A method for transmitting information based on the stochastic use of binary quasi orthogonal code sequences

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Abstract. The objective of the article is to develop the structure of a system for transmitting information with code division of channels and stochastic usage of systems of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments, as well as a description of the principle of its functioning. The aim of the article is to develop a method for transmitting information in satellite communication systems and global navigation satellite systems with code division of channels and stochastic usage of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments, providing an increase in structural secrecy. The elements of novelty are obtaining a new structure of an information transmission system with code division of channels and increased structural secrecy, as well as a description of the main stages of the information exchange method based on this system. The method differs from the known ones by stochastic use of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments. The main result of the article is that the presented method of information transmission makes it possible to reduce the impact of deliberate imitating interference and cases of substitution of the signals used by increasing the structural (signal) secrecy of the information transmission system with code division multiplexing and stochastic usage of systems of binary quasi-orthogonal code sequences.

Keywords: binary quasi-orthogonal code sequences; method of information transfer; functional transformations of pseudo-random arguments; code division of channels; structural secrecy

1. Introduction

The technology of code division of channels (CDC) allows you to get a number of advantages when organizing information exchange in satellite communication systems (CCS), which determines the feasibility of using CDC in the design of new CCS and global navigation satellite systems (GNSS) [1-6]. In a number of works [7-9] it is noted that at present, due to the increase in the volume of transmitted data in the CCS and GNSS, there is a high probability of realization of threats to disrupt their stable functioning due to the impact of deliberate imitating interference and substitution of the signals used. At the same time, the methods used to counter this interference do not provide effective protection for CCS and GNSS due to their limited capabilities.

In works [7,8], it is shown that increasing the noise immunity of CCS and GNSS with CDC when organizing imitating interference and substitution of NS is quite effective due to an increase in the structural secrecy of NS based on the stochastic usage of systems of code sequences. The work proved
that the required number of non-repeating binary code sequences (BCS), which can provide an increase in the structural secrecy of the NS GNSS when they are stochastic use, is \( A_r = 2.3652 \cdot 10^{13} \).

To assess the structural (signal) secrecy in [8-10], is used an indicator of the complexity of solving the structure of code sequences (CS) in the form of a coefficient \( H \). The coefficient \( H \) serves as a measure how the CS is estimated as random when analyzed by the radio monitoring subsystem of the radio-electronic interference station (REI). The most common variant for assessing the complexity of solving the structure of a code sequence is the Berlekamp-Messi algorithm. In this case, the coefficient \( H \) is determined based on the following expression:

\[
H = \frac{M}{N},
\]

where \( M \) - is the number of consecutive symbols of the code sequence that must be received by the monitoring subsystem of the REI station to build the structure of an equivalent shift register with linear feedback (SRLFB); \( N \) - code sequence length.

Since the normalized linear complexity of each individual BCS from the system of binary quasi-orthogonal code sequences (SBQCT) may differ, the averages \( H \) values were found. Table 1 shows the values of the averaged length-normalized code sequence complexity of solving the structure for the known types of code sequences Gold, Kasami, Kamaledinov, Kerdock, Weil and Bent sequences, considered in [8] and for code sequences obtained on the basis of functional transformations of pseudo-random arguments [11,12].

Comparative analysis shows that the average complexity of solving the structure \( H \) for BCS obtained on the basis of functional transformations of pseudo-random arguments for all three considered lengths 4095, 8191 and 10230 has the highest value, which is approximately equal to the length of the BCS itself \( M \approx N \) and is comparable with the same indicator for Kamaledinov's BCS, Weil and Bent sequences. However, the advantage of BCS obtained on the basis of functional transformations of pseudo-random arguments is that the number of nonrepeating BCSs is significantly larger than all known BCSs, and also closest of all analyzed to the required value \( A_r = 2.3652 \cdot 10^{13} \). For example, for BCS length equal to 4095 the advantage over Kerdock sequences is more than 10,000 times, for BCS length equal to 8191 the advantage over Weil sequences is about 10,000,000 times, for BCS length 10230 the advantage over Kerdock sequences is more than 1000 times. This circumstance indicates that with the stochastic usage of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments, they provide a higher structural (signal) secrecy in a code division multiplexing system in comparison with the case of usage known discrete quasi-orthogonal code sequences.

In works [1,4,8,9,11-19] approaches to obtaining various types of SBQCT are considered and their properties and the possibility of practical application in information transmission systems are evaluated. However, they are limited either using previously known SBQCTs, or by describing only the methods of their formation.

Information exchange methods based on the stochastic usage of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments were not considered in these works.

Proceeding from this, the development of the structure of the information transmission system with code division of channels and the stochastic usage of systems of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments, and the description of the principle of its functioning is an urgent task.

The aim of the article is to develop a method for transmitting information in CCS and GNSS with code division of channels and stochastic usage of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments, providing an increase in structural secrecy.
2. Method of information transmission with code division of channels and stochastic usage of binary quasi-orthogonal code sequences

The developing method of information transmission in CCS and GNSS with code division multiplexing and stochastic usage of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments develops a method of information transmission based on chaotically forming ensembles discrete multilevel orthogonal signals proposed in [15].

In the considered method of information transmission for message transmission, it is proposed to use binary quasi-orthogonal code sequences obtained by functional transformations of random functions [8, 14], based on the invariance property of the probability differential

$$g(\tau)d\tau = f(x)dx,$$

where $x$ - is the initial random variable; $f(x)$ - distribution density of the initial random variable; $\tau$ - a random time interval between instantaneous values converted by random variables; $g(\tau)$ - the distribution density of the transformed function, and the random variables $x$ and $\tau$ are connected by an unambiguous deterministic functional dependence $\tau = \phi(x)$, which is an unambiguous differentiable function that admits an inverse transformation $x = \psi(\tau)$.

It follows from this property that the distribution function of the random variable is

$$G(\tau) = \int_0^\tau f(x)dx$$

and allows us to determine the value of the random variable $\tau$:

$$\tau = \{F^{-1}[\text{rnd}(1)+F(a)]\},$$

where $F^{-1}$ - is the function inverse to the distribution function of the random function $x$, and $F'(x) = f(x)$; $\text{rnd}(1)$ - numerical values generated by a random number generator, evenly distributed over the interval [0,1]; $a$ - is the parameter determined from the normalization condition

$$\int_0^\infty f(x)dx = 1.$$

To obtain a random variable with a given distribution function, it is necessary to construct a deterministic function $\tau = G^{-1}(x)$ and obtain the desired random values of this function from the argument determined by the number, which is a random variable with a uniform distribution law on the interval [0,1]. Taking this remark into account, we rewrite the formula (3) for $\tau$

$$\tau = \phi\{F^{-1}[\text{rnd}(1)+F(a)]\}.$$

The analysis of the above shows that it is quite possible to obtain a binary code sequence in which both the pulse durations and the intervals between them would be a random value of the unit amplitude, it is quite possible if the sequence is fed to the counting C input of the RST-trigger, provided that it provides the distribution of trigger overturning according to the law, defined by expression (6).

This method for constructing SBQCT is based on the usage of pseudo-random numbers obtained as a result of functional transformation as a parameter that determines the length of series of consecutive elements of the same character in a discrete code sequence and is described in detail in [8, 14]. Taking into account the fact that each time the set of random numbers, in the amount determined by the length of the generated code sequence intended for information exchange in the developed method, will differ from each other on the interval [0,1], then the code sequences themselves will be different. In order for the code sequences obtained in this way to satisfy the quasi-orthogonality condition, in the process of their formation, their correlation properties can be checked for compliance with this condition.
We will describe the proposed method of information transmission using the example of an information transmission system with code division of channels and stochastic usage of systems of binary quasi-orthogonal code sequences, the structure of which is shown in Fig. 1.

Figure 1. Block diagram of a system for transmitting information with code division of channels and stochastic usage of systems of binary quasi-orthogonal code sequences

In fig. 1 the following notation is used: 1 – information channels, 2 – digital information block, 3 – modulator, 4 – input combiner, 5 – group signal forming unit, 6 – group signal forming unit modulator, 7 – phase modulation unit, 8 – power amplifier, 9 – transmitting antenna, 10 – synchronization signal generator, 11 – service information block, 12 – clock pulses generator, 13 – high-frequency selection unit, 14 – receiving antenna, 15 – correlation processing unit, 16 – information extraction unit, 17 – information recipient block, 18 – sync signal processing unit, 19 – search block, 20 – sync signal copy block, 21 – clock pulses generator unit, 22 – block for setting initial functions, 23 – functional transformation block, 24 – converter, 25 – random number generator, 26 – block for setting initial values, 27 – block for setting copies of original function, 28 – block of copies of functional transformations, 29 – random number copies generator, 30 – block for specifying copies of initial values.

The above system for transmitting information with code division multiplexing and stochastic usage of binary quasi-orthogonal code sequences includes transmitting and receiving equipment. The transmitting equipment contains \( N \) information channels 1, each of which consists of a block of digital information 2 connected by its output to the first input of the modulator 3, the output of which is the output of each information channel. Information transmitted from an individual user enters the information channel 1 of the information transmission system shown in Fig. 1.

In each information channel, information symbols of an individual User \( N \) are entered into digital information blocks 2 and modulated using modulator 3.

For the formation and stochastic usage of SBQCT as spreading sequences obtained on the basis of functional transformations of random functions in accordance with the procedures described by expressions (2) - (6), in the transmitting equipment it is proposed to use a block for setting initial functions 22, a block of functional transformations 23, a generator random numbers 25 and block for setting initial values 26. In the receiving equipment, it is similarly proposed to use a block for setting
copies of the original functions 27, a block for copies of functional transformations 28, a generator of copies of random numbers 29 and a block for setting copies of initial values 30.

Let us consider the operation of the information transmission system shown in Figure 1. The signals generated at the output of the modulator 3 of each information channel 1 are simultaneously fed to the group signal generation unit 5. Further, the information flows of each information channel 1 are combined using a combiner 4 of the group signal forming unit 5 and fed to the first input of the modulator of the group signal forming unit 6, on which the combined group signal is modulated. The second input of the modulator of the group signal generating unit 6 receives a signal from the output of the synchronization signal generator 10, which is controlled by the service information unit 11 and the clock pulses generator 12. In addition, the signal from the output of the synchronization signal generator 10 is fed to the inputs of the digital information units 2 of each N information channels 1. Under the control of the signals of the synchronization generator 10, clocked synchronous input of information symbols into the blocks of digital information 2 is carried out. After combining the information streams of each information channel 1 with the help of a combiner 4, in the block for forming the group signal 5 and superposition in the modulator 6 of the synchronization signal generated by the synchronization signal generator 10, a group signal is formed, the spectrum of which, after being transferred to the carrier frequency region in the phase modulation unit 7 and the power amplifier 8, is emitted into the air through the antenna 9.

The radio signal, after propagation in space, is fed to the input of the receiving antenna 14 of the receiving equipment. On the receiving side, the signal received by the receiving antenna is subjected to preprocessing in the high-frequency selection unit 13. From the output of this unit, the signal is simultaneously fed to the correlation processing unit 15 and the synchronization signal detection unit 18. In this case, the synchronization signal detection unit 18 together with the search unit 19 are brought into synchronism synchronization signal copy generator 20. The signal from the output of the correlation processing unit 15 is fed to the first input of the information extraction unit 16, which is connected by its output to the information recipient unit 17. Correlation processing in the correlation processing unit 15 is carried out using the binary quasi-orthogonal code sequences used by this receiving equipment, obtained on the basis of functional transformations random functions implemented using the block for setting copies of the original functions 27, the block for copies of functional transformations 28, the generator of copies of random numbers 29 and the block for setting copies of the initial values 30.

Since the block of functional transformations 23 on the transmitting side and the block of copies of functional transformations 28 on the receiving side are important elements in the proposed information transmission system, we will consider it in more detail. Taking into account that the block of functional transformations 23 on the transmitting side and the block of copies of functional transformations 28 on the receiving side are identical in their structure and functions, we will consider the composition and operation of the functional transformations block 23 on the transmitting side, taking into account that the composition of the elements and the operation of the block copies of functional transformations 28 will be similar.

In fig. 2 shows a block diagram of the block of functional transformations 23. The designations of elements for the case when they are included in the block of copies of functional transformations 28 on the receiving side are indicated in brackets.

In fig. 2 the following designations are used: 12 (21) - clock pulse generator; 22 (27) - block for setting initial functions; 23 (28) - block of functional transformations; 24 - converter; 25 (29) - random number generator; 31 - functional converter; 32 - block for calculating the inverse function; 33 - trigger; 34 - normalization block, 35 - segment selection block; 36 - frequency divider.

The procedure for generating a block of functional transformations of 23 binary quasi-orthogonal code sequences intended for use in the process of transmitting and receiving information in a code division multiplexing system is as follows:
1. Using the block for setting the initial functions 22, the initial functions are set to be used in the functional transformations. As a result, tables of initial functions are formed, which will be used to form working quasi-orthogonal code sequences. As the initial functions, analytical expressions are considered, which can be considered as distribution functions taking into account the formal properties and the field of assignment. As an example, the following function can be used:

\[
f(x) = \begin{cases} 0, & \text{with } x < \alpha, \\ \frac{x - \alpha}{\beta - \alpha}, & \text{with } \beta < x < \alpha, \\ 1, & \text{with } x > \beta. \end{cases}
\]

(7)

2. The setting of the initial values is carried out by the unit for setting the initial values 26 on the transmitting side and by the unit for setting copies of the initial values 30 on the receiving side. For instance, \( m_k = 1, q = 5^{17}, M = 2^{40} \).

3. Functional converter 31 of the block of functional transformations 23 carries out the functional transformation of the initial functions used in accordance with the expression (2)

\[
G(\tau) = 1 - \left( \frac{k}{\tau} \right)^a.
\]

(9)

4. A sequence of random numbers \( \text{rnd}(1) \) is generated using a random number generator 25, and the numerical values \( \text{rnd}(1) \), generated by the random number generator are uniformly distributed over the interval \( [0, 1] \). For instance

\[
m_{k+1} = m_k q \left[ \frac{m_k q}{M} \right] \cdot M.
\]

(10)

5. Using the block for calculating the inverse function 32, the inverse function \( F^{-1} \) in accordance with expression (3), where \( F^{-1} \) is the function inverse of the distribution function of the random function \( x \), moreover \( F(x) = f(x) \). For the function under consideration with \( \alpha = 2 \) we have

\[
\tau_n = \frac{k}{(1 - \text{rnd})^{\frac{1}{a}}}.
\]

(11)
6. In accordance with the obtained inverse distribution function of the random function $x$ at the output of the trigger 33, a sequence $U_T(t)$ is formed, shown in Fig. 3b.

7. Using normalization block 34, the generated sequence $U_T(t)$ is standardized.

8. By means of the segment separator 35, operated under the control of the frequency divider 36, the normalized sequence is segmented. Figure 3 shows timing diagrams of the operation of the main elements of the block of functional transformations 23.

Figure 3. Timing diagrams of the operation of the main elements of the block of functional transformations

On the receiving side, a similar procedure for generating copies of code sequences used in the process of receiving information in a code division multiplexing information transmission system is carried out using a block of copies of functional transformations 28. Figure 3 shows the following timing diagrams: signals generated at the output of the random number generator 25 (Fig. 3a); signals received at the output of trigger 33 (Fig. 3b); signals at the output of the segment allocation block 35 for $T_1 = [0-40]$ (Fig. 3c); signals at the output of the segment allocator 35 for $T_2 = [40-80]$ (Fig. 3d).

Received signal systems $U_{C1}(t)$, $U_{C2}(t)$, etc. at the output of the segment allocation unit are segment systems [4] and are formed from sequence segments, the lengths of which are determined by the period of operation of the random number generator 25. The segment length determines the working length of the code sequence and is specified as a characteristic of the transmission system and determines the signal base ($B = N$). This length is formed in the segmentation unit 35 by dividing the frequency of
the clock generator 12 using a frequency divider 36, the division factor of which determines the segment length.

Both on the transmitting and on the receiving side, tables of initial functions are preliminarily formed, which at the time of information transmission will be used to form working code combinations. These tables are stored in the memory of the transmission system on the transmitting side. Copies of these tables are stored on the receiving side. The order of using and changing the functions presented in these tables at each given moment of time is set by the service information block 11 on the transmitting side and its copy 18 on the receiving side.

In view of the above, the proposed method for transmitting information based on the stochastic use of binary quasi-orthogonal code sequences obtained on the basis of functional transformations of pseudo-random arguments is carried out in the following sequence:

Stage 1. Before the start of the information transfer process, the formation, manipulation and transmission of an auxiliary synchronization signal by the transmitting equipment is carried out. As a result, service information is transmitted to each subscriber station (a single initial cyclic phasing marker for all subscriber stations).

Stage 2. After the receiving equipment receives the service information (a single initial cyclic phasing marker), the receiving equipment of each subscriber station enters a state of synchronism with the transmitting equipment.

Stage 3. Using a random number generator, a block for setting initial functions, a block for setting initial values and a block of functional transformations in the transmitting equipment, a system of binary quasi-orthogonal code sequences is formed, obtained by functional transformation of random functions based on the invariance property of the probability differential (2), which is used as carriers of information.

Stage 4. Using a generator of copies of random numbers, a block for setting copies of initial functions, a block for setting copies of initial values and a block of copies of functional transformations in the receiving equipment, a set of copies of quasi-orthogonal code sequences is formed, obtained by functional transformations of random functions similar to those that were carried out in the transmitting equipment.

Stage 5. On the transmitting and on the receiving side, before the start of the information transfer process, tables of initial functions are formed, which at the time of information transfer are used to form working quasi-orthogonal code sequences. These tables are stored in the memory of the transmission system on the transmitting side. Copies of these tables are stored on the receiving side. The order of using and changing the functions presented in these tables, at each given moment in time, is set by the service information block in the transmitting equipment and, in a similar way, by its copy in the receiving equipment.

Stage 6. A modulated signal of an individual information channel is formed using individual quasi-orthogonal code sequences obtained by functional transformations of random functions obtained at the previous stage.

Stage 7. With the help of the formed set of quasi-orthogonal code sequences, digital information is simultaneously transmitted by all active subscribers of the transmitting equipment via a wireless communication channel. In this case, in each information path, a complex signal is assigned to an individual information bit, the structure of which is determined by the signal number of the original system of binary quasi-orthogonal code sequences and the value of the transmitted bit. If the information bit is zero, then during its duration one period of the quasi-orthogonal code sequence of the direct structure is transmitted, and if the information bit is equal to one, one period of the quasi-orthogonal code sequence of the inverse structure is transmitted.

Stage 8. A combined baseband signal is formed using a phase modulation unit and a power amplifier, which is emitted by the transmitting antenna of the transmitting part of the information transmission system.
Stage 9. With the help of the generated set of copies of the system of binary quasi-orthogonal code sequences in the receiving equipment, high-frequency selection, correlation processing and extraction of the information bit are carried out, which is issued to the recipient of information.

Stage 10. After the transmission of the next information bit in each information path on the transmitting side, the system of binary quasi-orthogonal code sequences used as information carriers is changed on the basis of a new functional transformation, carried out as described in the third step of the method under consideration. This procedure is performed by a command issued by the service information block of the transmitting side.

Stage 11. After high-frequency selection, correlation processing and extraction of the information bit issued to the recipient, at the command issued by the service information unit of the transmitting side, on the receiving side, synchronously with the transmitting side, the system of binary quasi-orthogonal code sequences is changed, which is used as information carriers based on a new functional transformation, carried out as described in the third step of the considered method. In this case, a copy of the system of binary quasi-orthogonal code sequences generated and used in the receiving equipment for correlation processing will have a structure that coincides with the system of binary quasi-orthogonal code sequences generated and used in the transmitting equipment.

Stage 12. The information transfer process is carried out similarly to steps 6-11 of the considered method using a new system of binary quasi-orthogonal code sequences. Since the structure of quasi-orthogonal code sequences after the transmission of the next information bit changes synchronously in the transmitting and receiving equipment, and is also not reused due to their increased number in comparison with the known sequences, this provides an increase in the structural secrecy of the code division multiplex information transmission system. The process of transmitting information is carried out until a command is received from the service information block of the transmitting side to suspend information exchange.

3. Conclusion

The advantage of BCSs obtained on the basis of functional transformations of pseudo-random arguments is that the number of non-repeating BCSs is significantly greater than all known ones. For a BCS length of 4095, the advantage over the most numerous Kerdock sequences is more than 10,000 times, for a BCS length of 8191, an advantage over the most numerous Weil sequences is about 10,000,000 times, for a BCS length of 10230, an advantage over the most numerous Kerdock sequences is more than 1000 times.

With the stochastic use of binary quasi-orthogonal code sequences in a code division multiplexing information transmission system, obtained on the basis of functional transformations of pseudo-random arguments, they provide a higher structural (signal) secrecy in comparison with the case of using the known discrete quasi-orthogonal code sequences of Gold, Kasami, Kamaletdinov, Weil and Bent sequences.

The developed information transmission system with code division of channels and stochastic use of systems of binary quasi-orthogonal code sequences has the structure shown in Fig. 1, a distinctive feature of which is the presence of a block of functional transformations on the transmitting and receiving sides.

For the formation and stochastic use of SBQCT as spreading sequences obtained on the basis of functional transformations of random functions in accordance with the procedures described by expressions (2) - (6), it is proposed to use a block for setting initial functions, a block of functional transformations, a random number generator in the transmitting equipment and a block for setting the initial values. In the receiving equipment, it is similarly proposed to use a block for specifying copies of the original functions, a block for copies of functional transformations, a generator of copies of random numbers and a block for specifying copies of initial values.

The proposed method for transmitting information based on the stochastic use of binary quasi-orthogonal code sequences is carried out through the implementation of 12 stages.
A distinctive feature of the developed method is the formation using a random number generator, a block for setting initial functions, a block for setting initial values and a block of functional transformations in the transmitting equipment of systems of binary quasi-orthogonal code sequences obtained by functional transformations of random functions based on the invariance property of the probability differential (2), which are stochastically used as carriers of information.

4. Acknowledgment
This work was supported by the Russian Foundation for Basic Research, project No. 18-07-01020.

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