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DEVELOPMENT OF METHOD FOUNDATIONS FOR GENERATING NOISE-LIKE SIGNALS BASED ON DIRECT SEQUENCE SPREAD SPECTRUM OF TIMING SIGNAL STRUCTURES

The object of the research is the process of forming complex noise-like signals based on timer signal constructions in secure communication systems operating under conditions of electronic warfare and counteraction to electronic intelligence systems.

The problem addressed in the paper is the lack of a theoretical framework for spectrum spreading of non-positional signals. An example of such signals is timer signal constructions, which are characterized by a more complex and variable temporal pulse structure within a combination.

The research solves the problem of developing a direct-sequence spread spectrum method for non-positional signals with a variable temporal pulse structure. It is shown that the classical spread spectrum method, designed for positional signals with fixed bit interval duration, cannot be directly applied to timer signal constructions. The proposed method provides for spectrum spreading not of an individual time interval of a binary bit element, but of the entire timer signal combination. A necessary condition for spectrum spreading in this case is the optimal selection of timer signal design parameters. This ensures the required interference immunity of the signal constructions, taking into account the interference level in the channel and the assessment of structural concealment.

The obtained results made it possible to establish the relationship between interference immunity and the level of concealment of timer signal constructions. It is shown that varying the parameters of timer noise-like signal formation significantly complicates their detection, recognition, and analysis by electronic intelligence means. According to the results of correlation analysis, the correlation coefficient varies in the range from 0.125 to 0.516, indicating reduced predictability and an increased level of structural concealment of the generated signal constructions.

The effectiveness of the proposed solution is explained by the fact that reception of broadband constructions is possible only when the correlation receiver is configured according to the timer signal design parameters. This practically prevents the reception of broadband timer signals generated with different design parameters, as well as by means of conventional classical correlation receivers.

The practical application of the results is possible in the design of secure special-purpose communication systems operating under conditions of intensive electronic countermeasures.

Keywords: *timer constructions, noise-like signals, spectrum, stealth, interference immunity, radio electronic intelligence, correlation reception.*

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1. Introduction

In the conditions of constant increase in the intensity of electronic warfare (EW) and improvement of electronic intelligence (EI) means, the development of special and civil communication systems is important [1]. This necessitates the creation of new methods of covert transmission of signal-code structures [2]. Such transmission methods should ensure a low probability of detection, recognition and interception of signals even in the presence of multi-channel radio monitoring. Such properties are characteristic of noise-like signals, with which a certain level of energy concealment can be ensured.

The practical value of research in this area lies in the possibility of increasing the main indicators of interference immunity of communication systems: concealment [3] and noise immunity [4]. This helps to reduce the impact of active and passive interference on the signal transmission process, and also complicates the operation of EIR means in EW conditions.

An analysis of scientific publications shows that the vast majority of research is focused on methods of expanding the spectrum of positional signals. In [3], the main directions of application of pseudorandom sequences (PRS) are considered. The main PRS parameters are analyzed and the requirements for PRS in special-purpose radio networks with multiple access based on code division multiplexing are formulated. It is determined that for the task of direct spectrum extension, as a rule, PRS with a fixed structure are used, in particular, Gold, Kasami, M-sequences and their modifications. Such approaches provide acceptable correlation and energy characteristics, but their spectral structure remains relatively predictable. This is explained by the fact that the structure of such PRS is known in advance.

Some scientific works [5, 6] suggest the use of chaotic oscillations to form noise-like signals in order to complicate the work of electronic reconnaissance. However, in most such approaches, chaotic processes are used only as a source of PRS, and the signal transmission structure itself remains positional. This limits the potential for increasing structural concealment and does not allow the full use of the time component of the signal as an information-significant parameter.

At the same time, in scientific publications [7, 8] devoted to non-positional timer signal structures (TSS), the main attention is paid to the issues of increasing the spectral efficiency and bandwidth of communication channels. The issues of their use for spectrum expansion and increasing the secrecy of information transmission are considered fragmentarily, without forming a single theoretical basis and without analyzing the consistency of classical spectrum expansion methods with the fundamentally non-positional structure of timer signals.

Thus, the results of the literature analysis indicate that the existing spectrum expansion methods [3, 9], oriented to positional binary signal structures, cannot be applied to non-positional timer signals, which are characterized by variable element duration and complex time-structure organization. The absence of theoretically justified methods for the synthesis of broadband signals based on non-positional TSSs with controlled parameters determines the presence of an unresolved scientific and technical problem. It is precisely these limitations of existing approaches that necessitate the author's research aimed at developing theoretical foundations for expanding the spectrum of timer signal structures and assessing the impact of their formation parameters on the indicators of energy, structural, and information secrecy.

A promising direction for overcoming these limitations is the use of non-positional TSSs [10, 11], which fundamentally differ from positional binary codes by the variable pulse duration within the combination. The structure of such signals is determined by the parameters of their construction and can be purposefully changed, which makes it possible to form various ensembles of signal-code structures. The complex structure of TSSs makes it impossible to directly apply classical methods of spectrum spreading, in particular, SEM methods using PRS, pseudo-random hopping of the operating frequency (PPHOF), linear frequency modulation (LFM), and others. At the same time, in known works [12, 13] the theoretical foundations of the formation of noise-like signals based on TSSs, as well as the influence of their structural, energy and information parameters on the level of concealment and noise immunity, have not been sufficiently studied. In this regard, the scientific and technical problem of substantiating the methods of spectrum spreading of TSSs, taking into account their complex and parametrically variable structure, remains unresolved. It is also necessary to determine the conditions for increasing the structural concealment and noise immunity of the proposed noise-like signals [14].

The object of research is the process of forming complex noise-like signals based on TSS in protected communication systems operating in EW conditions and countering EI means.

The subject of research is a method of expanding the spectrum of non-positional timer signals to increase the noise immunity of transmission.

The aim of research is to develop a method for forming noise-like signals based on direct expansion of the TSS spectrum and determine the influence of their construction parameters on the correlation characteristics, the level of structural concealment and noise immunity.

In a practical aspect, the aim of research is aimed at creating prerequisites for increasing the efficiency of information protection in communication systems operating in EW conditions. This will contribute to the complication of the processes of detection and analysis of signals by EI means.

To achieve the aim of research, it is necessary to solve the following objectives:

1) to justify the feasibility of complicating the structure of noise-like signals by expanding the TSS spectrum in order to increase the indicators of concealment and noise immunity;

2) to justify the limitations of the application of the classical method of direct spectrum expansion to non-positional TSSs and to develop an algorithm for their spectral expansion taking into account the variable pulse duration within the signal combination;

3) to analyze the correlation properties of timer noise-like signals taking into account the influence of TSS parameters and the Walsh PRS structure and to develop a correlation reception method for restoring the structure of TSSpulses.

2. Materials and Methods

The main hypothesis of research is that a more complex structure of TSS allows to increase the structural concealment of noise-like signals in comparison with positional codes. It is important to assess the TSS capabilities to ensure a given reliability and the influence of this indicator on the level of structural concealment. The choice of optimal TSS parameters to ensure a given reliability allows to calculate the structural concealment of a noise-like signal. In this case, the level of interference in the channel, the intensity of the operation of EW means are taken into account, which allows the communication system to make the right decision about changing the structure of signal-code structures. This, in turn, increases the frequency, energy and information efficiency and complicates the detection of signals by electronic warfare means [14].

With positional codes, information is transmitted in the form of a sequence of pulses with a fixed bit duration t_0. It is this time interval that determines the basic basis of signal pulses and is used to implement spectrum spreading algorithms. At the same time, each bit occupies a clearly defined time position, which allows the use of various methods of modulation and spectral expansion of the positional pulse.

The complexity of the TSS structure is expedient to assess using the potential structural concealment indicator [14], which is determined by the number of possible signal structures N_p intended for transmitting information symbols

$$S = log_2 N_p. \quad (1)$$

The structural concealment S is aimed at increasing the complexity of recognizing the structure of signals that were intercepted by EI means. Let's evaluate the possibility of increasing the number of implementations N_p using timer coding on the time interval $T_c = n \cdot t_0$, where n – the number of Nyquist elements. An important parameter for constructing the TSS structure on the interval T_c is the time element Δ, with the help of which the pulse durations are formed

$$t_c = t_0 + k\Delta, \quad (2)$$

where $k = 0, 1, 2, ..., s(n-2)$. It is possible to see that according to (2) the TSS pulses with duration t_c are multiples of the basic element Δ (where $\Delta = t_0/s$; $s = 1, 2, 3, ..., l$ – integers) and must satisfy the Nyquist condition

$$t_c \geq t_0 = 1/\Delta F. \quad (3)$$

The number of Δ on the interval t_0 determines the value of the parameter $s = t_0/\Delta$. With this algorithm for forming signal structures, the energy distance between them decreases and depends on the value $\Delta < t_0$. Compared to bit-digital coding (BDC), this leads to an increase in the number of TSS implementations on the interval T_c

$$N_{rtss} = [ns - i(s-1)]!/i!(ns - is), \quad (4)$$

where i – the number of significant modulation moments. The parameters n, s and i essentially represent a set of keys for the synthesis of a different set of TSS combinations with different construction structures and the number of implementations. The choice of parameters n, s and i allows to adapt the TSS structure, taking into account the level of interference in the channel to the required level of noise immunity. It is obvious that increasing N_{rtss} allows to increase the structural TSS concealment by reducing the value Δ. At the same time, there is an opposite pattern between the requirements for increasing the structural TSS concealment and ensuring the specified noise immunity, which requires the optimal choice of parameters n, s and i. Formation of the TSS N_{rtss} implementation is possible by two methods:

1) selection of combinations by parameters n, s and i;

2) use of the quality equation [10].

Fig. 1 shows examples of TSS structures with different pulse durations and code spacing d_0 with parameters $n = 7$, $i = 3$, $s = 5$: $t_{c1} = 5\Delta$, $t_{c2} = 6\Delta$, $t_{c3} = 24\Delta$ – TSS-1; $t_{c1} = 6\Delta$, $t_{c2} = 10\Delta$, $t_{c3} = 19\Delta$ for TSS-2; $t_{c1} = 10\Delta$, $t_{c2} = 17\Delta$, $t_{c3} = 8\Delta$ – TSS-3. Between the combinations TSS-1 and TSS-2 the distance $d_0(\Delta) = 6$, between TSS-1 and TSS-3 – $d_0(\Delta) = 21$, between TSS-2 and TSS-3 – $d_0(\Delta) = 15$.

A characteristic TSS feature is the ability to implement noise-resistant coding, which is achieved by using implementations with a certain value of the minimum code distance d_0 between neighboring allowed combinations. The error detection and correction mode significantly reduce the number of TSS implementations. Fig. 2 shows the dependence of the number of implementations N_{rtss}, obtained by selection, on the minimum code distance d_0 for different TSS parameters n, s and i. For BDC with $n = 7$, the number of combinations in total $N_{rBDC} = 2^7 = 128$. For TSS with parameters $n = 7$, $s = 5$ and $i = 3$ the number of realizations is $N_{rtss} = 1771$, and at $s = 6$ the number of $N_{rtss} = 2925$. At $n = 8$, $s = 5$ and $i = 3$ there is an increase in the number of realizations $N_{rtss} = 3276$. It is possible to see that an increase in d_0 leads to a decrease in the number of combinations N_{rtss}. Noise-resistant coding based on TSS can be implemented provided that

$$d_0 \geq 2. \quad (5)$$

Fulfillment of condition (2) allows the formation of allowed and disallowed TSS combinations. For TSS it is proposed to use the Hamming code distance between two combinations taking into account the number of time intervals of elements Δ by which they differ

$$d_0 = \sum_{j=1}^{W} x_j \oplus z_j, \quad (6)$$

where x_j and z_j – the logical states of TSS segments ("0" or "1") along elements Δ; $W = n \times s$ – the number of elements Δ on the time interval T_c.

The process of selecting allowed TSSs is simplified when using the quality equation [7, 8]

$$\sum_{k=1}^{i} A_k x_k \equiv 0\left(\operatorname{mod} A_0\right), \quad (7)$$

where $A_k(k = 1, i)$ – a set of weighting coefficients, which are prime numbers; A_0 – the modulus value; x_k – the numbers of the sections of the significant modulation moments (SMM) of the t_{ci} pulses. If the structure of TSD combinations satisfies condition (7), then they are allowed. Table 1 presents samples of allowed implementations of TSSs, which are formed using the quality equation ($A_0 = 19$, $A_1 = 2$, $A_2 = 3$, $A_3 = 7$) for different values of n, s, i and $d_0 \geq 4$. The number of allowed combinations obtained is significantly less than with a complete search of all possible TSSs. For example, from the total number of implementations $N_{rtot} = 1771$ for $n = 7$, $s = 5$, $i = 3$ and $d_0 = 4$, using the quality equation, it is possible to get only $N_p = 93$ combinations, while with full brute force $N_p = 146$. With a further increase in the code distance, for example, with $d_0 = 5$, the number of implementations $N_p = 37$ decreases significantly, while with full brute force $N_p = 79$.

Therefore, when developing data exchange algorithms in communication systems, it is necessary to take into account the contradictory nature of two key indicators: structural secrecy S_{tss} and noise immunity. From Fig. 3 it is possible to see that an increase in one of these indicators leads to a decrease in the other, which requires careful balancing of parameters to achieve optimal results. To compensate for a possible decrease in the structural secrecy indicator S_{tss}, it is proposed to use different sets of signal structures $\{N_{tss}(d_0)\}$ with a certain value of d_0 for different information transmission sessions. This allows to dynamically adapt to the conditions of the communication channel and increase the overall secrecy of the system. Formally, this can be expressed through the equation for calculating structural secrecy

$$S_{tss} = log_2\left(\sum_{z=1}^{L} N_{tss}\left(d_0\right)\right), \quad (8)$$

where L – the number of TSS4 sets; $N_{tss}(d_0)$ – the number of signal structures in the i-th set with the parameter d_0.

Thus, the key to using TSS for the synthesis of noise-like signals is a reasonable choice of their construction parameters. Timer coding allows for a given interval T_c to form, compared to positional codes, a significantly larger number of TSS implementations depending on the parameters n, s and i. This creates the prerequisites for increasing the secrecy of signal structures. In this regard, it is relevant to analyze the influence of TSS parameters on the complexity of signal implementation, their noise immunity and the level of secrecy.

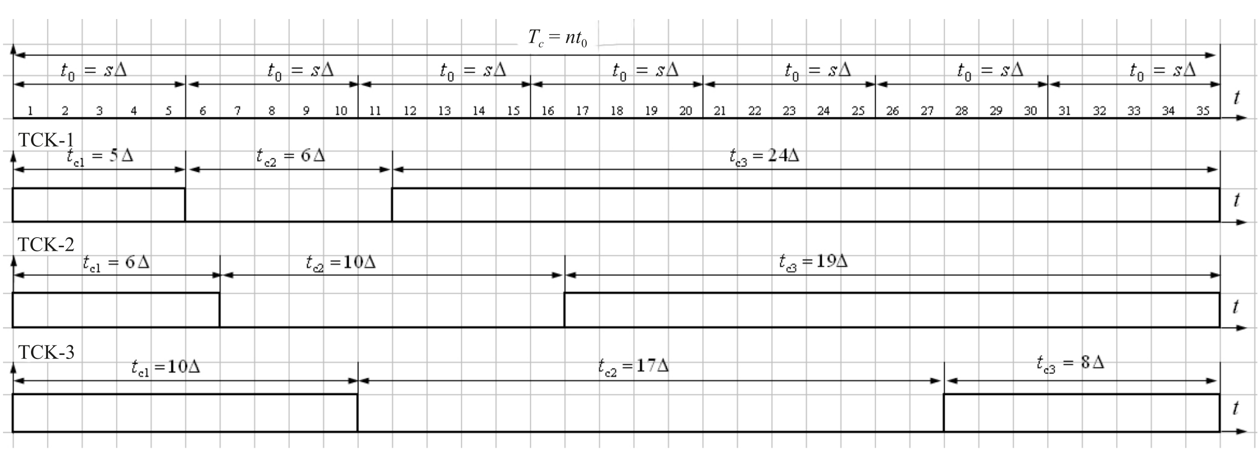

Fig. 1. TSS combinations with different values of $d_0(\Delta)$ on the time interval $T_c = 7t_0$

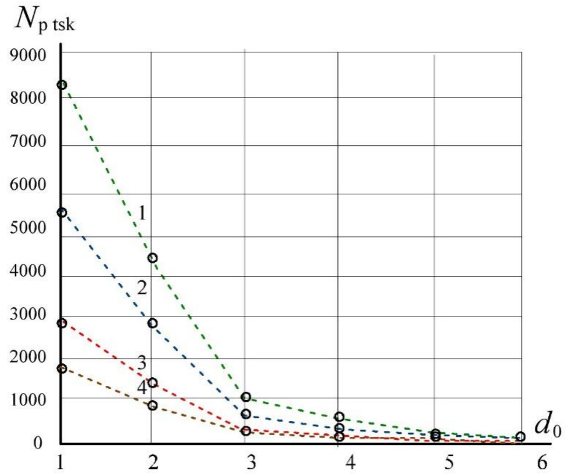

Fig. 2. Dependence of the minimum code distance d_0 on the number of realizations N_{rtss} for different TSS parameters: 1 – $n = 7$, $s = 5$, $i = 3$; 2 – $n = 7$, $s = 6$, $i = 3$; 3 – $n = 8$, $s = 6$, $i = 3$; 4 – $n = 8$, $s = 7$, $i = 3$

Table 1

Selections of allowed TSS implementations, which are formed using the quality equation ($A_0 = 19$, $A_1 = 2$, $A_2 = 3$, $A_3 = 7$) for different values of n, s, i and $d_0 \geq 4$

No.	TSS parameters			N_{rtss}	Implementations of allowed TSSs for the parameter d_0					
	n	I	s		4	5	6	7	8	9
1	7	3	5	1771	93	37	27	24	15	13
2	7	3	6	2925	154	59	43	41	23	19
3	7	3	7	4495	236	88	68	58	34	29
4	8	3	5	3276	173	65	52	40	27	22
5	8	3	6	5456	288	106	82	68	42	35
6	8	3	7	8436	444	156	123	98	60	49

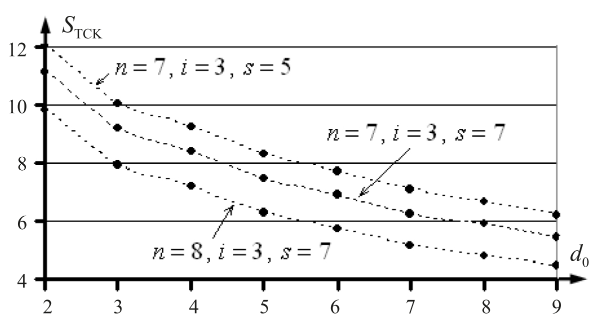

Fig. 3. Dependence of structural latency S_{tss} on d_0 for TSSs obtained by the selection method

The parameter n characterizes the dimension of the basic alphabet of durations from which TSSs are formed. With an increase in the value of n, the number of permissible TSS combinations on the interval $T_c = n \cdot t_0$ increases. At the same time, a significant increase in this parameter leads to a complication of the hardware and software implementation of the signal generation and decoding processes, which may limit their use in real-time modes.

The parameter s determines the value of the time interval Δ, on the basis of which, taking into account t_0, the pulse duration within the TSS is formed. This parameter significantly affects the level of structural latency and noise immunity. A decrease in the value of s contributes to an increase in noise immunity and a decrease in the requirements for synchronization accuracy, but at the same time reduces the structural latency of the signal. With an increase in the parameter s, the variety of timer code structures and the number of generated TSS combinations increase. This provides a higher level of structural secrecy, but requires solving more complex problems of ensuring stable cyclic and clock synchronization.

The parameter i specifies the number of SMMs, which can be both fixed and variable. The pseudo-random method of forming the value i ensures the unpredictability of the structure of the signal structure. This contributes to increasing the structural secrecy of the TSS and significantly complicates the process of restoring the signal structure by EI means during decryption.

Thus, the parameters n, s and i determine the variability of the key properties of the noise-like signal, in particular:

1) the complexity of implementing signal structures increases with increasing alphabet dimension and decreasing sampling step;

2) noise immunity improves due to the combined use of positional and non-positional noise-resistant coding;

3) structural secrecy increases with increasing number of N_{rtss} implementations on the interval T_c, which complicates the recognition of the signal structure by EI means without knowing the parameters and the timer coding algorithm;

4) the use of the TSS signal spectrum spreading method increases the concealment of the noise-like signal.

Taking into account the above, it is advisable to use an adaptive approach to selecting TSS parameters depending on the characteristics of the communication channel, the level of interference and the requirements for the level of security of the transmitted information.

3. Results and Discussion

3.1. Justification of the complexity of the structure of noise-like signals to increase interference immunity

One of the priority areas of development of modern radio communication systems is to ensure a given level of interference immunity, which includes protection of signal structures from interception and unauthorized access to transmitted messages. The concept of interference immunity covers a set of indicators that determine the effectiveness of the functioning of radio communication systems under the influence of interference and intentional interference. Among the main characteristics of interference immunity are resistance to radio electronic interference and a high level of concealment, which is divided into energy, structural, information and others.

Complicating the signal structure is a key approach to solving problems related to increasing the energy and structural concealment of signal structures [14]. This is especially relevant in conditions of interception of radio communication sessions by enemy EI means. In interference-protected radio communication systems, energy and structural concealment is achieved through the use of noise-like signals (NLS). It is known that the basis for NLS generation is the process of binary sequence spectrum expansion, which allows creating signals with low spectral density and high immunity to interference. Today, the development of NLS theory is aimed at the use of TSSs, which belong to the class of non-positional signals. Unlike classical positional signals, TSSs require the development of new NLS formation algorithms, since existing methods are focused on signals with a fixed structure. The introduction of timer NLS is justified in view of the need to increase the complexity of the signal structure, which contributes to a significant improvement in concealment indicators.

Timer signals have a number of advantages that make them promising for use in radio communication systems, especially in electronic warfare. The non-positional TSS structure significantly complicates the detection and analysis of the signal by EI means, since the absence of fixed time positions of signal elements makes it less predictable and more difficult to detect. The TSS structure does not require the use of check bits [10], which not only simplifies the implementation of

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noise-resistant coding, but also reduces the redundancy of code structures. The TSS advantage is the ability to form different ensembles of signal structures by varying the parameters n, s and i, which allows to adapt the transmission process to a specific state of the communication channel. However, along with the advantages, timer signals have disadvantages that must be taken into account in their practical application. The non-positional structure of TS requires the use of a more complex clock synchronization system for accurate restoration of time intervals. Adaptation of transmission parameters to the current state of the channel increases the requirements for computing resources and hardware complexity.

The synthesis of noise-like signals based on TSS ensures the achievement of such results. First, the use of a non-positional structure increases the level of structural concealment of signal structures, which complicates their analysis and recognition by EI means. Second, the TSS use as a noise-resistant code makes it possible to form allowed NLSs with reduced spectral predictability and increased resistance to intentional interference. Third, varying the TSS parameters ensures the adaptation of the signal structure to the current state of the communication channel, taking into account the requirements for noise immunity and concealment.

3.2. Algorithm for spreading the spectrum of non-positional timer signals

Unlike positional codes, timer signals have a variable pulse duration $t_c = t_0 + k\Delta$. This requires a different algorithm for spreading the spectrum, since the known method based on a fixed interval t_0 cannot be applied directly. For TSS, it is proposed to perform spectrum expansion not for individual pulses t_c, but over the entire interval of signal structure formation $T_c = t_0 \cdot n$. The number of PRS pulses used to expand the spectrum of the TSS combination is determined as

$$N_{\tau TSS} = B_{t_0} \cdot n, \quad (9)$$

where n – the number of elementary intervals within T_c; B_{t_0} – the signal base for the time interval t_0. The value of $N_{\tau TSS}$ must be a multiple of

$$N_{\Delta TSS} = s \cdot n, \quad (10)$$

where s – the number of possible values of pulse durations Δ. Increasing the values of the parameters s and n leads to an increase in the number of samples $N_{\Delta TSS}$ and, accordingly, to an increase in the base of the timer combination

$$B_{TSS} = N_{\tau TSS} \geq N_{\Delta TSS}. \quad (11)$$

Let's consider the synthesis of a noise-like signal on the interval $T_c = t_0 \cdot n$ by multiplying the TSS $x_{tssj}(T_c, \Delta)$ by the Walsh PRS $c_{PRSi}(\tau)$

$$X_{tss}(T_c, \Delta) = c_{PRSi}(\tau) \cdot x_{tssj}(T_c, \Delta). \quad (12)$$

As a result, each positive or negative value of the TSS $x_{tssj}(T_c, \Delta)$ is replaced by the corresponding PPRS pulses $s_{PRSi}(\tau)$. The use of phase modulation allows the formation of a noise-like timer signal

$$X_{tss\,pm}(T_c, \tau) = g(\tau) \cdot \cos(2\pi f_0 \tau + x_{tss}(T_c, \tau)). \quad (13)$$

3.3. Analysis of correlation properties of timer noise-like signals

A broadband signal based on direct spectrum expansion can be considered as a sequence of pulses or harmonics, the weighting coefficients of which are formed according to a pseudo-random law. In the general case, the signal is presented as an expansion in the basis of orthogonal functions

$$s(t) = \sum_{k=1}^{N_{ds}} a_k \varphi_k(\tau), \quad (14)$$

where a_k – weighting coefficients of random or pseudo-random sequences; $\varphi_k(\tau)$ – orthogonal or quasi-orthogonal basis functions; N_{ds} – dimension of the signal space.

It should be noted that the use of orthogonal functions when expanding the spectrum of positional signals does not provide a sufficient level of protection. This is explained by the fact that the structure of such a noise-like signal is predictable and can be restored using correlation analysis or statistical spectral monitoring. This reduces the effectiveness of countering EI means and justifies the need to use noise-like signals with a more complex and unstable structure.

Let's evaluate the TSS influence on the structure of a broadband signal when using direct spectrum spreading using Walsh PRS. Let's consider three TSSs with construction parameters $n = 4$, $s = 4$, $i = 3$ on the time interval $T_c = t_0 \cdot n$ with the following structure:

1) TSS-1: $t_{c1} = 4\Delta$, $t_{c2} = 7\Delta$, $t_{c3} = 5\Delta$;
2) TSS-2: $t_{c1} = 5\Delta$, $t_{c2} = 5\Delta$, $t_{c3} = 6\Delta$;
3) TSS-3: $t_{c1} = 6\Delta$, $t_{c2} = 4\Delta$, $t_{c3} = 6\Delta$.

To solve the spectrum spreading problem, it is possible to use different Walsh PRS with the following structure as a basis $B_{t_0} = 16$:

1) $c_{17} = \{1\ -1\ 1\ -1\ 1\ -1\ 1\ -1\ 1\ -1\ 1\ -1\ 1\ -1\ 1\ -1\}$;
2) $c_{37} = \{1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\}$;
3) $c_{47} = \{1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\}$;
4) $c_{07} = \{1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\}$;
5) $c_{55} = \{1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ -1\ 1\ 1\ -1\}$;
6) $c_{62} = \{1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\ -1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\}$.

Taking into account the given TSS parameters, the number of elements of the TSS expansion τ on the time interval T_c

$$N_{\tau TSS} = B_{t_0} \cdot n = 16 \cdot 4 = 64.$$

The number of elements Δ in the interval of the TSS construction

$$N_\Delta = n \cdot s = 4 \cdot 4 = 16.$$

The number of elements τ on the interval Δ

$$N_\Delta = B_t / s = 16/4 = 4.$$

In Table 2, using the correlation coefficient K_{cy}, an assessment of the influence of the TSS on the structure of the broadband signal is given.

Table 2

Assessment of the TSS influence on the structure of the broadband signal using the correlation coefficient K_{cy}

N	K_{cy}					
	c_{17}	c_{37}	c_{47}	c_{07}	c_{55}	c_{62}
TSS-1	0.125	0.135	0.126	0.125	0.135	0.126
TSS-2	0.375	0.387	0.387	0.375	0.387	–0.250
TSS-3	0.500	0.516	0.516	0.500	0.516	0.516

The shift of pulse durations $t_c = t_0 + k\Delta$ within the time interval $T_c = t_0 \cdot n$ creates an ensemble of signals with a variable structure. When expanding the TSS spectrum, the presence of shifts $\Delta = t_0/s$ changes the time structure of the Walsh sequence. This means that the adversary, even knowing the basic Walsh code, faces additional uncertainty in the signal design. Analysis of the correlation properties of broadband signals formed on the basis of TSS shows that the correlation coefficient K_{cy} between different implementations of signals significantly depends on the TSS structure and the selected Walsh PRS.

For example, for three different TSSs with parameters $n = 4$, $s = 4$, $i = 2$ and different pulse durations t_{c1}, t_{c2}, t_{c3}, different values of K_{cy} are observed for the same Walsh PRS (Table 2). When using the C_{17} PRS for TSS-1, TSS-2, TSS-3, it is possible to obtain the values of the correlation coefficient of 0.125, 0.375, 0.5, respectively. It is possible to see that changing the TSK structure leads to significant differences in the correlation properties of broadband signals, which makes it difficult to predict the exact duration of the pulses and their sequence. The structure of TSS pulses from a noise-like signal is restored using correlation reception after demodulation. Fig. 4 shows the time dependence of the voltage Ui at the output of the integrator of the correlation receiver within the TSS formation interval T_c. The abscissa axis shows the time, and the ordinate axis shows the level of the integrated voltage U_i. The graph has a broken triangular shape with clearly pronounced extrema, corresponding to significant moments of recovery (LTE – leading and trailing edges) of TSS pulses. Within the interval $T_c = 64\tau$, three time segments are distinguished: t_{c1}, t_{c2}, and t_{c3}, which determine the durations of individual pulses of the TSS-1 combination.

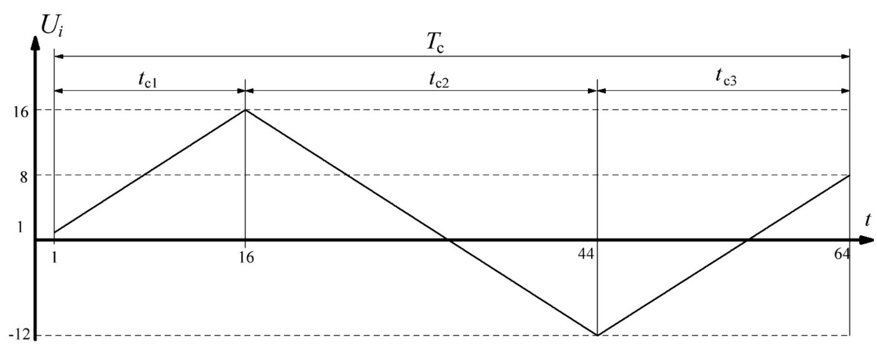

Fig. 4. Voltage level U_i at the output of the integrator of the correlation receiver for determining the durations t_{c1}, t_{c2}, t_{c3} of the TSS-1 combination

At the interval $t_{c1} = 16\tau$, the voltage increases to a local maximum, which corresponds to the accumulation of energy in the correlated signal section. Then, at the interval $t_{c2} = 28\tau$, a decrease to a minimum value is observed, which reflects the change in the LTE polarity of the TSS pulse. At the final interval $t_{c3} = 20\tau$, the voltage increases again, forming the next integration section. The maximum and minimum points are the LTE (leading and trailing edges), since it is by their coordinates that the durations of the t_{c1}, t_{c2}, t_{c3} pulses are determined. Within the interval

$$\Omega = [-\delta, \delta], \tag{15}$$

decision is made for each LTE on the position of the leading and trailing edges of the TSS pulses. The value of δ is determined by the code distance d_0 between the allowed combinations of TSSs: at $d_0 = \Delta$ the interval $\delta = \Delta/2$, and at $d_0 = 2\Delta$ let's obtain $\delta = \Delta$.

3.4. Discussion of the research results

The practical significance of the research is that the obtained results can be used in the design of special-purpose interference-protected radio communication systems operating in electronic warfare conditions. The proposed algorithm for expanding the spectrum of non-positional TSSs is expedient to be used in broadband systems with increased requirements for structural and energy concealment. The developed method of correlation reception with determination of pulse durations by the coordinates of the points of the extremum of the voltage from the integrator output can be implemented in real-time digital receivers, in particular in adaptive data transmission channels.

The limitations of research are that the results were obtained on the basis of analytical modeling and experimental calculations for a limited set of TSS parameters and fixed Walsh PRSs. It is advisable to expand the research to other TSS structures using random or quasi-orthogonal sequences of spectrum spreading, as well as with an increase in the B_{TSS} signal base. Practical implementation requires additional verification by simulation modeling in channels with different types of interference: additive, narrowband and pulsed. Prospects for further research should be directed to optimizing TSS parameters according to the criteria of minimizing cross-correlation and maximizing concealment. It is promising to develop adaptive algorithms for selecting spectrum spreading parameters depending on the current state of the interference level in the communication channel. Separate work requires the formation of a generalized metric for a comprehensive assessment of noise immunity and structural, energy, and information concealment of timer noise-like signals.

4. Conclusions

1. The feasibility of complicating the structure of the NLS based on direct spread TSS spectrum to increase the noise immunity of radio communication systems has been substantiated. It has been established that the use of a non-positional structure of the TSS provides an increase in the level of structural concealment of the NLS due to the absence of fixed time positions of elements within the combination. Varying the parameters of the construction of the TSS n, s and i allows to form different ensembles of signal structures and adapt them to the current state of the communication channel. It has been determined that the increase in the complexity of the TSS structure is accompanied by an increase in the requirements for clock synchronization systems, computing resources and hardware implementation.

2. An algorithm for spreading the TSS spectrum has been developed, which takes into account the structure of the non-positional combination. It has been established that for the TSS, it is advisable to carry out the spread spectrum over the entire interval $T_c = t_0 \cdot n$, which requires the use of spread pulses $N_{\tau TSS} = B_{t_0} \cdot n$ taking into account the signal base B_{t_0}. It is shown that increasing the values of the parameters n and s leads to a proportional increase in the number of $N_{\Delta TSS}$ samples, which must be taken into account when choosing the TSD base B_{TSS}. The application of the procedure of multiplying TSD with PRS (in particular, Walsh sequences) and subsequent phase modulation for the formation of a timer noise-like signal is justified.

3. An analysis of the correlation properties of timer noise-like signals during direct spectrum expansion is carried out. It is established that a change in the TSS structure in interaction with Walsh PRS leads to a significant variation in the correlation coefficient K_{cy} in the range from 0.125 to 0.516, which indicates a decrease in the predictability of the signal. It is shown that the shifts of pulse durations $t_c = t_0 + k\Delta$ within the time interval of the combination $T_c = t_0 \cdot n$ form an ensemble of signals with a variable time structure, creating additional uncertainty even under the condition of a known PRS expansion. An algorithm for correlation recovery of TSS has been developed, which is based on determining the coordinates of the integrator voltage extrema in the interval $\Omega = [-\delta, \delta]$, where the parameter δ depends on the code distance d_0. This ensures the LTE determination of the TSS pulse within the time interval T_c of the combination.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other nature, which could affect the research and its results presented in this article.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

Authors' contributions

Volodymyr Korchynskyi: Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Project administration; ***Vitalii Kildishev***: Methodology, Investigation, Formal analysis, Software, Validation, Writing – review and editing; ***Daniyar Bektursunov***: Investigation, Software, Formal analysis, Visualization; ***Serhii Havel***: Methodology, Investigation, Resources, Writing – original draft, Validation; ***Vadym Stepanov***: Software, Validation, Formal analysis, Data curation; ***Vasyl Slavych:*** Investigation, Resources, Writing – original draft, Writing – review and editing, Funding acquisition; ***Ruslan Petrovskyi***: Investigation, Visualization.

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