Improvement of the synthesis method and development of a simulation model of failure-resistant coding*

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Abstract

Reliability represents a critical performance attribute of contemporary data transmission and reception systems. Enhancing interference robustness while maintaining a constant data throughput remains a highly relevant challenge, particularly in applications such as unmanned aerial vehicle control. The investigated coding sequences make it possible to increase the effective energy of the received signal through the application of mirrored interference-resistant code structures. Improved noise immunity in data transmission is achieved by extending both the length and the power of the error-resistant code sequence employed for conveying a single message. These sequences offer a number of significant advantages, including strong resistance to high-power narrowband interference, the capability to distinguish multiple users based on code properties, increased transmission security, robustness against multipath propagation, and high accuracy in navigation measurements. Owing to these characteristics, the proposed sequences demonstrate substantial potential for practical deployment in geolocation systems and communication. An enhanced approach to the synthesis of interference-resistant code sequences based on ideal ring beams has been proposed. Additionally, an optimized method for the rapid search of such code sequences, enabling maximum error detection and correction efficiency as a function of the received sequence length, has been developed. A fast search algorithm for interference-resistant code sequences with maximal error detection and correction capability has been implemented. Furthermore, utilizing ideal ring bundles, a simulation model of interference-resistant coding has been designed, and a corresponding software implementation has been created for the detection and correction of errors in received code sequences. The presented interference-resistant code sequences are of practical significance, as they enable relatively simple and rapid detection of up to 50% of corrupted symbols and correction of up to 25% of errors within the length of the applied code sequence.

Keywords

non-uniform code sequence; non-uniform combinatorial configuration; mirror code sequence; ideal ring bundle [1]

1. Introduction

Assessing the scope of the problem. The sustained increase in the volume of information transmitted via communication channels has significantly intensified the demand for real-time error detection and correction techniques. An analysis of existing transmission channels indicates that deliberate, organized interference during data transmission occurs far more frequently than naturally occurring disturbances. Consequently, ensuring data protection must address both unauthorized access and signal degradation. One of the most effective approaches to information protection involves the application of error-correcting codes. Error-correcting coding constitutes a data processing technique that enables the identification and correction of a predefined number of transmission errors. Enhanced noise immunity in data transmission is usually achieved by increasing the length of the code sequence whilst ensuring the transmission of an individual message. However, the application of error-correcting codes inevitably results in increased transmission time, which in turn leads to higher energy consumption per transmitted message. When the transmission time is required to remain constant, improvements in noise immunity are

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obtained by shortening the symbol duration, thereby expanding the signal spectrum and increasing the bandwidth allocated to a single communication channel. Systems employing noise-tolerant coding are predominantly utilized in relay-based communication infrastructures, where the received modulated signal undergoes demodulation and, if necessary, decoding. This process effectively removes accumulated interference and noise, allowing each repeater to retransmit a restored signal without propagating distortions along the transmission path. As a result, interference and noise are confined to the segments between adjacent relay stations, which forms the foundation for reliable long-distance communication. In contrast, the transmission of modulated signals without the use of noise-tolerant coding leads to progressive error accumulation and signal distortion, ultimately failing to ensure the equivalence between transmitted and received data.

Relevance of solving the problem. Within this framework, the systematic synthesis of jamming-resistant codes with predefined properties for wireless communication systems represents a highly important research challenge.

Research task statement. The objective is to develop an algorithm that enables the rapid identification of noise-resistant code sequences capable of detecting and correcting errors as effectively as possible, in accordance with the length of the resulting code sequence.

Noise-resistant code sequences are the *object* of this study.

The method for synthesizing noise-resistant code sequences is the subject of this research.

Purpose of work – The aim of this work is to improve existing synthesis methods and to create a simulation model for noise-resistant coding. To ensure that this objective is achieved, the following research tasks need to be addressed:

1. to propose an improvement to the method of synthesis of noise-resistant code sequences using ideal ring bundles;
2. to propose a simulation model of noise-resistant coding based on ideal ring beams;
3. to implement an algorithm for searching and correcting errors in the resulting noise-resistant code sequences.

The scientific novelty of this research lies in the development of an enhanced method for synthesizing noise-resistant code sequences, which improves the effectiveness of error detection and correction in data transmission systems.

The practical application of the proposed noise-resistant code sequences is important, as the resulting coding structures enable the detection of up to 50% of corrupted symbols and the correction of up to 25% of distortions, depending on the specified length of the applied noise-resistant code sequence used.

2. Related works

Modern algorithms for designing noise-resistant code sequences are primarily based on the principle of redundancy, which allows for the searching and correction of errors arising from the internal structural properties of such sequences. In most cases, noise-resistant codes are constructed using cyclic code sequences, where a complete set of code combinations can be generated by cyclically shifting one or more basic code words. The basic concept of these coding schemes is based on the use of polynomials defined outside the binary field, which are divisible without remainder only by one or by the polynomial itself. The problem of constructing Barker-like codes of various lengths that can be adapted to the number of errors detected and corrected was studied in [1]. When implemented using Barker-like sequence encoding and decoding algorithms, a combination of software and hardware components is used, for example, by employing a processor core in conjunction with hardware modules containing configurable logic devices [2]. When designing a coding system based on barcode-like codes, it is important to ensure high technical and operational performance while minimizing equipment costs and strictly adhering to established technical requirements and constraints [3]. There is growing interest in developing specialized encryption and decryption algorithms for embedded cryptographic systems on mobile platforms, but there is a challenge in creating autonomous on-board cryptographic systems [4]. A noise-resistant Barker-like code ensures reliable data transmission with error detection and correction for embedded intelligent systems [5].

The analysis presented in [6–8] indicates that Bose–Chaudhury–Hocquenghem (BCH) codes are among the most extensively employed solutions for interference-resistant data transmission. Their decoding procedures are based on the Berlekamp algorithm and its principal modifications, which ensure correction of all error patterns with weights $W \leq W_o$, where $W_o+1=d_o$. Nevertheless, the computational complexity of this decoding approach reaches the order of $n^2 log_2 n$ operations and consumes approximately (5…20)n memory bit.

Studies [9, 10] show that non-binary Reed-Solomon (RS) codes constitute the dominant class of block codes used for noise suppression. The problem is that the bit rate of Barker-type codes cannot be adapted to the size of the interference [11]. The code length is determined by the size of the output field 2^l, where l denotes the cardinality of the symbol set. Similar to BCH codes, RS code decoding is also built on the Berlekamp algorithm. Notwithstanding extensive research efforts aimed at reducing computational demands, the decoding process remains highly resource-intensive. For instance, the developing of an RS decoder for a (31,15) code requires around 17 computational operations per decoded information bit, even when parallel processing techniques are applied and multiplication over non-binary fields is optimized using table-based methods.

Cascade coding schemes, discussed in [9–11], offer favorable performance in environments with relatively strong interference while maintaining relatively low decoding complexity. According to [12], the Viterbi algorithm is applicable in data transmission systems that use convolutional codes, which generally demonstrate better performance characteristics than block codes. Although, the computational burden associated with Viterbi decoding grows exponentially as the code length increases. In contrast, studies [13–16] examine classes of codes whose decoding complexity increases at a significantly slower rate, for example, proportionally to the square of the code length. The synthesis of interference-resistant codes based on ideal ring bundles is investigated in [17,18]. A major limitation of existing synthesis methods in this domain is their reliance on exhaustive search strategies, which substantially slows down the process of identifying optimized code sequences [19,20]. At the same time, ensuring a high level of information security remains a critical requirement for a wide range of modern cyber-physical systems [21].

3. Improvement of the method for synthesizing noise-resistant code sequences based on ideal ring bundles

The highest level of information security is achieved when all protective measures and methods are integrated into a unified and comprehensive protection framework. Effective information security must be implemented concurrently at three fundamental levels: hardware, software, and organizational. The hardware level includes card-based schemes, tokens, and cryptographic mechanisms realized through software–hardware solutions. The software level encompasses antivirus systems, data backup and archiving, mandatory authentication procedures, and encryption tools. The organizational level focuses on regulatory measures and control over compliance with established security policies.

At the same time, a significant number of experts emphasize that tamper-resistant encryption, whether implemented in software or hardware form, plays a particularly crucial role among protection methods. This is primarily because encryption safeguards the information itself rather than merely restricting access to it.

The advantage of this approach lies in the fact that a hacker cannot obtain meaningful information solely by gaining access to a storage medium or authentication data. Instead, the adversary must also possess knowledge of the encoding mechanism used to represent the protected data.

A noise-tolerant code sequence is defined as a binary sequence composed of zeros and ones, which is applied to transform information symbols during transmission and reception processes. The key characteristics of such sequences include enhanced capabilities for error detection and error correction.

The overall noise immunity of a communication system is determined mainly by the properties of the applied code sequences. Even for sequences of identical length, noise-tolerant codes may exhibit significantly different performance characteristics. In particular, noise immunity depends not only on the sequence length but also on additional parameters, such as cross-correlation properties.

Consequently, selecting an optimal noise-tolerant code sequence becomes a problem of designing efficient algorithms for searching and synthesizing suitable sequences. Existing transformation techniques for code sequences are unable to fully meet the growing demands placed on modern encoding and decoding systems.

Therefore, a critical research objective is the investigation of effective models capable of improving information encoding and decoding with respect to key performance indicators, including data transmission rate, noise immunity, and the simplicity of error detection and correction. Such models may involve irregularly spaced code sequences composed of integers, or numerical sequences defined by their values as well as by the cumulative sums of adjacent elements.

To address this challenge, unevenly spaced code sequences are considered. These sequences are characterized by permissible code combinations that exhibit non-uniform spacing between binary symbols. Unevenly spaced code sequences demonstrate several advantages over conventional noise-resistant sequences. In particular, they simplify error detection and correction at the receiver, since the occurrence of an unexpected “1” or “0” caused by noise indicates a violation of the predefined spacing structure.

An error remains undetected only in cases where the number of erroneous symbols is equal to or exceeds the spacing of the code. In all other situations, corrupted symbols a non-uniformly distributed code sequence are reliably identified, which enhances the high noise resilience of this class of sequences.

The problem of further enhancing the noise resistance of unevenly spaced code sequences must be addressed by applying ideal ring bundles (IRB).

An ideal ring bundle is defined as a structure in which the complete set of numerical values exhaustively corresponds to elements of a natural number sequence, with a predefined number of repeated values assigned to each element of the sequence.

An unevenly spaced code series is called a sequence $K_n = (k_1, k_2, ..., k_i, ..., k_n)$ elements in which all possible neighboring elements in the form of ring sums yield the values of all the numbers in the natural sequence 1, 2, ..., $S_n=n^2-(n-1)$.

Using the definition, we shall construct a table of the ring sums for the non-equidistant code sequence model K_n (Table 1).

The expression for the total sum of all ring sums of the weights of the elements of a non-equidistant code sequence, where different values occur, is as follows:

$$S_n=n^2-(n-1). \tag{1}$$

When values $p_j=1$, $q_j=n$, and also when values $p_j\neq 1$, $q_j=p_j-1$, the ring sums of the weights of the elements of non-equidistant code sequences satisfy the equality S_n.

The quantity $S_n^{'}$ the ring sums of the sequence of element weights are defined by the next relation:

$$S_n^{'}=n(n-1). \tag{2}$$

Let us examine the procedure for forming a noise-resistant code sequence. As the example shows, a non-uniformly spaced code sequence is considered, constructed on the basis of the weight coefficients corresponding to the eighth- and fourth-order elements of an ideal ring bundle (IRB):

1, 1, 1, 2, 2, 1, 3, 4.

Table 1

Permitted ring sums of a noise-tolerant non-equidistant code sequence

p_i	q_i					
	1	2	l-1	l	n-1	n
1	k_1	$\sum_{i=1}^{2} k_i$	$\sum_{i=1}^{l-1} k_i$	$\sum_{i=1}^{l} k_i$	$\sum_{i=1}^{n-1} k_i$	$\sum_{i=1}^{n} k_i$
2	$\sum_{i=1}^{n} k_i$	k_2	$\sum_{i=2}^{l-1} k_i$	$\sum_{i=2}^{l} k_i$	$\sum_{i=2}^{n-1} k_i$	$\sum_{i=2}^{n} k_i$
l-1	$\sum_{i=1-1}^{n} k_i + \sum_{i=1}^{1} k_i$	$\sum_{i=1-1}^{n} k_i + \sum_{i=1}^{2} k_i$	k_{l-1}	$\sum_{i=l-1}^{l} k_i$	$\sum_{i=l-1}^{n-1} k_i$	$\sum_{i=l-1}^{n} k_i$
l	$\sum_{i=1}^{n} k_i + \sum_{i=1}^{1} k_i$	$\sum_{i=1}^{n} k_i + \sum_{i=1}^{2} k_i$	$\sum_{i=1}^{n} k_i$	k_l	$\sum_{i=l}^{n-1} k_i$	$\sum_{i=l}^{n} k_i$
n-1	$\sum_{i=n-1}^{n} k_i + \sum_{i=1}^{1} k_i$	$\sum_{i=n-1}^{n} k_i + \sum_{i=1}^{2} k_i$	$\sum_{i=n-1}^{n} k_i + \sum_{i=1}^{l-1} k_i$	$\sum_{i=n-1}^{n} k_i + \sum_{i=1}^{l} k_i$	k_{n-1}	$\sum_{i=n-1}^{n} k_i$
n	$\sum_{i=n}^{n} k_i + \sum_{i=1}^{1} k_i$	$\sum_{i=n}^{n} k_i + \sum_{i=1}^{2} k_i$	$\sum_{i=n}^{n} k_i + \sum_{i=1}^{l-1} k_i$	$\sum_{i=n}^{n} k_i + \sum_{i=1}^{l} k_i$	$\sum_{i=1}^{n} k_i$	k_n

Given that the considered weight values correspond to node indices of order eight with a multiplicity of four, each natural number in the range from 1 to $n(n-1)/r=15$ can be expressed in four distinct forms. Consequently, the total number of possible representations coincides with the total number of values obtained.

For a non-uniformly spaced code sequence consisting of n elements, our proposed algorithm allows any numbers from 1 to $S_n=n(n-1)/r+1$ to be encoded.

The following code combinations of the non-equidistant code sequence 00100000, 00000100, 10000000, 01000000 specify four ways of encoding the number 1. When encoding the number 2, the following are used 00001000, 00010000, 11000000, 01100000. To encode the number 3, we get 00000010, 00001100, 11100000, 00110000, the number 4 is encoded as 00000001, 00000110, 01110000, 00011000, etc., for the number 14, we obtain the following encodings 10111111, 11111011, 11011111, 01111111, and for the number 15, 11111111.

The synthesized noise-resistant code sequence based on the IRB weights is exposed in Table 2.

Each numeric combination of a noise-resistant, non-uniformly distributed spaced code sequence is mapped to a specific binary pattern composed of ones and zeros, generated using IRB weight values according to a predefined rule. In particular, the number 1 is represented as 1, 2 as 10, 3 as 100, 4 as 1000, and so forth.

Owing to the properties of the zero-decomposition coding block, the total number of distinct code sequences equals $S_n(S_n-1)/2$ where each sequence contains accurately R from N distinct symbols in the corresponding bits, which results from the characteristics of the zero-decomposition coding block.

The remaining N-R symbols of any two non-uniformly spaced code sequences are distinguished by the fact that they occupy the same bit positions.

Table 2

Noise-resistant code sequence using IRB weights of order n=8 and multiplicity r=4: 1, 1, 1, 2, 2, 1, 3, 4

1	1	1	1	0	1	0	1	1	0	0	1	0	0	0
0	1	1	1	1	0	1	0	1	1	0	0	1	0	0
0	0	1	1	1	1	0	1	0	1	1	0	0	1	0
0	0	0	1	1	1	1	0	1	0	1	1	0	0	1
1	0	0	0	1	1	1	1	0	1	0	1	1	0	0
0	1	0	0	0	1	1	1	1	0	1	0	1	1	0
0	0	1	0	0	0	1	1	1	1	0	1	0	1	1
1	0	0	1	0	0	0	1	1	1	1	0	1	0	1
1	1	0	0	1	0	0	0	1	1	1	1	0	1	0
0	1	1	0	0	1	0	0	0	1	1	1	1	0	1
1	0	1	1	0	0	1	0	0	0	1	1	1	1	0
0	1	0	1	1	0	0	1	0	0	0	1	1	1	1
1	0	1	0	1	1	0	0	1	0	0	0	1	1	1
1	1	0	1	0	1	1	0	0	1	0	0	0	1	1
1	1	1	0	1	0	1	1	0	0	1	0	0	0	1

As a result, we obtain an expression for the minimum code distance of any noise-resistant heterogeneous code sequence constructed on the basis of a zero-decomposition coding block, which is determined by the ratio between the order and the multiplicity of the zero-decomposition coding block:

$$d_{min} = 2(n - r). \tag{3}$$

To expand the set of admissible combinations of non-uniform code sequences using IRB, a mirrored interference-resistant non-equidistant code sequence with IRB weights is constructed. In this approach, the encoding procedure is modified by interchanging binary symbols, that is, replacing ones with zeros and zeros with ones.

Within this mirrored representation, the value 1 is encoded in four alternative forms: 01111111, 10111111, 11011111, and 11111011. Similarly, the value 2 is represented by the combinations 00111111, 10011111, 11101111, and 11110111.

For the value 3, the corresponding code patterns are 00011111, 11001111, 11110011, and 11111101. The value 4 is encoded as 10001111, 11100111, 11111001, and 11111110, and so forth. For higher numerical values, this mapping continues accordingly; for example, the value 14 is represented by the combinations 10000000, 01000000, 00100000, and 00000100, while the value 15 corresponds to the all-zero sequence 00000000.

The implemented mirrored noise-resistant non-equidistant code sequence built using IRB weights is presented in Table 3.

Number of allowed combinations of main and mirror jamming code sequences:

$$P = 2 S_n^r. \tag{4}$$

Number of errors t_1, which are detected using a noise-resistant code sequence, are determined by the minimum code distance d_{min}:

$$t_1 \le d_{min} - 1. \tag{5}$$

Table 3
Values of a mirror-symmetric noise-resistant code sequence using IRB weight coefficients of order n=8 and multiplicity r=4: 1, 1, 1, 2, 2, 1, 3, 4

0	0	0	0	1	0	1	0	0	1	1	0	1	1	1
1	0	0	0	0	1	0	1	0	0	1	1	0	1	1
1	1	0	0	0	0	1	0	1	0	0	1	1	0	1
1	1	1	0	0	0	0	1	0	1	0	0	1	1	0
0	1	1	1	0	0	0	0	1	0	1	0	0	1	1
1	0	1	1	1	0	0	0	0	1	0	1	0	0	1
1	1	0	1	1	1	0	0	0	0	1	0	1	0	0
0	1	1	0	1	1	1	0	0	0	0	1	0	1	0
0	0	1	1	0	1	1	1	0	0	0	0	1	0	1
1	0	0	1	1	0	1	1	1	0	0	0	0	1	0
0	1	0	0	1	1	0	1	1	1	0	0	0	0	1
1	0	1	0	0	1	1	0	1	1	1	0	0	0	0
0	1	0	1	0	0	1	1	0	1	1	1	0	0	0
0	0	1	0	1	0	0	1	1	0	1	1	1	0	0
0	0	0	1	0	1	0	0	1	1	0	1	1	1	0

Number of errors t_2, which are corrected by a noise-tolerant code sequence, is determined by the number of errors detected t_1:

$$t_2 \leq (t_1 - 1)/2. \quad (6)$$

Let us define a ratio that determines the number of errors that can be detected by a noise-resistant code sequence t_1:

$$t_1 \leq 2(n - r) - 1. \quad (7)$$

Let us define the ratio that determines the number of errors that can be corrected by a t_2 noise-tolerant code sequence:

$$t_2 \leq n - r - 1. \quad (8)$$

The minimum code distance for a noise-tolerant code sequence is defined as

$$d_{1,2} \leq S_n - 2(n - r). \quad (9)$$

Let us find the ratios that determine the number of errors that can be detected using a noise-tolerant code sequence:

$$t_1 \leq 2(n - R) - 1, if\ S_n \geq 4(n - r), \quad (10)$$

$$t_1 \leq S_n - 2(n - r) - 1, if\ S_n < 4(n - r). \quad (11)$$

Let's find the ratios that allow us to determine the number of errors that can be corrected using a noise-resistant code sequence:

$$t_2 \leq n - r - 1, if\ S_n \geq 4(n - r), \quad (12)$$

$$t_2 \leq \frac{S_n - 2(n - r + 1)}{2}, if\ S_n < 4(n - r). \quad (13)$$

Let us determine the optimal relationship between the parameters n and r that ensures the highest error-correcting capability of an interference-resistant code sequence. The interference immunity of the proposed sequence increases as the difference $l=n-r$ grows.

The largest value of l will be provided that:

$$S_n = 2n. \tag{14}$$

Let us describe the dependence between the parameters n and r under conditions in which the noise-tolerant code sequence achieves the maximum possible error detection and correction capability:

$$L = \begin{cases} n/2, if\ n - even \\ (n-1)/2, if\ n - odd \end{cases}. \tag{15}$$

Noise-tolerant code sequences constructed on the basis of ideal ring bundles are capable of detecting up to n−1 errors and correcting up to n/2−1 errors when n is even. For odd values of n, such sequences can detect up to n errors and correct up to (n−1)/2 errors. In addition, the use of mirrored interference-tolerant code sequences theoretically doubles the set of beam-based interference-resistant code sequences.

4. Development of a simulation model of noise-tolerant coding

The simulation model algorithm for noise-tolerant coding has been implemented using non-uniform combinatorial configurations structured according to the ideal ring bundle concept, along with ASCII-based numerical encoding. In addition, a coding method based on the ideal ring node has been realized.

The simulation algorithm for noise-tolerant coding consists of the following stages:

1. entering the code parameter data and selecting the ideal ring bundle;
2. selecting the code combination using the ideal ring bundle;
3. generating a noise-resistant code for the selected number.

The algorithm for developing a simulation model of noise-tolerant coding using combinatorial non-equidistant configurations consists of the following stages:

1. Step “Selection of IRB-based code parameters” – the ideal ring bundle is chosen according to the specified values of the code parameters;
2. Step “Input of data for noise-resistant coding” – the required parameters for noise-resistant encoding are entered while considering the constraints imposed by the selected IRB;
3. Step “Verification of code power against IRB capacity” – the entered value is compared with the total sum of IRB elements. If the specified value exceeds the IRB sum, the input must be revised and an alternative IRB selected;
4. Step “Computation of code positions using the selected IRB” – the relevant IRB elements are identified and the corresponding element sums associated with the chosen value are calculated;
5. Step “Construction of a noise-resistant code table based on IRB positions” – a table containing the derived IRB combinations is generated;
6. Step “Formation of code combinations according to IRB values” – a code table is created in which each IRB element is assigned a unique binary code;
7. Step “Assembly of the final code combination using table indices” – the resulting noise-resistant code is produced by merging two four-bit code segments;

8. Step “Processing of the obtained code combination” – the received combination is analyzed by substituting groups of zeros and ones with the corresponding predefined groups in order to detect and correct errors;
9. Step “Output of the final code combination” – the results of the noise-resistant coding procedure are saved to an output file.

As an example, let us consider the calculation of the correcting ability of interference codes constructed using IRB with parameters: N=6, R=1; 2) N=15, R=7; 3) N=16, R=8.

Since the sum of the IRB S_n=31, the code combination length and code power are identical for all three cases considered. For the first coding scheme, the maximum number of detectable and correctable errors equals 9 and 4, respectively. In contrast, in each of the remaining two cases, the IRB generates a code capable of detecting up to 15 errors and correcting up to 7 errors. Consequently, the performance of the latter two approaches is substantially superior to that of the first one.

In the general case, any ideal ring bundle may be employed for the construction of a noise-resistant code. Nevertheless, the most efficient results are achieved when using codes synthesized on the basis of an IRB whose parameters satisfy relation (15).

A simulation model of noise-tolerant coding based on combinatorial non-uniform configurations was implemented using the C++ programming language. The developed simulation system operates reliably across a broad range of Windows operating systems.

The decoding procedure begins with opening the input file, followed by execution of the decoding command. The encoded data are sequentially read from the file in blocks until the end of the data stream is reached. Each block is then examined for the presence of errors. If errors are detected, the decoder performs the necessary correction. Subsequently, the corrected data block is decoded and written to an output file.

Upon completion of the decoding process, statistical information summarizing the decoding results is displayed.

The simulation model of noise-tolerant coding using combinatorial non-uniform configurations is characterized by the following features:

1. The input data will be the parameters of a noise-resistant, unevenly spaced sequence of codes of order multiple N;
2. Provides the performed encoding and decoding with the detection and correction of errors in the amount up to t_2.

The program has a simple and intuitive interface. The main elements are presented as windows (Figure 1):

1. Input data (IRB parameters of the order of N multiplicity R);
2. Number of errors to be corrected (no more than the number specified in the Info window);
3. The button labeled <OpenFile> allows you to select the file required for encoding, random noise generation, and error-correction decoding.

The outcomes of the encoding and decoding processes, carried out with the detection and correction of all errors ranging from one to four using noise-resistant heterogeneous code sequences, are presented in Fig. 2 and Fig. 3.

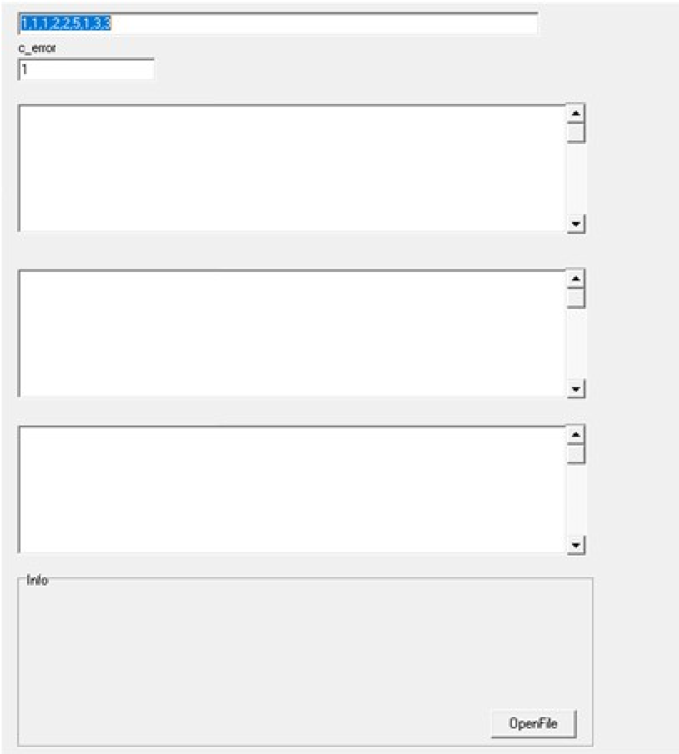
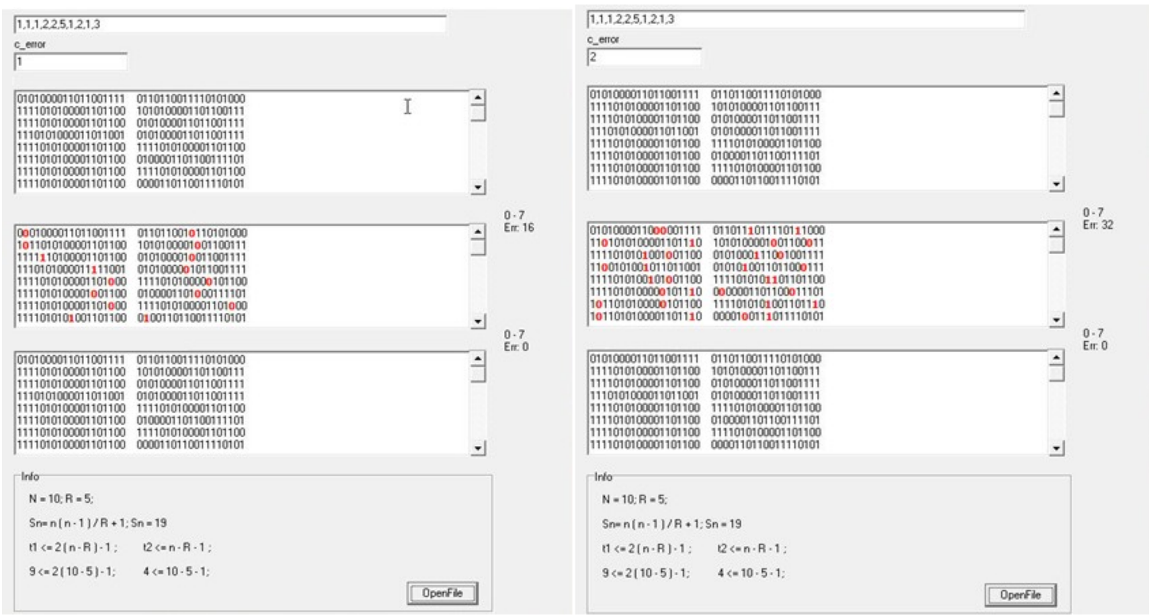


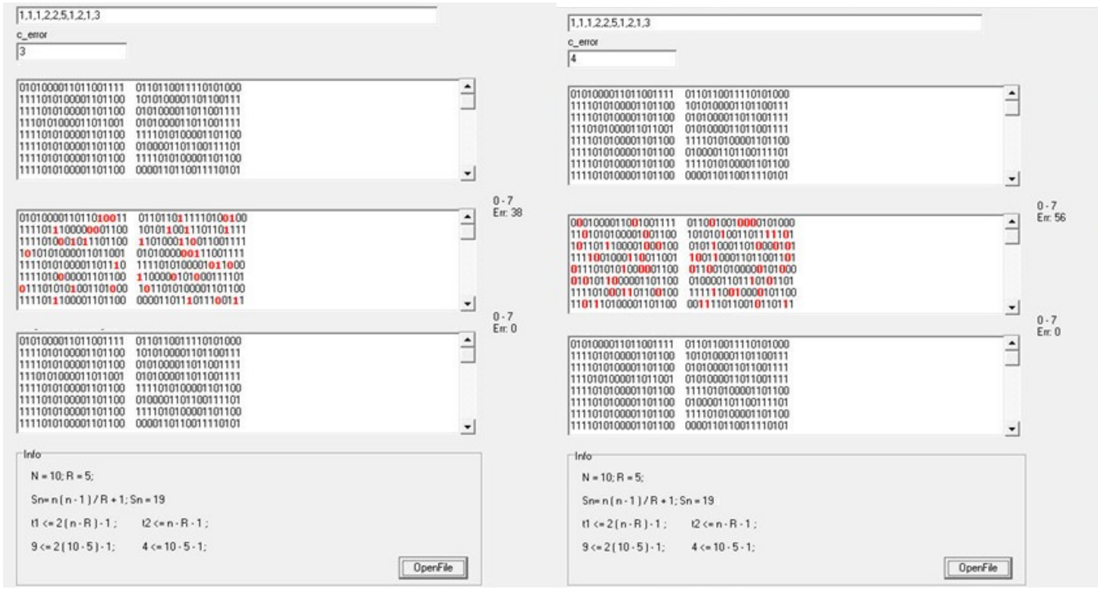
Figure 1: Main elements on the form of the encoding/decoding window with the possibility of correction using the IRB.



a b

Figure 2: Carrying out encoding operations, generating interference and decoding operations with correction of all single (a), double (b) errors.

Figure 2 and Figure 3 illustrates, in a top-to-bottom sequence, the text fields corresponding to a given code sequence, including the input data, the data distorted by randomly introduced errors, and the results obtained after the decoding procedure.



a b

Figure 3: Carrying out encoding operations, generating interference and decoding operations with correction of all triple (a), quadruple (b) errors.

Figure 4 presents the outcomes of the encoding and decoding processes performed under conditions where not all five-fold errors are detected and corrected, using noise-resistant non-uniformly distributed code sequences.

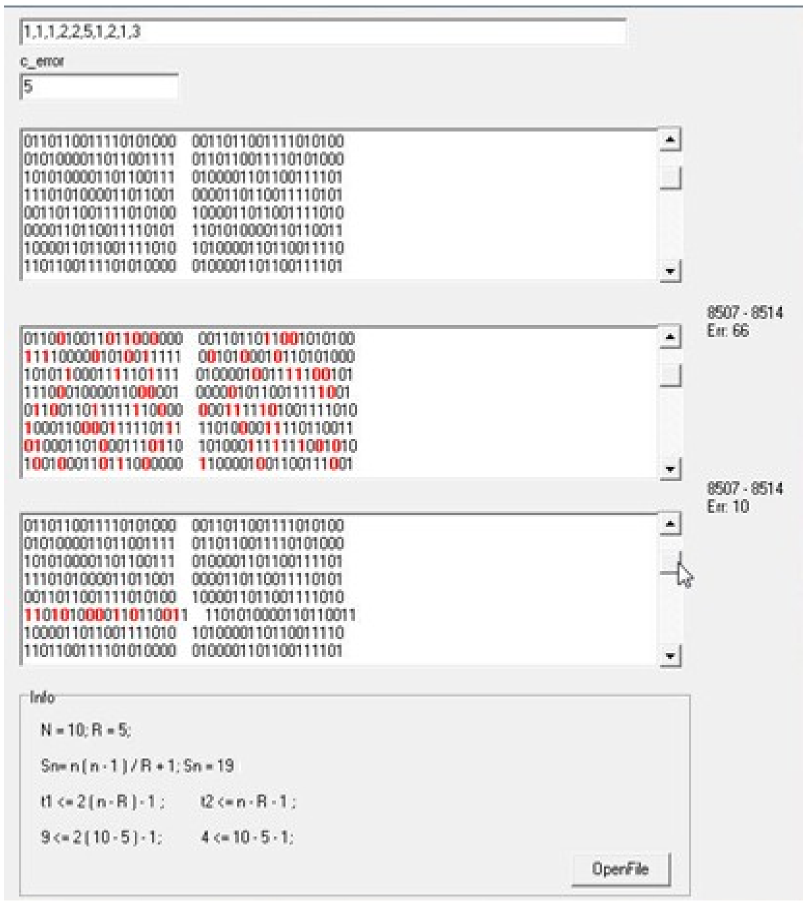


Figure 4: Carrying out encoding operations, noise generation and decoding operations with correction of not all five-fold errors.

An analysis of the experimental results obtained using the developed simulation model demonstrates that complete detection and correction of errors are illustrated in Figures 2 and Figure 3. At the same time, Figure 4 reveals a considerable number of errors that are successfully detected but not corrected. This behavior fully corresponds to the theoretical properties of non-equidistant noise-tolerant code sequences.

5. Conclusion

The study demonstrates that the application of noise-resistant coding is an effective approach for mitigating interference arising during the transmission of code sequences over wireless communication channels. An enhanced method for synthesizing noise-resistant code sequences has been proposed; through the use of ideal ring bundles, this method significantly improves the robustness of the received sequences, enabling the detection of up to 50% and the correction of up to 25% of distorted symbols across the length of the noise-resistant code sequence.

A simulation model for noise-resistant coding based on non-uniform combinatorial configurations has been implemented in the C++ programming language. The developed model is characterized by low computational complexity and reliable operation across a wide range of Windows operating systems.

It has been established that employing ideal ring bundles in the synthesis of noise-resistant code sequences substantially simplifies the synthesis procedure and enables its practical realization in real-time applications. Furthermore, the results indicate that a promising direction for future research involves reducing code redundancy, which may be achieved through the use of mirrored, unevenly spaced noise-tolerant code sequences.

Declaration on Generative AI

During the preparation of this work, the authors used Grammarly in order to: grammar and spelling check; DeepL Translate in order to: some phrases translation into English. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the publication’s content.

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