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*This study investigates the process that forms noise-like timer signal structures with combined spectrum spreading in secure radio communication systems. The work addressed the scientific and technical problem related to the lack of methods for forming noise-like signal structures that provide comprehensive use of the advantages of timer coding, direct spectrum spreading, as well as pseudo-random tuning of the operating frequency, in order to improve covert structure and noise immunity of information transmission.*

*The results include a combined method devised for spectrum spreading of non-positional timer signals based on a combination of direct spectrum spreading and pseudo-random tuning of the operating frequency. The method provides spectrum spreading in the time and frequency domains, as well as the generation of multidimensional signal structures by varying the time intervals between pulses, using pseudo-random sequences, and tuning of the operating frequencies.*

*An analytical approach to assessing covert structuring of a combined signal has been proposed, taking into account the parameters of timer coding, manipulation, and spectrum spreading. It was established that even with relatively small values of the signal parameters, a high level of structural covertness was achieved, which significantly complicated its reproduction by means of electronic reconnaissance.*

*The results are attributed to the combination of timer coding with spread spectrum methods, which ensured the generation of time, code, and frequency uncertainty of the signal. Changing the timer coding parameters made it possible to adapt signal structures depending on the level of interference in the communication channel. The proposed method could be implemented when designing promising secure radio communication systems under conditions of random and intentional interference*

**Keywords:** timer signals, spread spectrum, covert structuring, pseudo-random reconfiguration of operating frequency

# DEVISING A COMBINED SPECTRUM SPREADING METHOD FOR TIMER SIGNAL STRUCTURES TO IMPROVE COVERT INFORMATION TRANSMISSION

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## 1. Introduction

In wartime, the design of information and communication systems is particularly important, characterized by a significant complication of the conditions for their functioning. The reasons are the active use of electronic warfare (EW) and high-tech ra-

dio intelligence systems [1]. Therefore, it is absolutely necessary to ensure the reliability, noise immunity, and secrecy of the transmission of signal-code combinations (SCCs), which is one of the key tasks in building protected communication channels.

It should be noted that the modern radio-electronic environment is characterized by its high dynamics, uncertainty,

and multifactorial influences [2]. This means that radio-electronic intelligence (REI) is capable of performing a complex analysis of signals in a wide frequency range. To this end, methods of spatial-temporal processing are used to detect even noise-like signals. To ensure greater efficiency in signal detection, the use of multi-position surveillance systems and intelligent signal processing algorithms is characteristic.

Known methods for ensuring secrecy are based on the use of fixed parameters for SCCs or classical types of modulation, which is the reason for the decrease in their efficiency [3]. This is due to the fact that even complex SCCs can be partially reconstructed or detected using modern methods of spectral, correlation, and statistical analysis. In addition, the assessment of the level of SCC secrecy is complicated by the lack of universal criteria because of uncertainty in the parameters for the communication channel and the influence of interference.

One of the effective ways to increase noise immunity and reduce the probability of detection is to use signal spread spectrum technologies. In particular, the pseudo-random frequency hopping (FHSS) method provides signal energy distribution in a wide frequency range [4]. This makes it more difficult to intercept and also increases resistance to narrowband interference and intentional interference. Such spread spectrum methods are usually focused on fixed SCC parameters and partially adapted algorithms for adjusting the operating frequency [5]. This reduces their effectiveness under conditions of variable interference levels and active countermeasures.

To protect information based on covert structuring, it is important to study non-positional signals, an example of which are timer signal structures (TSS) [6]. Covert structuring is aimed at complicating the recognition of the structure of the intercepted message by means of electronic intelligence. For TSS, information is determined not by amplitude or frequency parameters but by time intervals between pulses. This technique of forming SCC provides a high level of covert structuring since the signal does not have clearly pronounced signs of classical modulation [6]. In addition, TSSs are characterized by low correlation predictability, which complicates their analysis by means of radio intelligence. At the same time, the use of TSSs is accompanied by a number of limitations, in particular, increased sensitivity to time distortions, the need for precise synchronization, and reduced noise immunity under conditions of intense interference. This necessitates their combination with other methods for improving security [7]. In this regard, a promising direction is the integration of timer coding with various methods of spectrum spreading [8, 9]. These methods include the methods of direct spectrum spreading using pseudo-random sequences (DSS-PRS) [10] and FHSS [3]. Additional improvement of SCC efficiency by integrating different technologies of their construction can be achieved by adapting the signal parameters to the current state of the communication channel taking into account the level of interference and conditions of the radio-electronic environment [5, 11]. This will make it possible to dynamically change the frequency hopping rate, spectrum width, PRS structure, and timer coding parameters. It is assumed that this could provide not only increased noise immunity but also a decrease in the probability of signal detection due to the unpredictability of its parameters in time.

Thus, our analysis of current radio-electronic environment and existing methods for ensuring covertness reveals

their limited effectiveness under conditions of active radio-electronic countermeasures. Classical technologies of spectrum spreading, focused mainly on positional signal designs, have limited capabilities to ensure structural signal covertness. The use of non-positional timer signals opens up additional opportunities for increasing the stealth of noise-like signals. However, this requires a combination of timer coding with methods of spectral masking of the signal. In this regard, it is a relevant task to integrate timer coding with direct spectrum spreading technologies using DSS-PRS and FHSS; it will contribute to improving covert structuring and noise immunity of protected radio communication systems.

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## 2. Literature review and problem statement

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Analysis of research [1, 2] reveals that spread spectrum technologies are one of the key areas in increasing the security of radio systems under electronic warfare (EW) conditions. The use of these technologies allows for effective counteraction to interference and signal interception. However, they are mainly focused on positional signal structures, which makes them vulnerable to spectral and correlation analysis. In addition, research is focused on individual methods – either DSS-PRS or FHSS, without taking into account the possibility of combining them. The papers do not investigate the dynamic change of signal parameters depending on EW conditions, which is associated with the complexity of mathematical modeling of combined methods.

In work [3], current approaches to the analysis of spread spectrum signals based on FHSS and LFM are considered. The authors considered the development of effective time-frequency analysis methods for identifying and monitoring signals in real conditions. However, these methods are focused only on expanding the spectrum of positional sequences, which does not provide proper covert structuring. In addition, the integration of FHSS with other methods of spectrum spreading has not been studied since there are no unified models for such a combination.

In [4, 5], algorithms for dynamic selection of frequency channels and adjustment of signal parameters depending on the level of interference have been proposed. It has been proven that adaptation of transmission parameters could increase the noise immunity of communication systems. However, these algorithms have limited adaptability as they do not take into account the temporal structure of the signal, in particular, timer coding. The possibility of combining adaptive algorithms with timer signals has not been studied either, which is explained by the high computational complexity and the lack of a systematic approach to investigating multidimensional signals.

In [7], Chirp Spread Spectrum (CSS) modulation was investigated as the basis of LoRaWAN technology for IoT networks. The authors analyzed the possibilities of signal detection taking into account spectral characteristics. However, the use of CSS to improve covert structure of signals under EW conditions was not investigated, nor was the combination of this modulation with other spread spectrum methods, such as FHSS or timed signal designs, considered. The reason is the complexity of modeling combined methods and the orientation to the technical aspects of IoT networks without taking into account military applications.

In paper [10], the designs of sets of frequency hopping (FHS) sequences with low influence zone (LHZ) for

quasi-synchronous multiple access systems (QS-FHMA) were investigated. The authors proposed three new designs of LHZ FHS sets, tested for optimality with respect to the Peng-Fan-Li limit. However, the possibility of using these sequences to improve covert structure of signals under EW conditions, as well as their combination with other spread spectrum methods, was not investigated. This is hindered by the complexity of modeling combined methods and the emphasis on reducing mutual interference without taking into account secure communication systems.

In [12], the use of chaotic sequences to increase the cryptographic strength of systems with FHSS was examined. It was proven that such sequences provide higher unpredictability compared to classical PRSs. However, the possibility of combining chaotic sequences with timer signals to increase covert structuring was not considered; no methods for dynamic control of their parameters were proposed. This is due to the complexity of implementing chaotic generators in real time and the lack of standardized approaches to assessing efficiency.

In [8], timer coding was investigated as a means of increasing noise immunity and covert structuring. The authors show that such coding provides non-positional representation of information, which complicates their detection by means of REI. However, the integration of timer coding with broadband technologies (FHSS or DSS-PRS) was not investigated; no methods for spectral masking of timer signals were proposed. The limitations are due to the lack of unified models for combining TSS with broadband technologies.

In [13, 14], the possibilities of timer signals for increasing noise immunity and compressing the frequency band of the communication channel were explored. It was proven that timer signals make it possible to detect errors without additional check bits due to the peculiarities of constructing combinations. However, the integration of TSS with broadband technologies (FHSS or DSS-PRS) was not investigated, as well as methods of dynamic control of timer signal parameters. The problem is the complexity of mathematical modeling of combined methods.

In [15], the issue of information security of timer signals in confidential communication systems was investigated. The authors analyze the features of the use of time-controlled signals for information protection. However, the possibility of combining timer signals with modern methods of spectrum spreading (FHSS or DSS-PRS) was not considered, and methods for dynamic control of their parameters were not proposed. This is hindered by the complexity of mathematical modeling of combined methods and the focus on theoretical aspects without taking into account practical applications.

Our review of related literature showed the effectiveness of the DSS-PRS and FHSS methods for increasing the noise immunity of signals. At the same time, these methods were mainly used for positional signal structures. In turn, timer signals are characterized by high covert structuring but do not provide sufficient spectral masking and noise immunity under conditions of intense electronic countermeasures.

Therefore, a scientific and technical contradiction arises between the need to simultaneously ensure high covert structuring, noise immunity, and adaptability of signals to the conditions of the electronic environment and the limited capabilities of existing methods, which provide only some of the specified properties.

The scientific and technical issue is the lack of a method for forming noise-like signal structures that would provide comprehensive use of the advantages of timer coding, di-

rect spectrum spreading, and pseudo-random tuning of the operating frequency to improve covert structure and noise immunity of information transmission under conditions of electronic countermeasures.

To solve this task, it is necessary to devise a combined method for spreading the spectrum of non-positional timer signals and evaluate its effectiveness in terms of covert structuring indicators.

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### 3. The aim and objectives of the study

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The purpose of our study is to improve covert structure and noise immunity of information transmission under conditions of electronic countermeasures by devising a combined method for spreading the spectrum of non-positional timer signals based on the integration of DSS-PRS and FHSS technologies. This will make it possible to improve the level of covert structuring and noise immunity of communication systems under conditions of random and artificial interference.

To achieve the goal, the following tasks were set:

- to investigate the influence of the parameters of the construction of timer signal structures on the number of possible signal implementations and to determine the parameters suitable for implementing manipulation and spectrum spreading procedures;
- to assess the frequency and energy efficiency of timer signal structures compared to positional signals and to determine the features of their use for the formation of noise-like signals;
- to determine the sequence of stages in spreading the spectrum of timer signal structures based on DSS-PRS and FHSS and to assess covert structuring of the formed signal-code structures.

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### 4. The study materials and methods

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The object of our study is the process of forming noise-like timer signal structures with combined spread spectrum in secure radio communication systems.

The principal hypothesis assumes that the combination of non-positional timer coding with multi-level spread spectrum methods makes it possible to significantly improve covert structure, noise immunity, and adaptability of communication systems compared to positional signals.

At the same time, some assumptions were adopted in the research process, namely:

- 1) the communication channel is considered as a channel with additive noise and possible intentional interference;
- 2) the parameters of clock and cycle synchronization of the transmitter and receiver are considered to be consistent;
- 3) pseudo-random sequences have close to ideal correlation properties;
- 4) the operating frequency is adjusted within a given frequency range without loss of synchronization.

Also, in the study, a simplification of the mathematical model was accepted, specifically:

- 1) the influence of nonlinearities of the transmitting and receiving paths was not taken into account;
- 2) multipath signal propagation was estimated in general;
- 3) the analysis was carried out for discrete values of parameters  $m$ ,  $s$ ,  $i$ ,  $N_{prs}$  and  $N_f$ ;
- 4) the probabilities of realizations of SCC were assumed to be equally likely.

The theoretical basis of our research is the provisions of information theory, the theory of noise-like signals, methods of spectrum expansion, the theory of pseudorandom sequences, technologies of pseudorandom rearrangement of the operating frequency, timer coding, interference-resistant data transmission, and the construction of secure radio communication systems.

A wide range of different methods were applied for our study. In particular, the following ones were used:

- 1) mathematical modeling methods for describing the processes of TSS formation and combined spectrum expansion;
- 2) analytical methods – for deriving dependences of covert structuring, entropy, and integral base of the signal;
- 3) methods from probability theory and mathematical statistics – for assessing the uncertainty of signal implementations.

In addition, when conducting the research, the method of comparative analysis was used, which made it possible to compare the properties of the proposed approach with the classical methods of DSS-PRS and FHSS, as well as to determine the advantages of using TSS in secure communication systems.

During the research, the methods of system analysis and parametric optimization were also employed, which allowed us to evaluate the influence of parameters  $m$ ,  $s$ ,  $i$ , the length of PRS, and the number of operating frequencies on the level of covert structuring, immunity, and complexity of the system implementation.

## 5. Results of investigating the spectrum spreading of non-positional timer signal structures

### 5.1. Determining the influence of parameters for timer signal structures on covert structuring and the possibility of spectrum spreading

To solve the first task of our study, a specific problem was stated. The following was predefined:

- 1) a timer signal structure with the formation parameters  $m$ ,  $s$ , and  $i$ ;
- 2) the interval of formation of timer combination  $T_c = mt_0$ ;
- 3) a fractional time interval  $\Delta = t_0/s$ .

It was required to determine the number of possible implementations of timer signal structures  $N_p = f(m, s, i)$ , as well as to establish the influence of parameters  $m$ ,  $s$ , and  $i$  on the covert structuring of signal  $S_{str}$  and the possibility of implementing manipulation and spectrum spreading procedures.

Classical methods of spectrum spreading were based on the use of positional codes, in which information was transmitted in fixed time or frequency positions [16]. This approach provided a controlled spectral structure and supported the implementation of known modulation methods. Unlike positional codes, in timer signal designs information was encoded by the duration of time intervals between pulses [13]. This principle of signal formation led to the emergence of a more complex time structure and increased the covert structuring of the signal [15]. These features determined the need for a separate analysis of TSS parameters for the implementation of manipulation and spectrum spreading procedures.

In positional codes [16], information transmission was implemented using pulses of fixed duration  $t_0$ , which determined the basic clock interval of the synchronization system. This meant that each information bit occupied a specific time position, which made it possible to implement different types of modulation. When using multi-position modulation, the number of information bits transmitted per symbol was determined similarly to [16]

$$k_b = \log_2 M, \tag{1}$$

where  $M$  is the number of possible positions or states of the signal. This allowed us to increase the specific speed of information transmission [16]

$$\gamma_{sst} = \frac{k_b}{t_0}, \tag{2}$$

and contributed to increasing the efficiency of using the frequency resource of the communication channel.

Unlike positional codes, in TSS information was determined by the time structure of interpulse intervals  $t_c$  within the code combination  $T_c$  [13]. The model of signal pulse formation was described by the following expression

$$t_c = t_0 + k\Delta, \quad k \in \{0, 1, \dots, I\}, \quad t_0 > \Delta, \tag{3}$$

where  $t_0$  is the base interval;  $\Delta = t_0/s$  is the base element for forming the pulse duration  $t_c$ ;  $k$  is the interval variation index. From formula (3) it followed that the pulse duration  $t_c$  would be no less than the Nyquist interval  $t_0$ . Unlike positional coding, where a combination of bit intervals  $t_0$  was used, in TSS, when forming the signal structure, time pulses  $t_0$  and  $\Delta$  were taken into account. This provided the possibility of forming a much larger number of variants of TSS signal states [6] at a given time interval

$$T_c = m \cdot t_0, \tag{4}$$

where  $m$  is the number of Nyquist intervals. The number of implementations with a given number of information segments was determined from the formula given in [6]

$$N_p = \frac{[ms - i(s-1)]!}{i!(ms - is)!}. \tag{5}$$

The parameter  $m$  determined the number of basic intervals  $t_0$ , on the basis of which the TSS was formed. With an increase in parameter  $m$ , the number of possible combinations of signals  $N_p$  on interval  $T_c = mt_0$  increased, which increased the structural latency of TSS [15]

$$S_{str} = \log N_p. \tag{6}$$

The dependence of the number of TSS implementations  $N_p$  on  $m$ ,  $s$ , and  $i$  is given in Table 1. At the same time, an excessive increase in these parameters complicates the hardware and software implementation of generation, synchronization, and decoding, which may limit the use of TSS in real communication systems.

Table 1

Number of timer signals depending on  $m$ ,  $s$ , and  $i$

m \ s	i = 2				i = 3				i = 4			
	3	4	5	6	3	4	5	6	3	4	5	6
4	28	45	66	91	20	35	56	84	-	-	-	-
5	55	91	136	190	84	165	286	455	35	70	126	210
6	91	153	231	325	220	455	816	1330	210	495	1001	1820
7	136	231	351	496	455	969	1771	2925	715	1820	3876	7315
8	190	325	496	703	816	1771	3276	5456	1820	4845	10626	20475
9	253	435	666	946	1330	2925	5456	9139	3876	10626	23751	46376

The parameter  $s$  determined the fractional time interval  $\Delta = t_0 / s$ , which was used to form pulse durations  $t_c$ . The value of the parameter  $s$  significantly affected the technical characteristics of the TSS communication system. Smaller values of  $s$  simplified the implementation of synchronization and increased noise immunity but reduced the number of possible structural implementations of the signal. An increase in  $s$ , on the contrary, provided higher variability of the timer code (Table 1) and increased covert structuring. But at the same time, higher requirements were put forward for ensuring the accuracy of cyclic and clock synchronization.

The parameter  $i$  characterizes the number of significant modulation moments (SMMS) of the information states of pulse intervals  $t_c$  within the signal structure. The fixed value  $i$  simplified the procedure for forming the TSS and decoding when determining the significant recovery moments (SRMs) of intervals  $t_c$ . Pseudo-random variation in the value of  $i$  provided additional unpredictability of the signal structure, which increased covert structuring and made it more difficult to recognize the TSS by electronic intelligence means.

Thus, the combination of parameters  $m$ ,  $s$ , and  $i$  allowed us to purposefully change the properties of the noise-like signal. With an increase in  $m$  and a decrease in the time discretization step  $\Delta$ , the complexity of implementing signal structures increased. The non-periodicity of the time structure of the combinations contributed to an increase in the covert structuring of TSS. The large number of possible implementations  $N_p$  significantly complicated the analysis of the signal without knowledge of the timer coding algorithm. Additional use of TSS spectrum spreading methods allowed us to improve covert structure of noise-like signals. Taking into account the above, it is advisable to use an adaptive approach to selecting TSS parameters depending on the level of interference in the channel and the requirements for the security of information transmission.

For TSS, the manipulation process fundamentally changed as information was encoded not by the absolute position of the pulse but by the variation of TSS time parameters  $t_0$  and  $\Delta$ . In this case, the value of  $\Delta$  was  $s$  times less than  $t_0$ . This meant that when implementing a certain type of manipulation for TSS, it was necessary to take into account the value of parameter  $\Delta$  and a certain number of its states. For example, for binary phase shift keying (BPSK), one  $\Delta$  interval was sufficient. Two  $\Delta$  intervals were required for quadrature phase shift keying (QPSK). For high-order quadrature amplitude shift keying (QAM-16 and higher), the number of  $\Delta$  intervals increased significantly. The total number of modulation states was defined as

$$M_{nms} = 2^{k_\Delta}, \quad t_M = \Delta \cdot k_\Delta, \quad (7)$$

where  $k_\Delta$  is the number of time intervals  $\Delta$ ;  $t_M$  is the manipulation interval. Therefore, the parameter  $\Delta$  determined the minimum time resolution of TSS and directly affected the number of possible manipulation states, which should be taken into account when synthesizing noise-like signals.

Thus, it was established that parameters  $m$ ,  $s$ , and  $i$  determine the number of possible implementations of timer signals  $N_p$ , and hence the level of their covert structuring. It is shown that an increase in  $m$  and  $s$  leads to an increase in the set of possible signal states, while the parameter determines the complexity of the time structure of the signal. Our results became the basis for further research into the possibilities of manipulation and combined spreading of the spectrum of timer signals.

## 5. 2. Evaluating the frequency and energy efficiency of positional and timer signal structures

To solve the second task of our research, the next problem is stated. For positional and timer signals, the following were specified:

- 1) information transfer rate  $R$ ;
- 2) the width of the frequency band  $\Delta F$ ;
- 3) timer coding parameters  $m$ ,  $s$ , and  $i$ .

It was required to determine the frequency efficiency  $\gamma$ , to derive the dependences  $\gamma = f(R, \Delta F)$  for positional and timer signal structures and to evaluate the effect of timer coding parameters on the efficiency of using the spectral resource.

To conduct a comparative analysis, the frequency efficiency of the signals was estimated similarly to [13]

$$\gamma = \frac{R}{\Delta F}, \quad (8)$$

where  $R$  is the information transfer rate;  $\Delta F$  is the signal bandwidth.

For positional codes, the frequency bandwidth was determined using the following expression:

$$\Delta F_{PK} \approx \frac{1}{t_0}, \quad \gamma_{PK} = R_{PK} \cdot t_0. \quad (9)$$

For timer signals, taking into account (3), the spectrum width had a variable character and was determined using the following ratio

$$\Delta F_{TSK} \leq \frac{1}{t_c} = \frac{1}{t_0 + k\Delta}. \quad (10)$$

The resulting expression showed that the frequency efficiency of timer signals could be expressed as

$$\gamma_{TSK} \geq R_{TSK} \cdot t_0. \quad (11)$$

Under the same conditions of spectral resource use, the following relationship was fulfilled

$$\gamma_{TSK} \geq \gamma_{PK}. \quad (12)$$

Our analysis revealed that the variable time structure of TSS and the use of fractional time intervals  $\Delta$  provided more efficient use of the spectral resource compared to positional signal structures. Unlike classical signals, in TSS the signal structure was formed simultaneously in the time and frequency domains.

As a result of our study, it was found that timer signal structures provided an increase in the frequency efficiency and covert structuring of the signal by increasing the number of possible time implementations. The results confirmed the feasibility of using TSS as a basis for further implementation of the combined method for spectrum spreading.

## 5. 3. Determining the stages in combined spectrum spreading of non-positional timer signals and assessment of their covert structuring

The next problem is stated. We have specified the following:

- 1) timer signal  $x_{tsk}(T_c, \Delta)$  that was formed by parameters  $m$ ,  $s$ , and  $i$ ;
- 2) a set of pseudo-random sequences  $C = \{c_1, c_2, \dots, c_{N_{prs}}\}$ ;
- 3) a set of possible manipulation states  $M = \{m_1, m_2, \dots, m_{N_{ms}}\}$ ;
- 4) a set of operating frequencies  $F = \{f_1, f_2, \dots, f_{N_f}\}$ .

It was required to determine the sequence of stages in the formation of a noise-like signal  $x_{comb}(t)$  based on timer coding, direct spectrum spreading using pseudo-random sequences, and pseudo-random tuning of the operating frequency.

In this case, it was necessary to determine the covert structuring index  $S_{isc}^{PRS-FHSS}$  as a function of parameters  $S_{isc}^{PRS-FHSS} = f(N_p, N_{PRS}, N_{ms}, N_f)$ , and to evaluate the influence of the parameters of timer coding, manipulation, and frequency tuning on the level of covert structuring of the formed signal-code structures.

Fig. 1 shows the generalized structure of the proposed method. The problem was solved by sequentially applying timer coding, direct spectrum spreading using pseudo-random sequences, and pseudo-random tuning of the operating frequency.

The information message from the message source (MS) was received in the form of a sequence of bit-digital code (BDK) to the timer signal generation unit (TSC).

The first stage of spectrum spreading (SS) was implemented on the basis of DSS-PRS. Let  $x_{isc}(T_c, \Delta)$  be a binary timer signal generated on the interval  $T_c = mt_0$ , and  $c_{prs}(\tau)$  be a PRS on the interval  $t_0$ . In this case, the duration of the PRS elements satisfied the condition  $\tau \leq \Delta$ . The broadband signal was generated by multiplying the timer signal from PRS

$$x_{isc}(T_c, \tau) = c_{prs,i}(\tau) \cdot x_{isc,j}(T_c, \Delta). \quad (13)$$

As a result, each element of the timer signal  $\Delta$ , which took the value “+1” or “-1”, was replaced by the corresponding PRS pulses with a duration of  $\tau$ . The use of direct and inverted PRS ensured the preservation of the polarity of TSS pulses and made it possible to restore them during correlation reception.

Next, the process of manipulation of the obtained sequence  $x_{isc}(T_c, \Delta)$  was carried out. At the same time, the parameters of the signal  $x_{isc}(T_c, \Delta)$  were consistent with the chosen modulation method, in particular, phase manipulation (FM-2). As a result, a noisy signal was formed at the output of the phase modulator

$$x_{bisk}^{fm}(T_c, \tau) = g(\tau) \cdot \cos\left(\frac{2\pi f_0 \tau +}{+x_{isc}(T_c, \tau)}\right). \quad (14)$$

The implementation of DSS-PRS for TSS provided the formation of SCC with a uniform energy distribution in a wide frequency band and an autocorrelation function characteristic of broadband signals. Then a certain method of FHSS was used.

Fig. 2 shows an example of the generation of a noise-like TSS  $x_{b_isc}^{fm}(T_c, \tau)$  with parameters  $m = 4$ ,  $s = 4$ ,  $i = 2$  and  $B_0 = 16$ . The process of expanding the TSS spectrum (Fig. 2, a) was determined not by interval  $t_0$ , as for RCC, but by the entire TSS generation interval  $T_c$ . Under such conditions, the number of spreading pulses was  $N_{isc} = B_t \times m = 64$  (Fig. 2, b), which was determined by parameters  $B_0$  and  $m$ .

The second stage of spectrum spreading was implemented using the fast FHSS method. Each block of elements  $\Delta$ , previously expanded using PRS (Fig. 2, c) and modulated,

was transmitted at the operating frequency  $f_i$ , which was selected from the set

$$F = \{F_{min}, F_{min} + \Delta f, \dots, F_{max}\}, \quad (15)$$

according to the pseudo-random law. After phase manipulation, the generated noise-like timer signal  $x_{bisk}^{fm}(T_c, \tau)$  (Fig. 2, d) was subjected to additional spectrum spreading by rapid frequency tuning (Fig. 3, a). In general, the generated signal was represented as

$$u'(t) = x_{bisk}^{fm}(T_c, \tau) \cdot U_0 \cos(\omega(g(t))t), \quad (16)$$

where  $\omega(g(t))$  is the instantaneous angular frequency, which was determined by the control pseudorandom sequence  $g(t)$ .

At the final stage, the generated noise-like signal was transmitted to the communication channel. Due to the constant change in the spectrum spreading sequences and frequency positions, the frequency structure of the signal acquired a dynamic character. That made it difficult to detect and demodulate it without knowledge of the algorithms for generating PRS and frequency tuning.

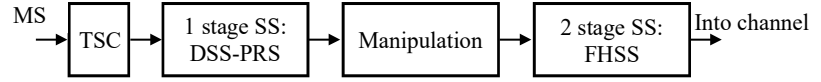


Fig. 1. Generalized structure of the combined TSC spread spectrum method for generating a noise-like signal

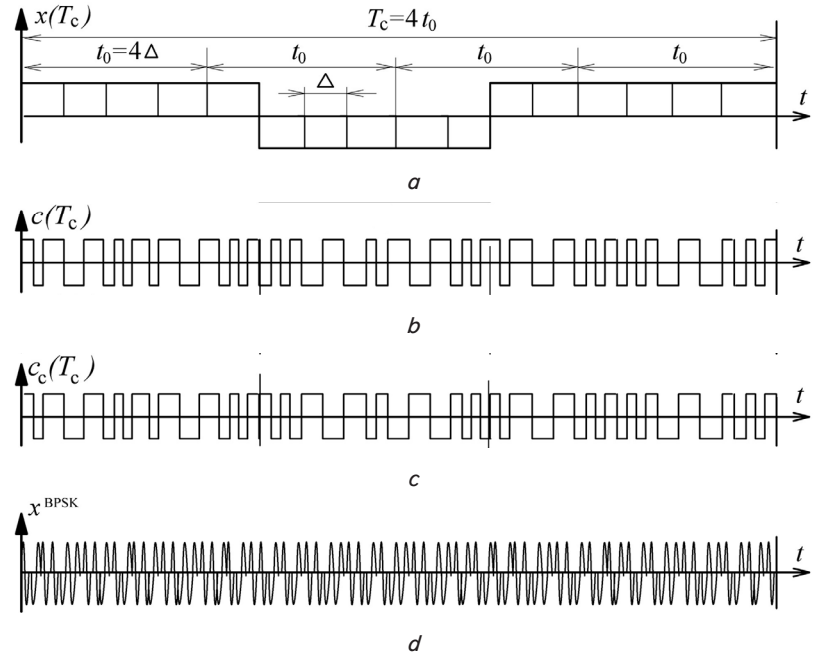


Fig. 2. The first stage in the combined method for spreading the spectrum of timer signal structures based on direct spectrum spreading: a – timer signal structure; b – pseudo-random sequence; c – signal after direct spectrum spreading; d – modulated noise-like signal

To quantitatively assess the effectiveness of the combined approach, the covert structuring indicator was used

$$S_{isc}^{PRS-FHSS} = \log_2 N_p + \log_2 N_{prs} + \log_2 N_{ms} + \log_2 N_{fms}, \quad (17)$$

where  $N_p$  is the number of TSS implementations;  $N_{prs}$  is the number of PRS;  $N_{ms}$  is the number of manipulation states;

$N_{fhss}$  is the number of frequency positions. The contribution of FHSS to the overall level of covert structuring was described by the following expression

$$\log_2 N_{fhss} = S_{tsk}^{fhss}. \tag{18}$$

Calculations showed that at parameters  $m = 4, s = 4, i = 2, N_{tsk} = 2^{16}, N_f = 32$  and using FM-2, the structural latency was

$$S_{tsk}^{PRS-FHSS} = \log_2 45 + \log_2 2^{16} + \log_2 2 + \log_2 32^{16} = 102 \text{ bin. ext.}$$

Our result showed that even with moderate values of parameters  $N_{tsk}, N_f, m$  and  $s$ , a high level of covert structuring of the noise-like signal was ensured. To restore the structure of such a signal, a potential intruder would need to check about  $2^{102}$  possible options. This practically excluded the possibility of operational signal reproduction. This result is explained by the generation of a multidimensional signal structure, in which time, code, and frequency methods of spectrum spreading were simultaneously implemented. The integral basis of the combined signal was defined as

$$B_{comb} = B_{i_0} \cdot B_f, \tag{19}$$

where  $B_{i_0}$  – base of the DSS-PRS signal;  $B_f$  – base of the FHSS signal. The use of the combined method enabled generation of signals with increased entropy. According to the provisions by K. Shannon, the entropy of the signal source was determined as

$$H = -\sum_i p_i \log_2 p_i, \tag{20}$$

and characterized the degree of uncertainty of the signal. In this formula,  $p_i$  is the probability of the  $i$ -th SCC, which was determined by a specific combination of parameters in the “time-frequency-code” space.

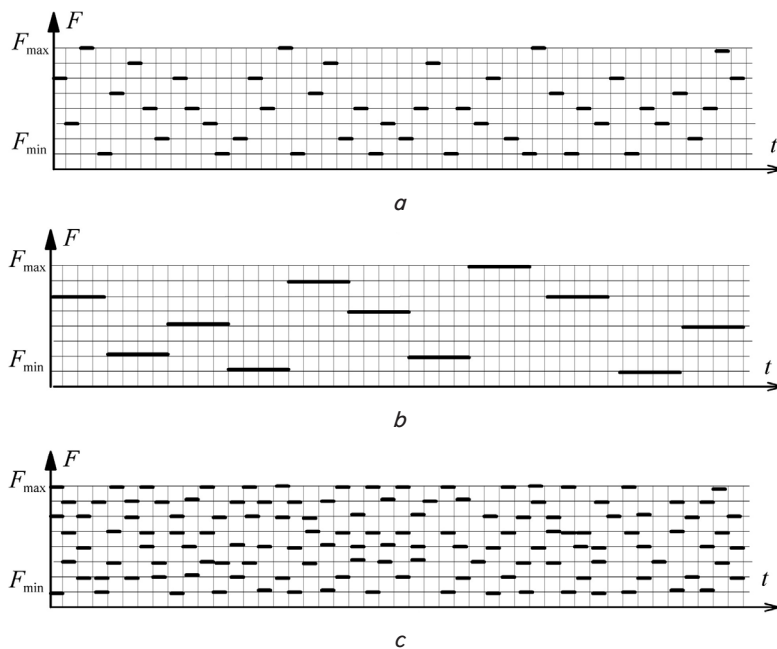


Fig. 3. The second stage in the combined method for extending the spectrum of timer signal structures based on pseudo-random tuning of the operating frequency: *a* – fast frequency tuning; *b* – slow frequency tuning; *c* – multi-channel frequency tuning

With the combined use of the DSS-PRS and FHSS methods to expand the TSS spectrum, the signal structure became more complicated. This was manifested in an increase in the dimensionality of the signal space due to the independent variation of the TSS time parameters, frequency characteristics, as well as the amplitude-phase components of the signal. At the same time, the number of possible realizations of the signal during a given time interval increased significantly, which increased its uncertainty for an outside observer. In addition, the statistical characteristics of such a signal approached the properties of a pseudo-random (quasi-stationary) process, which complicated its analysis and reproduction by means of electronic reconnaissance. Under the condition of statistical independence of the specified processes, the total entropy of the combined signal was given in the form

$$H_{comb} \approx H_{i_0} + H_f, \tag{21}$$

which was consistent with the increase in the integral signal base  $B_{comb} = B_{i_0} \cdot B_f$ .

One could see that the increase in the  $B_{comb}$  value led to an exponential increase in the number of possible SCCs. This provided an increase in the covert structuring of the signal and complicated the tasks of synchronization, detection, and classification of the signal by means of electronic reconnaissance. At the same time, varying the  $B_{comb}$  value of the combined signal allowed for adaptive control over the SCC transmission parameters depending on the current state of the communication channel. In particular, an increase in  $B_{comb}$  led to an increase in the entropy of the signal and, as a result, to an increase in the noise immunity and the level of SCC covert structuring. In turn, a decrease in  $B_{comb}$  ensured more efficient use of the frequency resource and reduced energy costs for signal transmission.

Thus, the optimal choice  $B_{i_0}$  and  $B_f$  provided the possibility of adapting SCC to the current level of interference in the communication channel to achieve the necessary balance between noise immunity and covert structuring.

It should be noted that the expansion of the TSS spectrum based on DSS-PRS was combined with different techniques for implementing FFHS: slow, high-speed, and multi-channel. The choice of a specific technique was determined by the requirements for noise immunity, covert structuring, and bandwidth of the system.

The slow FFHS technique (Fig. 3, *b*) involved changing the operating frequency in an interval exceeding the duration of one or more elements  $\Delta$ . This simplified the implementation of synchronization but reduced the level of protection against intentional interference.

The high-speed FFHS technique, on the contrary, provided for changing one or more carrier frequencies within the interval  $\Delta$ . This significantly increased noise immunity and complicated the process of signal detection by electronic warfare means but required increased accuracy of the clock synchronization system for matching the transmitter and receiver.

The multi-channel FHSS technique (Fig. 3, *c*) involved the simultaneous use of several frequency channels, which provided the possibility of implementing spatial-frequency signal diversity

and additionally increased the noise immunity and bandwidth of the system.

Therefore, the use of adaptive algorithms for selecting the FHSS technique allowed us to dynamically change the frequency tuning parameters depending on the state of the communication channel and the radio-electronic environment.

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## 6. Discussion of results related to the generation of a noise-like timer signal based on combined spectrum spreading

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Our results include analysis of the structure and parameters of timer signals, the assessment of their frequency efficiency, and the development of a combined method for TSS spectrum spreading.

When using non-positional TSSs, there was a possibility of a significant increase in the number of combinations (5) compared to classical RCCs. This was achieved by encoding information not by fixed time positions  $t_0$  but by the durations of interpulse intervals  $t_c$  (3) within the combination  $T_c = mt_0$  (4) [6]. It was found that the covert structuring and noise immunity were influenced by the TSS construction parameters  $m$ ,  $s$ , and  $i$ . A contradiction was found between the indicators of covert structuring and noise immunity. An increase in the value of  $m$  led to an increase in the number of possible TSS implementations  $N_p$  (Table 1) and, therefore, to an increase in the covert structuring of the signal (6).

The increase in the number of implementations  $N_p$  (Table 1) also occurred due to the increase in the value of  $s$ . At the same time, the basic time element  $\Delta$  (3) decreased, which allowed the generation of more variable structures of timer signals. As a result, the energy distance between neighboring TSSs decreased, which caused a drop in noise immunity. In addition, the processes of synchronization, generation, and decoding of signals became more complicated.

Another option for increasing the number of TSS implementations  $N_p$  was the use of combinations with different numbers of SMMs  $i$  (Table 1). This complicated determining the SRM during decoding and required higher requirements for the complexity of the transmitter and receiver. Analysis results also confirmed that the pseudo-random variation of the parameter  $i$  provided additional uncertainty in the signal structure and complicated its recognition by means of electronic reconnaissance. Thus, the combined use of parameters  $m$ ,  $s$ , and  $i$  allowed us to adaptively change the properties of the noise-like signal depending on the requirements for covert structuring and the level of interference in the communication channel.

The manipulation process for TSS fundamentally changed as information was encoded not by the position of SMM pulse  $t_0$  [3] but by the variation in time intervals  $t_c$  (3) within the code combination  $T_c$ . This meant that to implement a certain type of manipulation, it was necessary to take into account the value of parameter  $\Delta$  and a certain number of its states (7).

The results of our analysis of frequency efficiency  $\gamma_{TSK}$  (11) showed that TSS provided more efficient use of the spectral resource  $\Delta F_{TSK}$  (10) compared to the positional codes  $\Delta F_{PK}$  (9) [10]. It was found that the variable structure of interpulse intervals  $t_c$  (3) allowed us to further increase the signal space in the time domain without increasing the frequency band  $\Delta F$ . This was achieved by reducing the energy distance between adjacent timer signals.

It was found that under the same conditions of using the spectrum  $\Delta F_{TSK} = \Delta F_{PK}$ , the frequency efficiency of TSS (10) was greater than for positional signals. The results confirmed the prospects of using TSS for the synthesis of noise-like signals by expanding the spectrum in both the time (14) and frequency domains (16). Unlike the classical noise-like signals based on DSS-PRS and FHSS, considered in [10, 16], the proposed method added a third level of uncertainty – a timer structure (Table 1).

It has been shown that the growth of the integral base of signal  $B_{comb}$  (19) led to an exponential increase in the number of possible realizations of the signal and an increase in covert structuring. The results of our calculations confirmed that even with relatively small values of the parameters for generation of a noise-like signal ( $m = 4$ ,  $s = 4$ ,  $i = 2$ ,  $N_{PRS} = 2^{16}$ ,  $N_f = 32$  and FM-2) a high level of covert structuring was achieved –  $S_{str} = 102$  bits (17). This meant that in the event of unauthorized interception of a message, it would be necessary to check about  $2^{119}$  possible options to restore the structure of such a signal. That practically has made it impossible to quickly restore the signal structure [17] under conditions of electronic countermeasures.

It should be noted that the proposed combined method for generating a noise-like signal has a certain number of limitations on the range of input parameters ( $m$ ,  $s$ ,  $i$ ,  $N_{PRS}$  and  $N_f$ ) for building signal structures. In particular, parameters  $m \leq 10$ ,  $s \leq 7$  were adequate from the point of view of ensuring the necessary balance between covert structuring and noise immunity. However, further increasing the values of parameters  $m$  and  $s$  in order to increase covert structuring led to a decrease in noise immunity.

The main drawback of our study is the lack of methods devised for clock and cycle synchronization. This was an important component as a given communication system is sensitive to the accuracy of synchronization of time intervals: when the value of  $\Delta$  is reduced, even a slight error could lead to erroneous decoding of the interval  $t_c = t_0 + k\Delta$ . The prospect of eliminating this drawback is the introduction of adaptive algorithms for adjusting the time grid and the use of pilot signals with increased energy to stabilize the synchronization process. In addition, an increase in the computational complexity of the receiver was noted at large  $N_{PRS}$  and  $N_f$  values.

Further studies will combine timer signals with MIMO technologies to enable spatial signal diversity. In this case, mathematical difficulties may arise related to the need to construct new models for assessing the noise immunity of TSSs in multi-antenna systems. Methodological difficulties may also arise due to the high computational capacity of the joint optimization of parameters  $m$ ,  $s$ ,  $i$  and spatial gain coefficients in real time within a dynamically changing interference environment.

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## 7. Conclusions

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1. Based on the results of our analysis of the structure of non-positional timer signals depending on parameters  $m$ ,  $s$ ,  $i$ , the variability in the generation of different sets of signal structures has been established. Unlike positional methods, the use of timer signals has made it possible to form a larger number of implementations  $N_p$  at a fixed time interval  $N_c = mt_0$ . That provided an increase in the level of covert structuring and justified the feasibility of using timer signals

to protect transmitted information from unauthorized access. It was found that changing the parameters within  $5 \leq m \leq 10$ ,  $4 \leq s \leq 7$ ,  $2 \leq i \leq m - 1$  provided sufficient technical capabilities for implementing manipulation and spectrum spreading processes. A contradiction was found between covert structuring and noise immunity when increasing the values of parameters  $m$  and  $s$  as reducing the base interval  $\Delta$  led to a decrease in the noise immunity of the system. At the same time, the use of timer signals by changing parameters  $m$ ,  $s$ , and  $i$  allowed us to adapt the signal structures to the current state of the communication channel.

2. Based on the comparative evaluation of frequency and energy efficiency, it was found that the proposed timer signals demonstrated higher frequency efficiency  $\gamma_{TSK}$  compared to classical positional codes. Quantitative analysis confirmed the possibility of increasing the signal space in the time domain with an unchanged frequency band  $\Delta F_{TSK} \leq 1 / (t_0 - k\Delta)$ . This result is explained by the decrease in the energy distance between neighboring timer signals, which required more accurate clock synchronization.

3. The sequence of stages in combined spectrum spreading of non-positional timer signals has been determined, which included timer coding, direct spectrum spreading using pseudo-random sequences, signal manipulation, and pseudo-random reconfiguration of the operating frequency. It was established that the combination of time, code, and frequency spectrum spreading techniques enabled generation of a multidimensional signal structure and the growth of the integrated signal base. It has been shown that at parameters  $m = 4$ ,  $s = 4$ ,  $i = 2$ ,  $N_{PRS} = 2^{16}$ ,  $N_f = 32$ , the level of covert structuring  $S_{str} = 102$  bin. ext. was ensured. That corresponded to the need to check about  $2^{102}$  possible variants of signal-code constructions to restore the signal structure,

which significantly complicated its detection and analysis by means of electronic intelligence.

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#### Conflicts of interest

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The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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The study was conducted without financial support.

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#### Data availability

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All data are available in the main text of the manuscript.

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#### Use of artificial intelligence

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The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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#### Authors' contributions

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**Vadym Stepanov:** Methodology; **Volodymyr Korchynskyi:** Conceptualization; **Vitalii Kildishev:** Formal analysis; **Ruslan Zarovskiy:** Resources; **Serhii Havel:** Validation; **Vasyl Slavych:** Software; **Ruslan Petrovskiy:** Investigation.

#### References

- Zaitsev, D. V., Yafonkin, A. O., Yarema, V. V. (2021). *Osnovy v'v'iazku ta radioelektronna borotba yak vyd boiovoho zabezpechennia*. Irpin, 280. Available at: <https://ir.dpu.edu.ua/entities/publication/931c8879-4752-4096-a76d-6ab33b3b95e7/full>
- Sholokhov, S. M., Samborskyi, I. I., Vakulenko, O. V., Nikolaienko, B. A. (2021). *Zavadozakhyst radioelektronnykh zasobiv*. Chastyna 1. *Osnovy zavadozakhystu system v'v'iazku*. Kyiv: ISZZI KPI im. Ihoria Sikorskoho, 210. Available at: <https://ela.kpi.ua/handle/123456789/63622>
- Horbatiy, I., Usatyi, O. (2025). Investigation of spread spectrum signal analysis methods in modern communication systems. *Information and Communication Technologies, Electronic Engineering*, 5 (1), 125–135. <https://doi.org/10.23939/ict2025.01.125>
- Stasev, Y., Netrenko, K., Khmelnychenko, K. (2022). Method of synthesis of signals with pseudorandom tuning of the operating frequency. *Information Processing Systems*, 3 (170), 52–57. <https://doi.org/10.30748/soi.2022.170.07>
- Hrynenko, O., Kalchenko, V., Obodyak, V., Pugach, I., Savchenko, T. (2025). Adaptive pseudo-random reconfiguration of the operating frequency with information-extreme control for protected unmanned networks. *COMPUTER-INTEGRATED TECHNOLOGIES: EDUCATION, SCIENCE, PRODUCTION*, 60, 112–119. <https://doi.org/10.36910/6775-2524-0560-2025-60-11>
- Zaharchenko, M., Hadzhyiev, M., Salmanov, N., Shvets, N., Havel, S. (2021). Analysis and evaluation of qualitative and quantitative indicators of information when solving problems of construction systems of data transmission and transformation. *Cybersecurity: Education, Science, Technique*, 3 (11), 136–143. <https://doi.org/10.28925/2663-4023.2021.11.136143>
- Maleki, A., Nguyen, H. H., Bedeer, E., Barton, R. (2024). A Tutorial on Chirp Spread Spectrum Modulation for LoRaWAN: Basics and Key Advances. *IEEE Open Journal of the Communications Society*, 5, 4578–4612. <https://doi.org/10.1109/ojcoms.2024.3433502>
- Hordiichuk, V., Shyshatskyi, A., Korchynskyi, V., Kildishev, V., Pozdniakov, P. (2021). Timing pulse code modulation as a tool for quantization noise reduction in special-purpose IT systems. *Journal of Physics: Conference Series*, 1839 (1), 12005. <https://doi.org/10.1088/1742-6596/1839/1/012005>
- Burkinsky, B. V., Nazarenko, O., Laiko, O. I., Khadzhyradieva, S. (Eds.) (2024). *Sustainable development and digital innovations*. Odesa. <https://doi.org/10.31520/978-617-14-0253-9>

10. Tian, X., Han, H., Niu, X., Liu, X. (2023). Construction of Optimal Frequency Hopping Sequence Set with Low-Hit-Zone. *Entropy*, 25 (7), 1044. <https://doi.org/10.3390/e25071044>
11. Hordiichuk, V., Korchynskyi, V., Kildishev, V., Molodetskyi, B., Staikutsa, S., Alfaiomi, K. (2024). Adaptive Synthesis of Wideband Timer Signals in the Conditions of Radio-Electronic Warfare. 2024 IEEE 17th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET), 1–4. <https://doi.org/10.1109/tcset64720.2024.10755658>
12. Azim, A. W., Shubair, R., Chafii, M. (2024). Chirp Spread Spectrum-Based Waveform Design and Detection Mechanisms for LPWAN-Based IoT: A Survey. *IEEE Access*, 12, 24949–25017. <https://doi.org/10.1109/access.2024.3352591>
13. Zakharchenko, M. V., Horokhov, Y. S., Kril, A. S., Kovalchuk, S. V. (2015). Code division multiplexing in timer signals. *Modern Information Technologies in the Sphere of Security and Defence*, 24 (3), 38–42. Available at: <https://sit.nuou.org.ua/article/view/61290/>
14. Zaharchenko, M., Hadzhyiev, M., Salmanov, N., Golev, D., Shvets, N. (2020). Information parameters of codes that are synthesized on the basis of one module. *Cybersecurity: Education, Science, Technique*, 3 (7), 95–102. <https://doi.org/10.28925/2663-4023.2020.7.95102>
15. Zakharchenko, N., Korchinsky, V., Radzimovsky, B. (2012). Information security of time-controlled signals in confidential communication systems. *Modern problems of radio engineering, telecommunications and computer science: XI Int. Conf. TCSET. Lviv-Slavske*. Lviv: Publishing House of Lviv Polytechnic, 317. Available at: <https://ena.lpnu.ua/handle/ntb/14569>
16. Ristić, V., Todorović, B., Stojanović, N. (2022). Frequency hopping spread spectrum: History, principles and applications. *Vojnotehnicki Glasnik*, 70 (4), 856–876. <https://doi.org/10.5937/vojtehg70-38342>
17. Kaplan, B., Kahraman, I., Ekti, A. R., Yarkan, S., Gorcin, A., Ozdemir, M. K., Cirpan, H. A. (2021). Detection, Identification, and Direction of Arrival Estimation of Drone FHSS Signals With Uniform Linear Antenna Array. *IEEE Access*, 9, 152057–152069. <https://doi.org/10.1109/access.2021.3127199>