many conditional operators in the procedure for choosing polynomial of error locators.

Then, a number of data storing devices in the distributed system of storing data may have data presented in table 3.

Table 3
Distribution of data in storages

ds_1	ds_2	ds_3	ds_4	ds_5	ds_6	ds_7
α^1	α^2	α^3	α^2	α^6	α^3	α^1
α^5	α^6	α^4	α^5	α^2	α^2	α^6
α^5	α^2	α^6	α^4	α^4	α^5	α^6
....	………..	……….	………..	………..	……….	………

Here, data in storages ds_1, ds_2 and $ds_3$are presented as true, and are redundant in all other storages. Let data from storage ds_2 be lost as a result of destructive factor, and the most reliable channels for exchanging data (or data storage points topologically closest to the lost storage) when restoring information from storage ds_2will be communication directions, transmitting data from storages with numbers (1 3 5), and less reliable directions (more distant storage points) in a descending order of their reliability values are placed according to sequential order of numbers (7 2 4 6). Then, it follows from expression (4):

$$\mathbf{G_p} = \begin{Vmatrix} \alpha^0 & 0 & \alpha^0 & \alpha^5 & 0 & \alpha^4 & \alpha^4 \\ 0 & 0 & \alpha^0 & \alpha^6 & \alpha^0 & \alpha^2 & \alpha^6 \\ 0 & \alpha^0 & \alpha^0 & \alpha^3 & 0 & \alpha^3 & \alpha^1 \end{Vmatrix} \Rightarrow \mathbf{Q}_{3\times 3} = \begin{Vmatrix} \alpha^0 & 0 & \alpha^0 \\ 0 & 0 & \alpha^0 \\ 0 & \alpha^0 & \alpha^0 \end{Vmatrix}, \quad (9)$$

Using known transformations for transition towards an inverse matrix, the following will be obtained

$$\mathbf{Q}_{3\times3}^{-1} = \left\| \begin{matrix} \alpha^0 & \alpha^0 & 0 \\ 0 & \alpha^0 & \alpha^0 \\ 0 & \alpha^0 & 0 \end{matrix} \right\| . \qquad (10)$$

Matrix (10) is a key to a procedure for transforming matrix $\mathbf{G_p}$ into a systematic form. In order to do that, the first row of matrix $\mathbf{G_p}$ shall be multiplied by α^0, afterwards the second row of this matrix shall be multiplied by α^0 from the second column of the first row of matrix $\mathbf{Q}_{3\times3}$ and, since the third element of the first row of matrix $\mathbf{Q}_{3\times3}$ equals to zero, add bit-wise only the first two results as shown below

$$+\begin{cases} \alpha^0 & \alpha^0 & * & \alpha^0 & \alpha^5 & 0 & \alpha^4 & \alpha^4 \cdot \\ \alpha^0 \times & 0 & * & \alpha^0 & \alpha^6 & \alpha^0 & \alpha^2 & \alpha^6 \\ 0 & 0 & * & 0 & 0 & 0 & 0 & 0 \end{cases}$$

As a result of addition, the first row of the systematic generating matrix takes on form $\alpha^0 \quad * \quad 0 \quad \alpha^1 \quad \alpha^0 \quad \alpha^1 \quad \alpha^3$. Similar actions with the second and third rows of matrix $\mathbf{G_p}$ considering matrix $\mathbf{Q}_{3\times3}^{-1}$ configuration will produce:

$$\mathbf{G}_\mathrm{p} \Rightarrow \mathbf{G}_{\mathrm{s}1357246} \left\| \begin{matrix} \alpha^0 & 0 & 0 & \alpha^1 & \alpha^0 & \alpha^1 & \alpha^3 \\ 0 & \alpha^0 & 0 & \alpha^4 & \alpha^0 & \alpha^5 & \alpha^5 \\ 0 & 0 & \alpha^0 & \alpha^6 & \alpha^0 & \alpha^2 & \alpha^6 \end{matrix} \right\|$$

Therefore, a reference pattern of matrix is created in a canonical form for collecting information elements with numbers (1 3 5) with no regard for a unit matrix

$$\begin{matrix} \alpha^0 & \alpha^1 & \alpha^3 & \alpha^1 & 1 \\ \alpha^0 & \alpha^5 & \alpha^5 & \alpha^4 & 3 \\ \alpha^0 & \alpha^2 & \alpha^6 & \alpha^6 & 5 \\ 2 & 4 & 6 & 7 & \end{matrix} \qquad (11)$$

Using value (11), it becomes possible to obtain matrices for any permutations of row numbers (1 3 5) and column numbers (2 4 6 7). Therefore, to restore data in storage ds_2, multiplication of vectors from directions (1 3 5) by column-vector with number 2 in expression (11) will suffice. Indeed,

$$\left\| \alpha^1 \quad \alpha^3 \quad \alpha^6 \right\| \times \begin{matrix} \alpha^0 \\ \alpha^0 \\ \alpha^0 \end{matrix} = \alpha^1 + \alpha^3 + \alpha^6 = \alpha^2 \; ;$$

$$\left\| \alpha^5 \quad \alpha^4 \quad \alpha^2 \right\| \times \begin{matrix} \alpha^0 \\ \alpha^0 \\ \alpha^0 \end{matrix} = \alpha^5 + \alpha^4 + \alpha^2 = \alpha^6 \; ;$$

$$\left\| \alpha^5 \quad \alpha^6 \quad \alpha^4 \right\| \times \begin{matrix} \alpha^0 \\ \alpha^0 \\ \alpha^0 \end{matrix} = \alpha^5 + \alpha^6 + \alpha^4 = \alpha^2 .$$

Data in storage ds_2 are being restored properly. A simplicity of permutation RS code decoding becomes clear that allows to reduce complexity in implementing a receiver processing unit by excluding Chien and Forney procedure. Furthermore, in case of losing all redundant storages, their data may be restored simultaneously according to the described pattern. It is important to stress that if configuration of reliable directions of communication is not changed, value of reference standard matrix $\boldsymbol{G}_{eg}$ is computed only once.

Probabilistic characteristics of permutation decoders

Assessment of energy gain provided for by a particular error control scheme is the most important indicator for any system of exchanging data. The first part of this study is devoted to similar asymptotic assessments with no reference to the models of continuous communication channel. With regard to a channel with independent flow of errors, such assessments for classical schemes of processing data within Hamming distance were discussed in [1,4]. It is obvious that probability of error per a bit p_b is a function of signal-noise ratio, defined in analytical model by expression E_b/N_0, where $N_0 = 2\sigma^2$. Here σ^2 is a dispersion of a white Gaussian noise [4]. Then

$$p_b = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{\sqrt{E_b}} e^{-\frac{(x+\sqrt{E_b})^2}{2\sigma^2}} dx . \qquad (9)$$

Results of analytical modelling of various Hamming code decoding schemes (7,4,3) are given in Fig. 2, where preferential use of permutation decoding method is obvious.

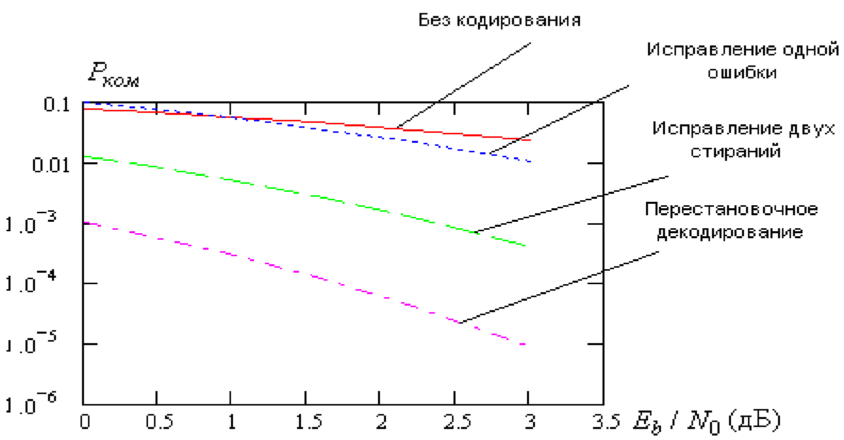

Figure 2 – Probabilities of error reception of combination depending on signal-noise ratio for Hamming code (7,4,3)

Based on characteristics presented in Fig.2, probability of error per a bit might always be calculated by formula $p_b \approx P_{comb}/n$ [1, 4]. Here, energy gain obtained in the system with Hamming code using permutation coding will amount to about 6dB that is in line with the above asymptotic estimations. Maximum effect of applying permutation decoding of binary codes becomes clear while using them within successive turbo codes as internal codes [4]. Here, probability of error registration of non-binary symbol in RS code is determined by formula

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$$P_{симPC} = \frac{1}{2^m - 1} \sum_{i=(n_2-k_2)/2}^{n_2} i \times C_{n_2}^i \times P_{ком}^i \times (1 - P_{ком})^{n_2 - i}, \qquad (10)$$

where n_2 – length of RS code vector, k_2 - number of information symbols in such code, m - a degree of extension of Galois binary field. Characteristics of various alternatives proposed to make such constructions are given in Fig. 3.

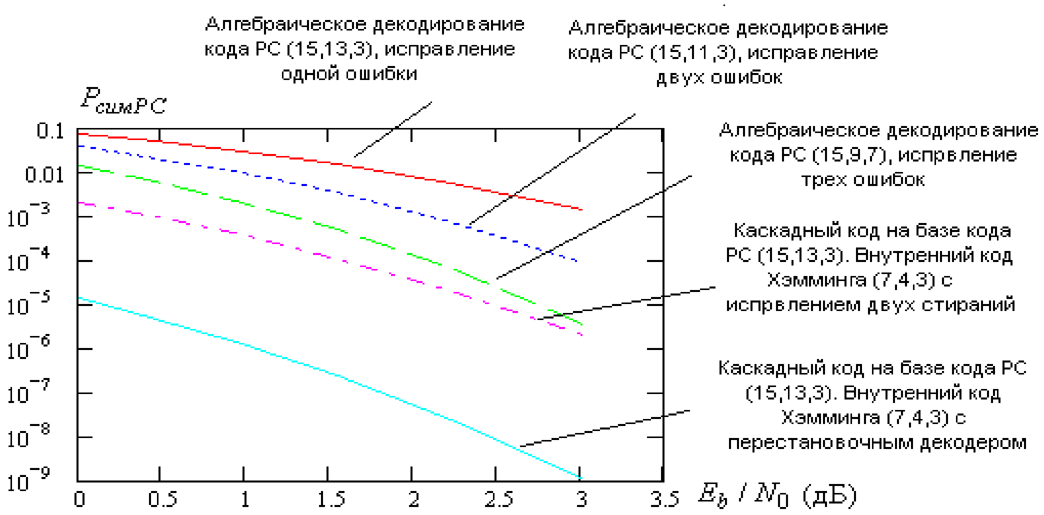

Figure 3 – Comparative assessments of distorting non-binary symbols depending on method for processing data and signal-noise ratio

Thus, probability of error per a bit is defined by formula $p_b \approx P_{symRS}/n$. Again, codes decoded by principle of permutation decoding have clear advantage.

CONCLUSION

Permutation decoding is a variety of soft decoding of block nose-immune codes. It is based on computing for each code vector transmitted via error channel an equivalent code formed through sequential ranking of soft decisions and creating bijection for the received vector, that serves as a basis for generation of an equivalent code vector. Major challenges in implementing classical permutation decoding algorithm lie in transforming matrices to identify nondegeneracy condition of permutation matrix of a code and bringing such matrix into a systematic form.

The study covers principles of matrix transformations typical of group redundant codes, being utilized to considerably reduce complexity of decoder's implementation.

Such implementation is based on creating decoder's cognitive map in a canonical form that enables to compute equivalent code pursuant to the ready-made pattern.

Using the method allows to considerably reduce probability of error reception of code vector due to correcting erases beyond Hamming distance. It allows to improve efficiency of cascade coding schemes and obtain additional energy gain in the system of exchanging data.

Application of principles for cognitive two-stage processing of data in non-binary code decoder allows to:

first, create an objective pattern of communication channel in decoder's memory in compliance with the decoder's actual parameters. It ensures justified selection of soft decisions to implement PD.

second, application of a reduced decoder's cognitive map makes implementation of decoding less complex due to using a system for fast matrix transformations in the system of generating matrices of interleaved codes.

Regularities of such transformations were found, and methods for processing combinations of non-binary codes were suggested being the most effective in a system of restoring large volumes of data in a lost storage, since here it is possible to launch a strictly erasing communication channel with the only generating matrix

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