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APPLICATION OF HIGH-PRECISION ITERATIVE TECHNIQUES TO IMPROVE THE EFFICIENCY OF ENCODING AND DECODING

Abstract: *The article discusses the methods and algorithms of high-precision iterative coding and decoding, which can improve the efficiency of error correction during decoding, finalized the basic principles of high-precision iterative code as a separate area in the field of noise-resistant coding, and obtained new results by modeling the work and the mathematical apparatus of the high-precision iterative coding system and decoding.*

Key words: *signal; code; coding; decoder; high-precision; iteration; decoding; error.*

Language: *English*

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Introduction

Currently, digital television (DTV) services are penetrating rapidly into all spheres of human activity. In information transmission systems based on digital methods, the most urgent task is to prevent signal distortion, i.e. ensuring high noise immunity. With the large-scale transition to DTV (DVB-T/T2/T4, DVB-S/S2), this task becomes even more important. Because digital television (TV) signals are an electronic form of dynamic action and their elements are transmitted on a point-to-point basis with a strictly synchronized law. Under conditions of noise intensity in the channel, changes in the properties of these elements are observed, as a result of which the structure of the transmitted useful code sequence changes and, therefore, logical “0” can be accepted as logical “1” or vice versa. The problem of increasing the noise immunity of signal transmission in ever-increasing volumes and the requirement for the quality of received television and multimedia information by users is relevant at the present stage of the development of digital equipment and technology.

At present, the theory and practice of high-precision iterative coding and decoding (HICD), which is a new achievement in coding theory, is developing at an accelerated pace. In the works [1-4, 7, 8, 12-15] the fundamental aspects of this direction are described in detail, methods and algorithms of HICD are presented. High-precision iterative coding methods are based on the parity of the processed symbols, presented in the form of a square matrix, which is added to each row and column by a verification symbol.

Figure 1 shows the implementation of the rule of parity of units in rows and columns, where in Figure 1, (*a*) serial data transmission is shown (the first is the bit on the far right).

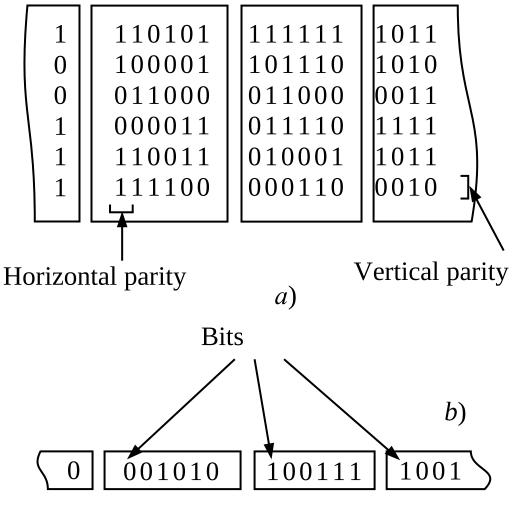
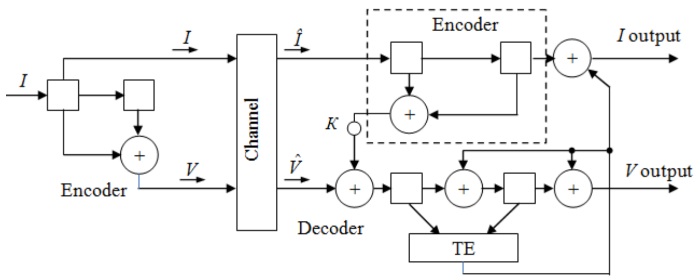


Figure 1. Parity check for serial (*a*) and parallel (*b*) the structure of the iterative code

One parity bit is added to each block (the leftmost bit in each block), giving positive parity. Figure 1, (*b*) shows a parallel structure of parity, which consists of horizontal and vertical parity in information bits.

I. Representation of a high-precision iterative encoder and decoder

Figure 2 shows the simplest coding and threshold decoding system with a code rate of r=1/2 and a minimum code distance of d_{min} = 3.



TE – Threshold element

Figure 2. A special kind of coding system that explains the new interpretation of the syndrome vector

As follows from the form of the encoder and the simplest majority decoder correcting one error in this example, this decoder includes an exact copy of the encoder, which generates its estimates of the code verification characters from the received from the channel, possibly informational code symbols with errors. These symbols appear at point K of the decoder and then, after addition on the half-adder with the test symbols $\hat{V}$ received from the channel, they form the symbols of the syndrome vector S, which depends only on the channel error vector. These symbols then arrive at the threshold element of the decoder from the syndrome register (Figure 2). On the presented coding and threshold decoding scheme, you can find a simple way to organize the correct optimization procedure, i.e. finding the best possible decoding solution. The constructive addition comes from the fact that in the register of the decoder syndrome there is a difference in the test characters between the vector $Q=[\hat{I},\hat{V}]$ received with distortions from the channel and such a code word A_r, the information symbols of which coincide with the information part of the vector Q received from the channel. The complete difference between the codeword - the current hypothesis-decision of decoder A_i about the transmitted codeword and the received noisy vector Q will be in such a modified majority type decoder, where another vector will be added to the threshold decoder, which should always correspond to the difference between the received vector Q and A_i - the current hypothesis of the decoder for information symbols. Such a decoder will contain the current value of the total difference and, therefore, the total distance between the decision of the decoder and the received vector. This distance should be sought to reduce to the minimum possible, which will correspond to the decision of the optimal decoder (OD).

2.1 Previous (old) decoders

Today, specialists and experts believe that many previously created devices for the implementation of error-correcting coding and decoding are methodically outdated due to the increasing requirements for noise-suppressing codecs and systems in the field of ensuring high noise immunity and efficiency. Specialists mention obsolete ones because these existing methods and algorithms have become vulnerable to large interference, unable to work in the field of high noise immunity, unresponsive to new challenges in the field of science and technology of noise-resistant coding.

2.1.1. Threshold decoders (TD)

In order to optimize the error-correcting decoding (EDc) problem, the threshold decoding algorithm proposed by Massey [5] is implemented. A threshold decoder is one of the simplest error correction algorithms, applicable to majority decoded codes. This method can be used to decode both binary and non-binary codes.

The schemes of a noise-resistant encoder and a threshold decoder of a convolutional self-orthogonal code (CSOC) with a code distance of d=5, a code rate of r=1/2, a code restriction length of n_A=13, and a generating polynomial are shown in Figure 3 *a* and *b*.

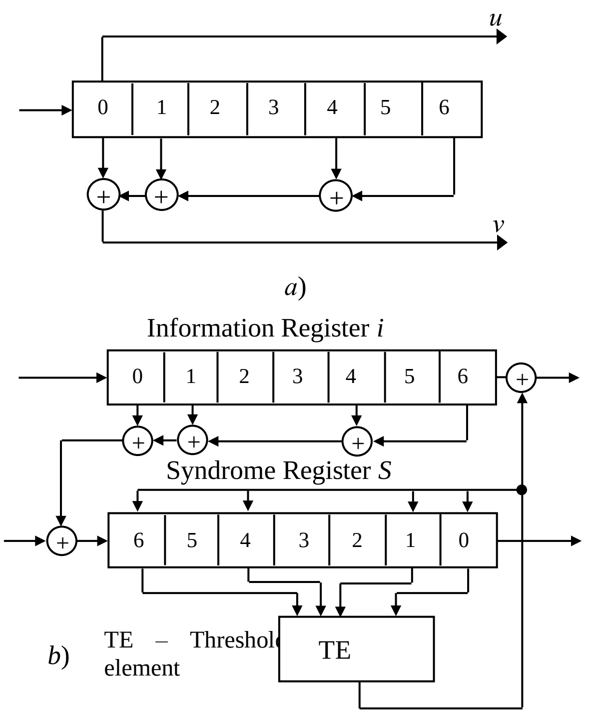


Figure 3. Scheme of error-correcting encoder (*a*) and TD (*b*) convolutional self-orthogonal code

The disadvantages of threshold decoding. This threshold decoding method has a weak correcting ability, which requires decoder optimization to improve the performance of both probability-energy characteristics (PECh) and information sequence processing.

2.1.2. Multithreshold decoders (MTD)

From the point of view of design difficulties of threshold decoding, taking into account its further improvement, a multithreshold decoding algorithm was developed. As was the case with threshold decoders, this algorithm also works on the basis of iterative decoding [10, 12, 13].

The disadvantages of multithreshold decoding. Figure 4 shows the structural diagram of the MTD (TD), consisting of two iterations. The multithreshold decoding method can be used to decode convolutional self-orthogonal codes, majority block codes, and cascading codes.

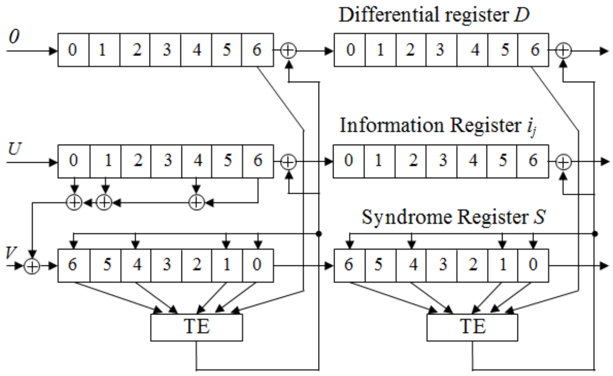


Figure 4. Structural diagram of the MTD convolutional SOC with *r*=1/2, *d*=5 and n_A=13 for two iterations of decoding

For example, suppose that the output of the first MTD (TD) (Figure 4) received a slightly improved sequence at the first attempt to decode. Then, if there are no errors in the information sequence after the first MTD (TD), then a second decoder is not needed. But when an error occurs on the output of the first MTD (TD), which is usually the beginning of a typical error packet for this MTD (TD), it turns out that the second decoder, which accurately repeats the scheme of the first and is configured to correct only random errors, most likely will not fix this package. Therefore, it is not needed in this case either.

But the main drawback of this algorithm, like turbo codes, is the relatively high decoding complexity and a large delay, which makes it inefficient and inconvenient for some applications.

II. New high-precision iterative decoder

Here we need an algorithm that corrects not only random errors, but also effectively corrects system errors associated with the design characteristics of the codes used. Therefore, with the work on a multi-threshold decoder from the point of view of optimizing the processing of information and test characters (bits), while also expanding the space of the element base and methods of syndromic error detection, an algorithm for high-precision iterative decoding (HIDk) and a **high-precision iterative decoder** (HID) operating on the basis of this algorithm are developed. Figure 5 shows the structure of the HID, taking into account the information symbols stored in the difference register.

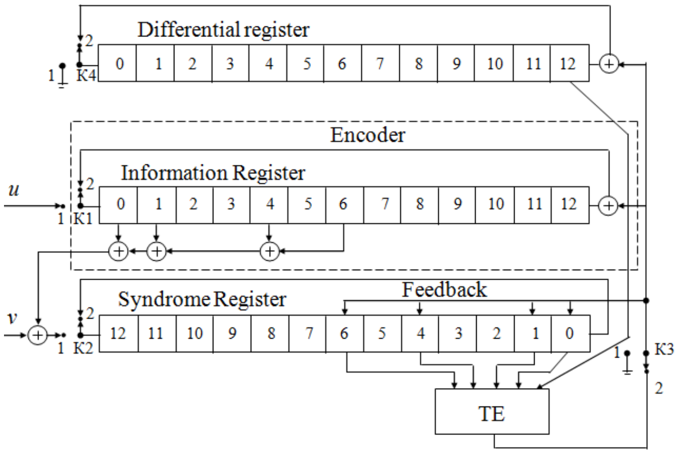


Figure 5. High-precision iterative decoder HICC with *r*=1/2, *d*=5, *n*=26 and $g(x)=1+x+x^4+x^6$. The upper inputs of the cells 0, 1, 4 and 6 of the register of the syndrome are assumed to be inverting

For effective and accurate coupling of the first and second decoder (Figure 4) for the sequential reception of code signals for maximum detection and correction of symbolic errors, high-precision iterative decoding methods with feedbacks are applied, which work on the basis of horizontal and vertical check for the parity of bits in their transmission and reception .

For this, the development of high-precision iterative algorithms for error-correcting decoding of block and convolutional codes using MTD-based repeated decoding schemes is important and relevant.

Using high-precision iterative codes during operation, the MTD turns into a high-precision iterative decoder, which differs from it only in the use of a new algorithm, which is based on the syndromic method for determining errors and posterior solutions.

A comparison of the scheme of a high-precision iterative decoder (HID, Figure 5) with the scheme of a threshold decoder (TD, Figure 3, *b*) shows that they differ only in the presence of a difference register, i.e. when HID works, in case of its software implementation, only one addition operation is added when calculating the sum on the TE and one addition operation modulo 2 (or inversion) if necessary, correct the information symbol.

Thus, the number of N_{HID} operations required to decode a single information bit is approximately equal to:

$$N_{HID} \approx I(d+2)+d-1 \approx (I+2)(d+2), \quad (1)$$

where I is the number of decoding iterations, and the term $d-1$ corresponds to the calculation of the syndrome, performed only at the first decoding iteration.

You can notice that in most cases, with a slight loss in efficiency (about 0,1 dB), it is possible to reduce the total number of operations to the value:

$$N_{HID} \approx 4d+3I \quad (2)$$

In the case of hardware implementation of the HID of an iterative block code, the speed of its operation V_{HID} is also determined by the speed of data advancement in the shift registers V_R, i.e.:

$$V_{HID} \approx \frac{k_0 V_R}{I} \quad (3)$$

where k_0 is the number of information branches.

A HID of self-orthogonal, convolutional, and block codes [1, 2, 4] is the development of the simplest multi-threshold decoder (threshold decoder) Massey and allows you to decode very long codes with a linear execution complexity. The basis of HID operation is iterative decoding, which allows you to come close to solving the optimal decoder in a fairly wide range of code rates and noise levels in the channel.

At the same time, HID retains the simplicity and speed of a conventional multithreshold (threshold) decoder, which makes it very effective and in demand for use in existing and newly created DTV systems. HID can be used for decoding high-precision iterative convolutional and block codes (HICC and HIBC), also convolutional SOCs. Moreover, as in the MTD structure, a high-precision iterative decoder will consist of several decoding blocks connected in series. The view presented in Figure 5 contains only one iteration of decoding. But it can easily be converted into a view with a large number of iterations by simply adding a few more decoding units, the structural diagram of which completely coincides with the first decoding unit.

The main decoding step is that for an arbitrary symbol u_j, the likelihood function L_j is calculated, depending on the related checks and the *j*-th element of the vector.

$$\overline{D} : L_j = \sum_{\{j_k\}} S_{j_k} + d_j . \quad (4)$$

The total number of terms in equation (4) is equal to the minimum code distance *d*.

If $L_j > T$, where $T=(d-1)/2$ is the threshold value, then the symbol u_j, all checks $\{S_{j_k}\}$ and the symbol d_j are inverted, after which another symbol is selected u_m, $m \neq j$, the sum L_m is calculated again for it, and this continues.

If $L_j \le T$, then we immediately go to the next symbol u_m.

III. High-precision iterative code as a new type of error-correcting code

Existing schemes for re-decoding based on TD and MTD have low efficiency due to strong grouping, i.e. error grouping in a threshold decoder. Error grouping is manifested by the incorrect operation of the threshold decoder, which consists of two parts due to the inability to timely accurately determine the error in the code sequence by the first or intermediate decoder.

Therefore, with the help of corrective iterative codes and with the use of horizontal and vertical parity, the first decoder, which is shown in Figure 4, should generate a highly accurate diagnosis of the presence of even or odd errors in the code sequence, for their further correction on the second or *n*-th decoder. It is here that we come to the main essence and concept of high-precision iterative code. Iterative code that meets these criteria, i.e. having the property (ability) of developing high-precision diagnostics for efficient interconnection of decoders, is called a **high-precision iterative code** (HIC). In high-precision iterative decoding, the process of correcting and correcting errors in a code sequence is carried out by successive iterations (approximations), which, depending on the number of iterations in each cycle, do not change the established (channel) parameters of digital signals. When some channel parameters are held in each separate iteration, the probability of a symbolic or bit error decreases to such a level of values that depends on the applied EDc algorithm. For example, with a value of E_b/N_0=6,4 dB, with an average probability of character distortion in the channel
$p=10^{-3}$, using a convolutional code with a hard decision in the decoder: in the first iteration, the probability of a bit error is $P_B=3{,}2\cdot10^{-2}$; in the 2nd iteration, $P_B=7{,}6\cdot10^{-3}$; in the 3rd iteration, $P_B=4{,}9\cdot10^{-4}$; in the 4th iteration, $P_B=9{,}2\cdot10^{-5}$, etc.

High-precision iterative codes attached to information symbols, passing through the shift registers and adders modulo 2, work in the form of a square matrix and should effectively associate information symbols not only of this block, but also with the blocks of the previous and next sequences. In this case, the iterative code should work in the exact transmission mode to the second or *n*-th decoder of the result of the parity check and transmit the complete analyzed diagnostic information on these checks about the status of the transmitted code block.

It has been stated above that the decoder can only detect that an odd number of errors are present in the code symbol, the decoder can determine by the horizontal and vertical parity checks whether there is an error (the sum modulo 2 is 1) or not (the sum modulo 2 is 0) Also, if the error enters an even number of bits, then the parity check will show an example of an undetected error. **In order to effectively evaluate and correct such cases, some changes have been made to the HIC mathematical apparatus**, which takes into account the invisibility of errors.

For identical, equal-energy orthogonal signals (EEOS), the probability of error in the P_E code symbol can be estimated from above, as

$$P_E(M) \le (M-1)Q\left(\sqrt{\frac{E_s}{N_0}}\right), \quad (5)$$

where the size of the set of codewords M is 2^k, k is the number of information bits in the codeword.

We assume that errors in all digits are equally probable and appear independently, then we can record the probability of occurrence of j errors in a block of n characters:

$$P(j,n) = \binom{n}{j} p^j (1-p)^{n-j} \quad (6)$$

here p is the probability of obtaining a channel symbol with an error, and after

$$\binom{n}{j} = \left(\frac{n!}{j!(n-j)!}\right) \quad (7)$$

denotes the number of different ways of choosing from n bits j erroneous. For a high-precision iterative code with one parity bit, the probability of an undetected error P_{nd} in a block of n bits is calculated as follows:

$$P_{nd} = \sum_{j=1}^{\substack{n/2(\text{when } n \text{ is even}) \\ (n-1)/2(\text{when } n \text{ is odd})}} \binom{n}{2j} p^{2j} (1-p)^{n-2j} \quad (8)$$

Based on the probability of j errors in a block of n characters written in (5), we can write down the error probability of a message for a high-precision iterative code that can correct error models consisting of t or less error bits:

$$P_M = \frac{1}{n}\sum_{j=t+1}^{n} j\binom{n}{j} p^{2j}(1-p)^{n-2j} \quad (9)$$

HIC consists of two types of codes – high-precision iterative block code (HIBC) and high-precision iterative convolutional code (HICC), which fully assign to themselves all the design and organizational properties and characteristics of block and convolutional error-correcting coding (ECd) codes.

High-precision iterative codes are generated by parallel cascading of two or more components of systematic HIBC and HIBC. HIC is an improved type of conventional cascade and turbo code, which, when forming an estimate of information bits, takes into account the invisibility of errors during horizontal and vertical control of the parity of bits in the decoder [6-9, 12-15]. In [9, 11-15], as a new type of error-correcting codes, the basic properties of HICs are determined, including HIBC and HIBC.

IV. Method for estimating the error probability of a high-precision iterative decoder

Using the methodology for estimating the probability of MTD error when operating in a binary symmetric channel (BSC) and in a channel with additive white Gaussian noise (AWGN), we use this technique to estimate and determine the probability of a reception error when using HIDs. In the calculations, we assume that at the last iteration of decoding, the probability of HID error P_{HID} is equal to the probability of error of the optimal decoder.

So, frequent events are as follows:

1. There are three errors in the Hamming code block. The probability of this event can be estimated as

$$P_1 = C_{N_2}^3 P_{\text{HID}}^3 (1-P_{\text{HID}})^{N_2-3} \quad (10)$$

Here, P_{HID} is the probability of the error of the type of internal HID. For BSC

$$P_{\text{HID}} \approx \sum_{i=\frac{d_1+1}{2}}^{d_1} C_{d_1}^i p_0^i (1-p_0)^{d_1-i}, \quad (11)$$

where p_0 is the probability of error in the BSC, d_1 is the HID code distance. For a channel with AWGN and binary phase shift keying (BPSK-2)

$$P_{\text{HID}} \approx Q\left(\sqrt{2Rd_1\frac{E_b}{N_0}}\right), \quad (12)$$

where $Q(x)$ is the error integral, R is the code rate of the composite HID.

2. There are two errors in the Hamming code block, and among the correct bits there are two errors whose total reliability is less than the reliability of two

error bits. The probability of such an event is estimated as

$$P_2 = C_n^2 P_{\text{HID}}^2 (1 - P_{\text{HID}})^{n-2} \sum_{i_1=T}^{J} \sum_{i_2=T}^{J} \left[C_J^{i_1} C_J^{i_2} p_0^{i_1+i_2} (1 - p_0)^{2J-i_1-i_2} P_{2x}(i_1 + i_2) \right], \quad (13)$$

where $J=d_1-1$ is the number of checks of the internal code relative to the information bit; $T=(d_1+1)/2$ – the threshold value on TE HID (Figure 5); $P_{2x}(k)$ is the probability that there are more errors in the check bits for two correct information bits than in $2d_1-k$, defined as

$$P_{2x}(k) = C_{N_2-2}^2 \sum_{i_3=0}^{T-1} \sum_{i_4=0}^{T-1} f(i_3, i_4, k), \quad (14)$$

where the function $f(i, k)$ is defined as follows:

$$f(i_3, i_4, k) = \begin{cases} 0, & \text{if } i_3 + i_4 \le 2d_1 - k; \\ C_J^{i_3} C_J^{i_4} p_0^{i_3+i_4} (1 - p_0)^{2d_1 - i_3 - i_4} & \text{otherwise} \end{cases} \quad (15)$$

Other events, due to the low probability of the P_{HID} error in the field of effective operation of the HID, can be neglected. As a result of the occurrence of the listed events, 4 errors will appear in the Hamming code block of N_2 bits. Then the lower bound for the decoding error probability of the entire compositional scheme is defined as

$$P_b^{(L)} = 4 \cdot \frac{P_1 + P_2}{N}. \quad (16)$$

V. Development of High-Precision Iterative Coding and Decoding Algorithms

In order to specify the structure of a high-precision iterative encoder, it is necessary to indicate which bits of the shift register are associated with each of the adders modulo 2. The connections of the j-th adder modulo 2 are described by setting the j-th generating sequence. The basis of the HICC coding is a sequence of characters that are not divided into separate code combinations. Denoting information symbols by a_i, and correcting by b_i, we get the main expression of the sequence of characters of the HICC:

$$a_1 b_1 a_2 b_2 a_3 b_3 \ldots \ldots a_k b_k a_{k+1} b_{k+1} \ldots \quad (17)$$

Information symbols are determined by the transmitted message, the input information sequence, and corrective are formed according to the following rule:

$$b_i = a_{k-S} + a_{k+S+1} \ (\text{mod } 2), \quad (18)$$

where s is an arbitrary integer called a code step.

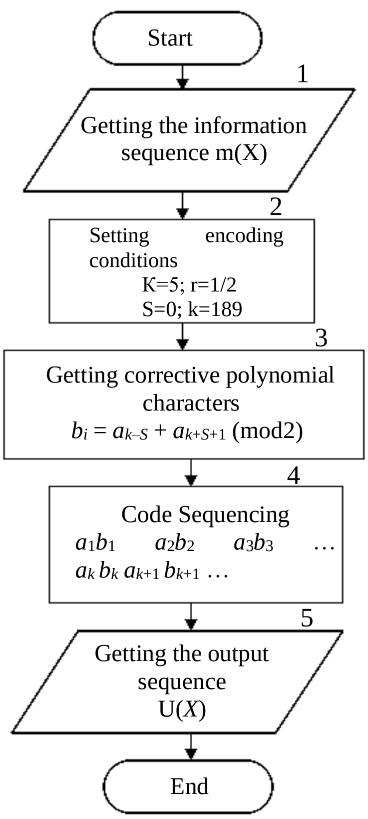


Figure 6. Encoder Algorithm HICC

It can be seen that with the erroneous reception of some correction symbol b_i, relation (18) in the accepted sequence will not be satisfied for $i=k$. In the case of the erroneous reception of the information symbol a_i, relation (18) will not hold for two values of k, namely, for $k_1=i–s–1$ and for $k_2=i+s$. In the adopted code sequence for each b_k, the relation (18) is checked. If it was not fulfilled for two values of k ($k=k_1$ and $k=k_2$), then the informative element a_{k_1+S+1} should be replaced by the opposite.

$$k_2 – k_1 = 2s+1. \quad (19)$$

Equation (20) presents the form of high-precision iterative block codes through the parameters n, k, t and some positive number m>2.

$$(n, k) = (2^m–1, 2^m–1–2t) \quad (20)$$

here $n–k=2t$ is the number of control characters, t is the number of error bits in the character that the iterative code can correct. In this case, the generating polynomial for HIBC has the following form:

$$g(X) = g_0 + g_1X + g_2X^2 + \ldots + g_{2t-1}X^{2t-1} + X^{2t} \quad (21)$$
$$X^{n-k}\, m(X)=q(X)g(X) + p(X). \quad (22)$$

here $q(X)$ and $p(X)$ is the quotient and the remainder of polynomial division. As with binary encoding, the remainder will be even.

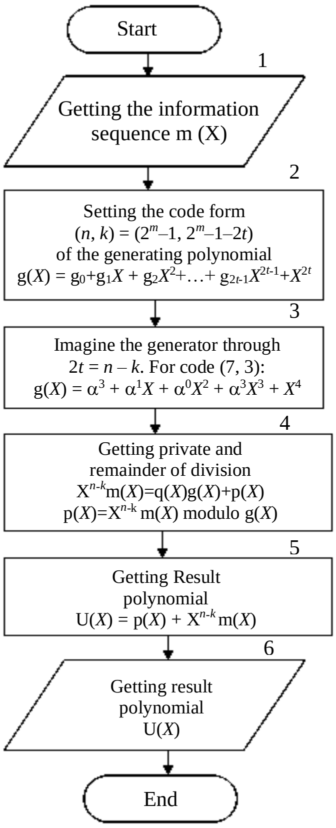


Figure 7. Encoder Algorithm HIBC

Equation (22) can be rewritten as follows:

$$p(X)=X^{n-k}m(X) \bmod g(X) \quad (23)$$

The main resulting polynomial of the codeword $U(X)$ can be rewritten as follows:

$$U(X) = p(X) + X^{n-k}\, m(X) \quad (24)$$

To fulfill this condition, the presented method implements a scheme of high-precision iterative coding by an external high-precision iterative block and convolutional code (Figure 6 and Figure 7).

Consider the decoding operations of the HIBC code (based on the Reed-Solomon block code). In this case, the received polynomial of the damaged codeword $r(X)$ is represented as the sum of the polynomial of the transmitted codeword and the polynomial of the error model, as shown below:

$$r(X) = U(X) + e(X) \quad (25)$$

The calculation of the syndrome. If r is a member of the set, then S syndrome has a value of 0. Any nonzero value of S means errors, S syndrome consists of $n–k$ characters, $\{S_i\}$ (i=1, ..., $n–k$):

$$U(X) = m(X)g(X) \quad (26)$$

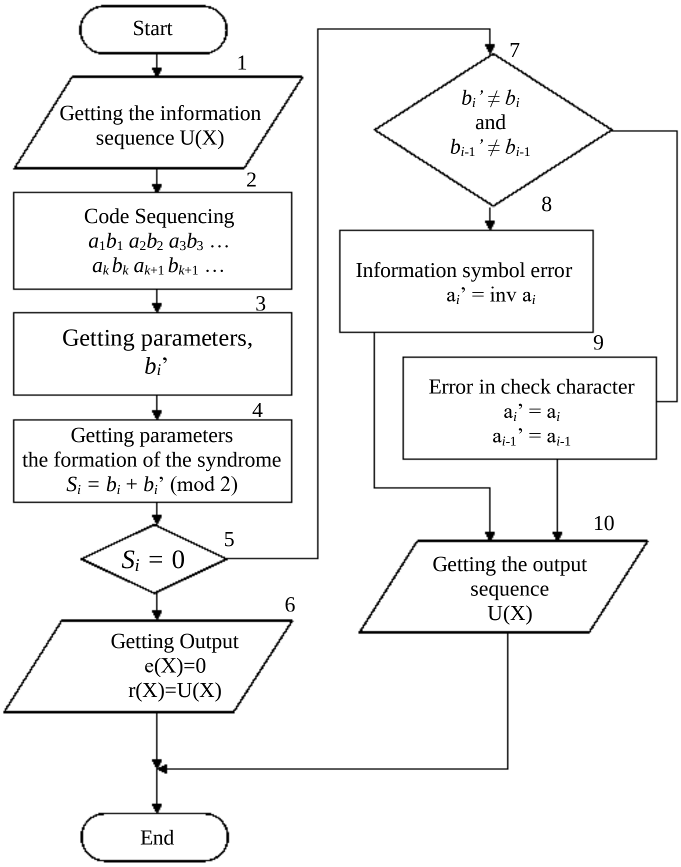


Figure 8. HICC decoding algorithm (APP Decoder 1)

From this structure it can be seen that each regular polynomial of the codeword $U(X)$ is a multiple of the polynomial generator $g(X)$.

Therefore, the roots of $g(X)$ must also be the roots of $U(X)$. The calculation of the symbols of the syndrome can be written as follows:

$$S_i = r(X)\big|_{X=\alpha^i} = r(\alpha^i) \quad i = 1,\ \ldots,\ n-k \tag{27}$$

Error localization. To implement this algorithm, a high-precision iterative decoding scheme for HIBC and HICC was constructed (Figure 8 and Figure 9). Suppose a codeword contains υ errors located at positions X^{j1}, X^{j2}, ..., $X^{j\upsilon}$. Then the error polynomial can be written as follows:

$$e(X) = e_{j1}X^{j1} + e_{j2}X^{j2} + \ldots + e_{j\upsilon}X^{j\upsilon}. \tag{28}$$

If a non-zero syndrome vector is computed, this means that an error has been received. Next, you need to find out the location of the error. The error locator polynomial can be defined as follows:

$$\sigma(X)=(1+\beta_1X)(1+\beta_2X)\ldots(1+\beta_\upsilon X)=$$
$$=1+\sigma_1X+\sigma_2X^2+\ldots+\sigma_\upsilon X^\upsilon \tag{29}$$

The roots of $\sigma(X)$ are $1/\beta_1$, $1/\beta_2$, ..., $1/\beta_\upsilon$. The values that are inverse to the roots will represent the location numbers of the error models $e(X)$.

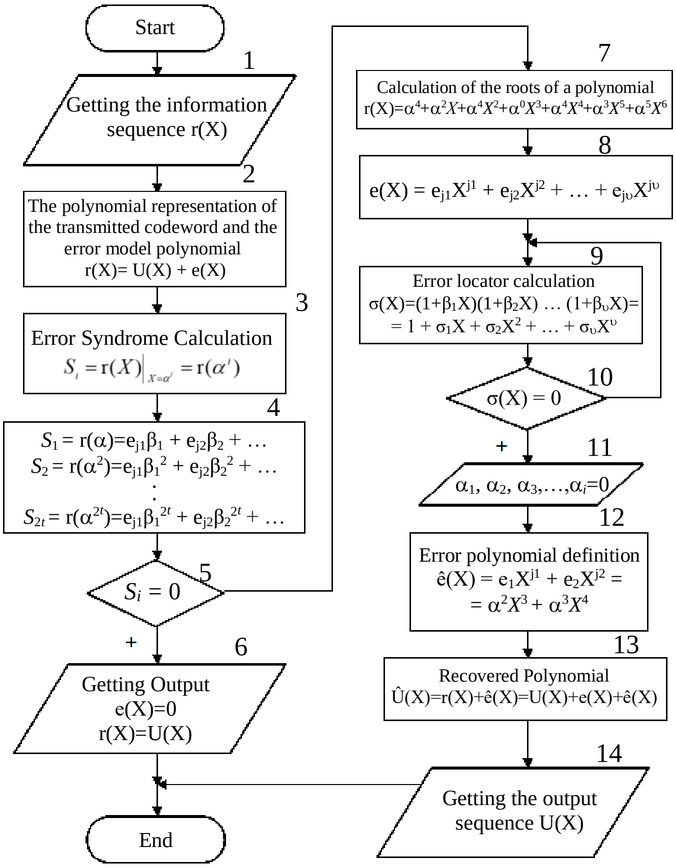


Figure 9. HIBC decoding algorithm (APP Decoder 2)

Based on the above equations, we recover the received polynomial, eventually yielding the expected transmitted codeword and ultimately the decoded message.

$$\hat{U}(X)=r(X) + \hat{e}(X) = U(X) + e(X) + \hat{e}(X) \qquad (30)$$

Based on the considered procedures and models, we can write an algorithm for the work of the codec of error-correcting coding and decoding of high-precision iterative codes (the main stages of the algorithm):

1. The obtained input sequence first goes through the HIBC code coding stage (Figure 7), then follows an interleaving (deinterleaving) algorithm that performs pseudo-random permutation of the symbols of the external code and, accordingly, restores the original order of the symbols at the decoding stage.

2. The converted sequence is encoded by an internal HICC, the peculiarity of which is the inclusion of check characters in the information sequence (Figure 6).

3. Then follows the step of punching the information sequence. This procedure determines the length of the code and accordingly sets the desired coding rate by excluding a number of elements from the sequence.

4. Code deperforation is the restoration of the original (up to the stage of perforating the code) sequence by analyzing and comparing information with the elements of the perforation matrix, which determines the order in which elements are excluded from the code.

5. High-precision iterative decoding of HICC is carried out in the reverse order with respect to the encoding procedure. HICC decoding (**APP Decoder 1**) is based on determining the indicator of the error syndrome by analyzing the values of the check symbols (Figure 8).

6. After the corresponding stage of deinterleaving and the HIBC decoder (**APP Decoder 2**), we obtain the desired information sequence (Figure 9).

VI. Modeling the HICD System and Research Results

Based on the data of the algorithms presented in the block diagrams (Figure 6, Figure 7 and Figure 8, Figure 9) of the individual modules, a system of noise-resistant coding and decoding of high-precision iterative codes is constructed.

Some of the results of this study were published at the 2019 Sixteenth International Conference on

Wireless and Optical Communication Networks (WOCN), which were held in Bhopal, India, from December 19-21, 2019. But after this large conference, research continued and a model of the system was built that implements high-precision iterative coding and decoding of high-precision iterative codes (SHICDHIC –"encoder-decoder" system). New results of signal processing using high-precision iterative codes are obtained, new limits of error probability are obtained depending on the number of decoding iterations.

Figure 10 shows a functional diagram of the interaction of individual modules of the built SHICDHIC system.

The main ones are the modules of the composite HIC encoder and decoder, performing direct signal conversion and consisting of encoders and decoders of high-precision iterative codes HIBC and HICC. Based on the coding rate matching algorithm, modules for perforation and deperforation of the code are constructed. The model allows you to generate the input information sequence, errors in the simulated communication channel, as well as to compare the original and received at the output of the decoder sequence.

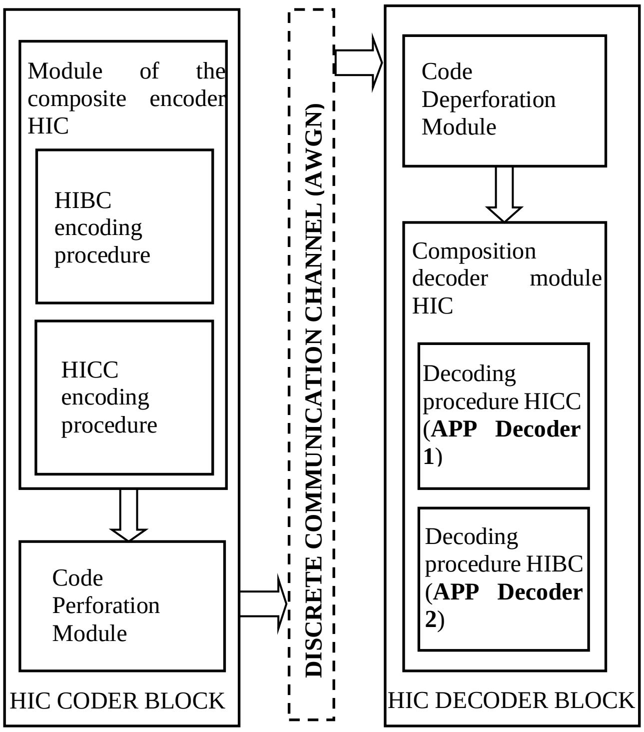


Figure 10. Model of the system SHICDHIC

In this work, in the Matlab environment, we developed a model of a system of high-precision iterative coding and decoding of high-precision iterative codes (SHICDHIC – system "encoder-decoder") with two decoders (APP Decoder 1 and APP Decoder 2), which operate on the basis of posterior solutions and correspond to simulation decoding of high-precision iterative convolutional (APP Decoder 1) and block (APP Decoder 2), what is the novelty of this work [1].

As the modulation, phase shift keying with the number of positions M=2 (2-PSK) was used. Sequences are combined into packets of 1024 bits, after encoding, respectively, the packet length will be approximately equal to 2048 bits [1, 2].

The tables and graphs below show the results of a study of the constructed system of high-precision iterative coding and decoding of high-precision iterative codes (SHICDHIC – "encoder-decoder" system).

TABLE I. **EVALUATION OF THE EFFECTIVENESS OF THE SYSTEM WITH A SIGNAL-TO-NOISE RATIO: ES/N0 = -1,32 DB (EB/N0 = 1,70 DB)**

A TOTAL OF 1000160 BITS AND 665 BLOCKS ARE DECODED.
THE NUMBER OF ERRONEOUSLY DECODED BITS IS 0. THE PROBABILITY OF ERROR IS 3,4E-012.
THE NUMBER OF ERRONEOUSLY DECODED BLOCKS IS 0. THE PROBABILITY OF ERROR IS 3,4E-010.
ITERATION STATISTICS:

Iteration number	1	2	3	4	5	6	7	8	9	10
The number of errors in bits										
1st decoder (APP Decoder 1)	83373	19416	3112	484	73	35	14	2	6	0
2st decoder (APP Decoder 2)	41274	7887	1210	192	26	19	12	5	0	0
Error probability P_b, BER										
1st decoder (APP Decoder 1)	8,3E-02	1,9E-02	3,1E-03	4,8E-04	7,3E-05	3,5E-05	1,4E-05	4,0E-06	2,0E-06	3,4E-09
2st decoder (APP Decoder 2)	4,1E-02	7,9E-03	1,2E-03	1,9E-04	2,6E-05	1,9E-05	5,3E-06	5,0E-07	2,3E-07	3,4E-12
The number of errors in blocks										
1st decoder (APP Decoder 1)	665	646	255	48	12	3	1	1	1	0
2st decoder (APP Decoder 2)	665	491	112	20	6	1	1	1	0	0
Probability of error in blocks, P_s, PER										
1st decoder (APP Decoder 1)	1,0E+00	9,7E-01	3,8E-01	7,2E-02	1,8E-02	4,5E-03	1,5E-03	4,5E-05	4,5E-06	5,3E-08
2st decoder (APP Decoder 2)	1,0E+00	7,4E-01	1,7E-01	3,0E-02	9,0E-03	1,5E-03	6,5E-04	1,5E-05	1,5E-06	3,4E-10

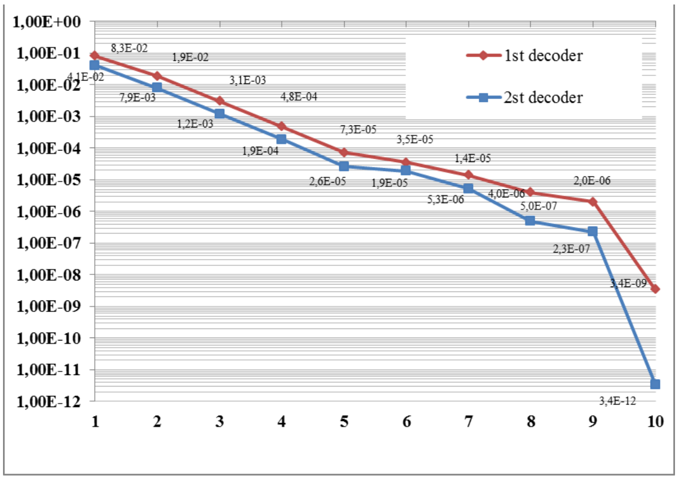


FIGURE 11. ERROR PROBABILITY P_B IN BITS OF THE NUMBER OF ITERATIONS (E_S/N_0=-1,32 DB, E_B/N_0= 1,70 DB)

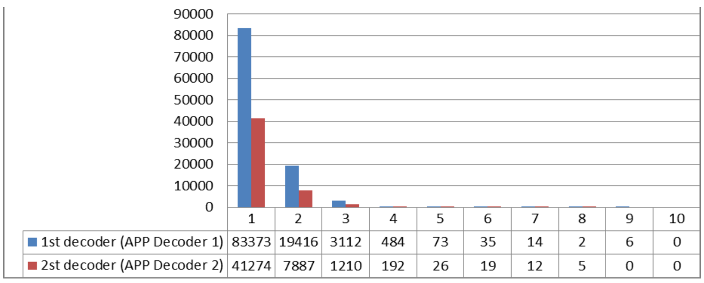


FIGURE 12. THE NUMBER OF ERRORS IN BITS OF THE NUMBER OF ITERATIONS (E_S/N_0=-1,32 DB, E_B/N_0= 1,70 DB)

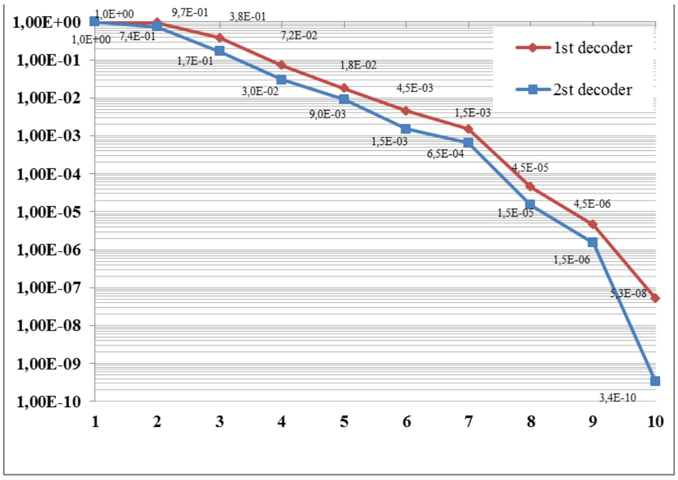
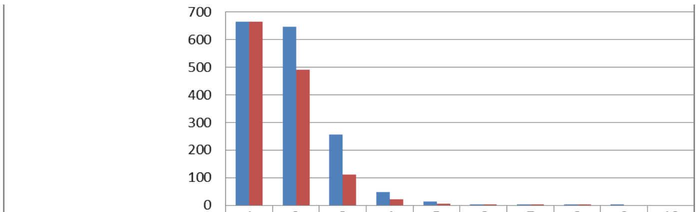


FIGURE 13. PROBABILITY OF ERROR IN BLOCKS, P_S, (E_S/N_0=-1,32 DB, E_B/N_0= 1,70 DB)



	1	2	3	4	5	6	7	8	9	10
1st decoder (APP Decoder 1)	665	646	255	48	12	3	1	1	1	0
2st decoder (APP Decoder 2)	665	491	112	20	6	1	1	1	0	0

FIGURE 14. PROBABILITY OF ERROR IN BLOCKS, P_S, (E_S/N_0=-1,32 DB, E_B/N_0= 1,70 DB)

CONCLUSION

The use of HIC in digital television systems (DTV) gives very tangible results in the field of ensuring noise immunity of transmitted and received signals. As a result, HID with hardware implementation is two to three orders of magnitude faster than comparable convolutional, block, and powerful turbo codes in terms of efficiency. The complexity of the software implementation of the type of iterative convolutional code is equal to the complexity of the type of iterative block code with negligible energy (about 0,1 dB). In the latter case, HID with the same efficiency with rather powerful turbo codes turn out to be almost 100 times faster.

Due to the design properties and information processing methods (low opposition to error propagation and the failure of efficient processing of a dense error packet), the use of a multi-threshold decoder in the field of large noise is limited. In the field of ensuring high noise immunity (10^{-8}–10^{-12}) and the probability of error per bit P_b, which value exceeds 10^{-7}, the MTD characteristics give incomplete results. These problems are solved using the high-precision iterative decoding algorithm (HIDc). The HIDc algorithm is developed taking into account the detection and correction of not only random errors, but also system errors associated with the design characteristics of the codes used.

The effectiveness of a particular code is determined by the energy gain of coding (EGC) this code. In this case, the energy gain from high-precision iterative coding relative to convolutional codes is 1,7–6 dB, and for Hamming codes, the EGC is reached in the limit of 2,7–11 dB.

HIDs work effectively in channels with high noise (DVB-T/T2/T4, DVB-S2/S4, DVB-H2/H4). Under such conditions, high-precision iterative coding and decoding (HICD) equipment is required to operate in a special mode to ensure high noise immunity of transmitted digital TV signals. At the same time, the noise immunity of the transmitted digital content should be at the level of $P_b \leq 10^{-12}$, i.e. mode of super-protection of bits and correction on high accuracy of erroneous bits in reception.

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