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A METHOD FOR FORMING ENSEMBLES OF COMPLEX SIGNALS BASED ON PARAMETERIZED STRUCTURAL TRANSFORMATION OF TIME SEGMENTS

Shubina H., Lysechko V. A method for forming ensembles of complex signals based on parameterized structural transformation of time segments. The article proposes a method for forming ensembles of complex signals based on parameterized structural transformation of time segments, which provides controlled modification of the internal signal structure. The method is based on the introduction of the parameter θ, which defines the rule for permuting time segments and allows regulating the correlation and structural characteristics of signal ensembles without altering their energy properties. This enables targeted reduction of the level of correlation sidelobes, integral correlation energy, and structural ordering of signals under complex interference conditions. To evaluate the effectiveness of the proposed method, simulation of the influence of the parameter θ on the correlation and structural characteristics of signal ensembles was performed. The evaluation was carried out using the peak sidelobe level (PSL), integrated sidelobe level (ISL), and structural entropy. The study covers a wide range of θ values, which makes it possible to analyze transitions between different modes of structural signal transformation and to establish patterns in the variation of signal properties depending on the degree of time-segment permutation. The experimental results showed that the use of the parameter θ provides a reduction of PSL and ISL values by up to 47% and a decrease in structural entropy by up to 26% compared to the baseline case. It was established that the minimum values of the considered indicators are achieved at θ≈0.618, which corresponds to quasi-uniform ordering of segments and ensures coordinated reduction of both correlation and structural characteristics of signal ensembles. The obtained results confirm the effectiveness of the proposed method and the feasibility of its application for forming signal ensembles with reduced correlation interference and an ordered structure under complex interference conditions.
Keywords: telecommunication systems, permutations, signal ensembles, time domain, correlation, entropy, interference resistance, optimization.

Шубіна Г.В., Лисечко В.П. Метод формування ансамблів складних сигналів на основі параметризованого структурного перетворення часових сегментів. У статті запропоновано метод формування ансамблів складних сигналів на основі параметризованого структурного перетворення часових сегментів, що забезпечує керовану зміну внутрішньої структури сигналу. Метод базується на введенні параметра θ, який визначає правило перестановки часових сегментів і дозволяє регулювати кореляційні та структурні характеристики сигналів ансамблю без зміни їх енергетичних властивостей. Це забезпечує можливість цілеспрямованого зменшення рівня бічних пелюсток кореляційної функції, інтегральної кореляційної енергії та впорядкування структури сигналів в складних завадових умовах. Для оцінки ефективності запропонованого методу проведено моделювання впливу параметра θ на кореляційні та структурні характеристики сигналів ансамблю. Оцінювання виконано за показниками пікового рівня бічних пелюсток (PSL), інтегрального рівня бічних пелюсток (ISL) та структурної ентропії. Дослідження охоплює широкий діапазон значень параметра θ, що дозволяє проаналізувати перехід між різними режимами структурного перетворення сигналу та встановити закономірності зміни його властивостей залежно від ступеня перестановки часових сегментів. Результати експерименту показали, що використання параметра θ забезпечує зменшення показників PSL та ISL до 47 % та зниження структурної ентропії до 26 % порівняно з базовим випадком. Встановлено, що мінімальні значення досліджуваних показників досягаються при θ≈0,618, що відповідає квазі-рівномірному упорядкуванню сегментів та забезпечує узгоджене зменшення кореляційних і структурних характеристик сигналів ансамблю. Отримані результати підтверджують ефективність запропонованого методу та доцільність його використання для формування ансамблів сигналів зі зниженим рівнем кореляційних завад і впорядкованою структурою в умовах складного завадового середовища.
Ключові слова: телекомунікаційні системи, перестановки, ансамблі сигналів, часова область, кореляція, ентропія, завадостійкість, оптимізація.

Statement of a scientific problem.

In modern telecommunication systems, particularly under conditions of high spectrum utilization, multiple-access interference, and dynamic channel variations, ensuring low mutual correlation between signals remains a critical challenge. The efficiency of signal separation and interference resistance largely depends on the correlation properties of signal ensembles, which necessitates the development of methods for their controlled formation.

Existing approaches to signal design primarily focus either on constructing sequences with predefined correlation characteristics or on analyzing the structural complexity of signals using entropy-based measures. However, these approaches do not provide a unified framework for controlled modification of the internal structure of signals while simultaneously accounting for correlation, energy, and spectral properties.

In particular, deterministic permutation-based methods enable the generation of signal ensembles but lack mechanisms for adaptive control of structural transformations and their impact on correlation characteristics. At the same time, entropy-based methods allow the evaluation of signal complexity but are not directly integrated into the process of ensemble formation.

Therefore, a scientific problem arises in the development of a method for forming ensembles of complex signals that ensures controlled structural transformation of time segments and provides simultaneous regulation of correlation and structural characteristics under interference conditions.

Research analysis.

Despite significant advances in signal processing and communication theory, the problem of forming ensembles of complex signals with controlled correlation properties and balanced structure remains relevant. The review of current approaches [1–17] includes methods of signal design, optimization of correlation characteristics, and entropy-based analysis of complex time-domain structures.

Fundamental studies [6, 8, 13] established the foundations of signal design with predefined correlation properties, enabling the development of approaches for constructing sequences with limited cross-correlation levels. Further development of these approaches is presented in works [4, 7, 14, 17], where new classes of frequency-hopping sequences and combinatorial construction methods were proposed to minimize correlation interference.

Studies [2, 9, 10] address modern approaches to the formation of signal ensembles and optimization of their correlation characteristics, including the use of permutations in time and frequency domains. The obtained results confirm the effectiveness of deterministic transformations in reducing mutual correlation and increasing the structural variability of signal ensembles.

A separate group of studies [5, 11, 12, 16] focuses on entropy-based signal analysis and complexity evaluation of time-series processes. These approaches provide quantitative measures of structural organization and dynamic properties of signals; however, they do not consider controlled modification of the internal signal structure during ensemble formation.

Works [1, 15] examine the characteristics of modern telecommunication systems operating under wideband conditions and high interference levels, which necessitate the use of signals with improved correlation properties.

Thus, the analysis of the literature indicates that existing approaches either focus on signal design with predefined correlation characteristics or on the assessment of structural complexity, but do not provide a unified framework for their joint consideration. The absence of a method that integrates parameterized structural transformation with the evaluation of correlation and structural properties determines the need to develop an appropriate method for forming ensembles of complex signals.

The purpose of the work.

The purpose of this work is to develop a method for forming ensembles of complex signals based on parameterized structural transformation of time segments, employing an operator for controlled modification of the signal structure with consideration of correlation, energy, and spectral properties, enabling increased ensemble size and reduced multiple-access interference.

Presentation of the main material and substantiation of the obtained research results.

In modern telecommunication environments, particularly in 5G NR, LTE, and cognitive radio networks, the interference conditions become increasingly complex due to high spectrum utilization, multi-user access, inter-channel interference, and dynamic channel variations. Addressing these challenges requires the development of methods for forming signals with controlled correlation and structural characteristics, ensuring improved interference resistance and efficient channel separation.

To this end, a method for forming ensembles of complex signals based on parameterized structural transformation of time segments is proposed. The step-by-step structure of the method is shown in Fig. 1.

A distinctive feature of the proposed method is the introduction of the control parameter θ, which defines the rule of structural transformation of signal time segments and determines the individual configuration of their ordering. In essence, the parameter θ provides a mechanism for controlled formation of the signal space, which is particularly important for systems with dynamic spectrum allocation and adaptive access (e.g., 5G NR and cognitive networks).

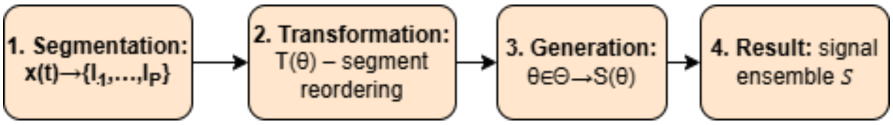

Figure 1 – Block diagram of the method for forming signal ensembles based on parameterized structural transformation of time segments

Unlike random or fixed permutations, the parameter θ establishes a deterministic law of structural signal transformation, enabling targeted modification of its internal time organization without altering its duration and energy balance. This ensures:

– adaptation of the signal structure to the interference level in the channel;

– controlled reduction of mutual correlation between signals within the ensemble;

– formation of a set of signals with different structural properties without modifying the base realization;

– improved interference resistance under multipath propagation, fading, and inter-system interference conditions.

Variation of the parameter θ leads to a transition from weak to strong structural transformations, enabling the formation of complex signal ensembles with predefined characteristics and their adaptation to network operating conditions (Table 1, Fig. 2).

Table 1 – Influence of parameter θ on signal structure

Value of θ	Transformation type	Structure characteristics	Expected effect
$\theta \approx 0$	Minimal changes	Close to the original	High correlation
$\theta \in (0,1)$	Quasi-random ordering	Moderately modified structure	Correlation reduction
$\theta \to \varphi$	Quasi-uniform distribution (irrational rule)	Uniform structure	Minimization of peak correlation values
$\theta \to 1$	Maximum permutation	Highly modified structure	Decorrelation, increase in ensemble size

As shown in Table 1, variation of the parameter θ provides a controlled transition between different modes of signal structural organization, enabling targeted influence on its correlation properties and the formation of signal ensembles with required characteristics for given interference conditions.

Figure 2 illustrates the mechanism of influence of the control parameter θ, which defines the rule for permutation of signal segments and determines its structure. The original signal $x(t)$ is divided into P time segments $\{I_0, I_1, \ldots, I_{P-1}\}$, each marked with a distinct color corresponding to its initial position in the signal structure. Variation of the parameter θ determines the permutation rule $\pi(\theta)$, according to which a new ordering of the segments is formed.

For small values of the parameter θ, the ordering of segments remains close to the original, corresponding to minor structural modifications of the signal. For intermediate values of θ, partial mixing of segments is observed, leading to moderate changes in the signal structure. At high values of θ, a significantly altered signal structure is formed with pronounced segment permutations. Thus, the parameter θ acts as a control factor governing the level of structural transformation of the signal.

The color coding in the figure enables visual tracking of the displacement of individual segments and the nature of their permutation (Fig. 3).

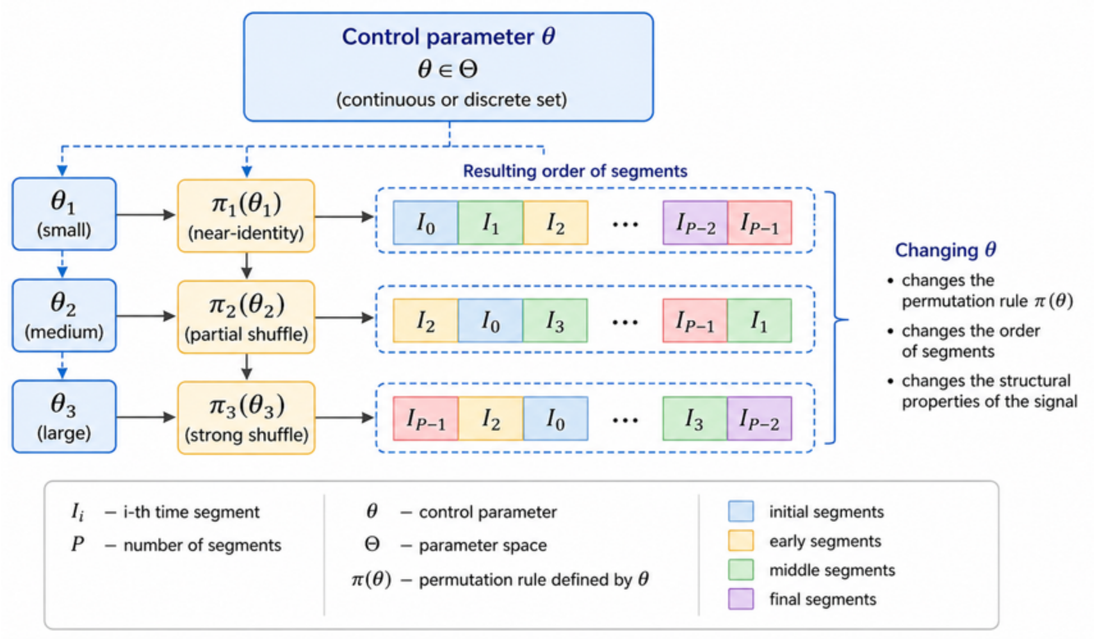

Figure 2 – Mechanism of the parameter θ influence on signal segment ordering

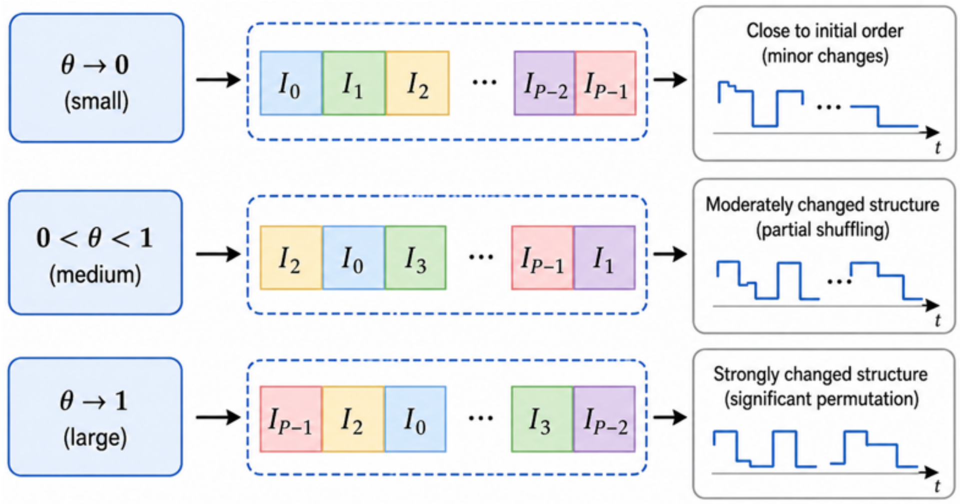

Figure 3 – Effect of parameter θ on signal structural transformation

Figure 3 presents a visualization of the transformation results for different values of the parameter θ, illustrating the variation in the degree of structural transformation of the signal, from preserving the original segment order to their permutation.

The generalization and formalization of this process in the form of a sequence of stages for implementing the signal ensemble formation method are presented in Fig. 4.

Let us consider in more detail the formalized model of the proposed method. Let the input signal *x(t)* be defined over the time interval *T*. At the first stage, the signal is divided into *P* time segments of equal duration:

$$\tau_0 = \frac{T}{P} \quad (1)$$

Then, the input signal can be represented as an ordered set of time segments:

$$x(t) \to \{I_0, I_1, \dots, I_{P-1}\} \quad (2)$$

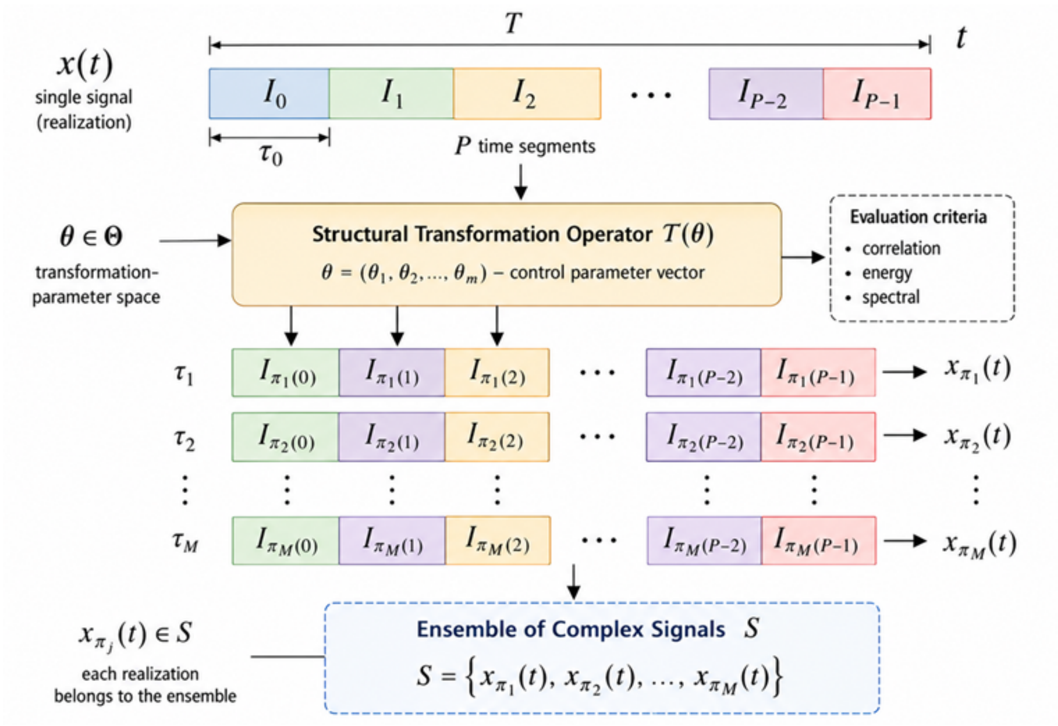

Figure 4 – Block diagram of the method based on parameterized structural transformation of time segments

For the formed set of segments, the structural transformation operator proposed in this study is applied:

$$\mathcal{T}(\theta): \{I_0, I_1, \dots, I_{P-1}\} \to \left\{I_{\pi_{\theta(0)}}, I_{\pi_{\theta(1)}}, \dots, I_{\pi_{\theta(P-1)}}\right\} \quad (3)$$

where $\theta \in \Theta$ is the control parameter, Θ is the space of admissible parameters, π_θ is the segment permutation rule determined by the value of θ.

As a result, a separate signal realization is formed for each value θ_m:

$$x_{\pi_{\theta_m}}(t) = \mathcal{T}(\theta_m)x(t), \qquad m = 1,2,3, \dots M \quad (4)$$

The collection of such realizations constitutes an ensemble of complex signals:

$$S = \left\{x_{\pi_{\theta_1}}(t), x_{\pi_{\theta_2}}(t), \dots, x_{\pi_{\theta_M}}(t)\right\} \quad (5)$$

The evaluation of the generated realizations is carried out using a set of correlation, energy, and spectral criteria. This enables the selection of structural transformation variants that ensure a reduction in mutual correlation between signals within the ensemble while preserving acceptable energy and spectral properties.

To verify the proposed method for forming ensembles of complex signals based on parameterized structural transformation of time segments, simulation of the influence of the control parameter θ on the correlation and structural characteristics of signal ensembles was performed.

The aim of the experiment was to determine the role of the parameter θ as a control parameter of the proposed method, which defines the degree of time-segment permutation and affects the level of correlation sidelobes, the integrated sidelobe level, and the structural ordering of the generated signal realizations.

The evaluation was carried out using three indicators: peak sidelobe level (PSL), integrated sidelobe level (ISL), and structural entropy H. The PSL characterizes the maximum level of sidelobes of the cross-correlation function of signal ensembles and allows the assessment of peak correlation interaction between signals. The ISL reflects the total energy of the sidelobes of the cross-correlation function and characterizes the integral level of correlation interference within the signal ensemble. The structural entropy H is used to evaluate the degree of signal ordering after time-segment permutation and reflects the level of structural complexity of the generated realizations. The results of the simulation are presented in Table 2, Figs. 5 and 6.

Table 2 – Results of evaluation of the influence of parameter θ

θ	Transformation	PSL	ISL	Entropy	Result
0,00	Minimal changes	0,092	18,402	0,861	High correlation
0,10	Slight segment displacement	0,084	16,953	0,822	Slight reduction in correlation
0,20	Partial permutation	0,076	15,201	0,782	Moderate reduction in PSL
0,30	Quasi-random ordering	0,069	13,803	0,741	Reduction in ISL
0,40	Moderately modified structure	0,063	12,454	0,713	Structural stabilization
0,50	Transitional regime	0,057	11,302	0,685	Reduction of sidelobe level
0,618	Quasi-uniform ordering	0,049	9,852	0,633	Minimization of peak correlation
0,70	Enhanced permutation	0,052	10,407	0,653	Near-optimal regime
0,80	Enhanced permutation	0,055	11,104	0,676	Signal decorrelation
0,90	Significantly modified structure	0,059	12,203	0,702	Increased structural diversity
1,00	Maximum permutation	0,064	13,501	0,732	Increased ensemble structural variability

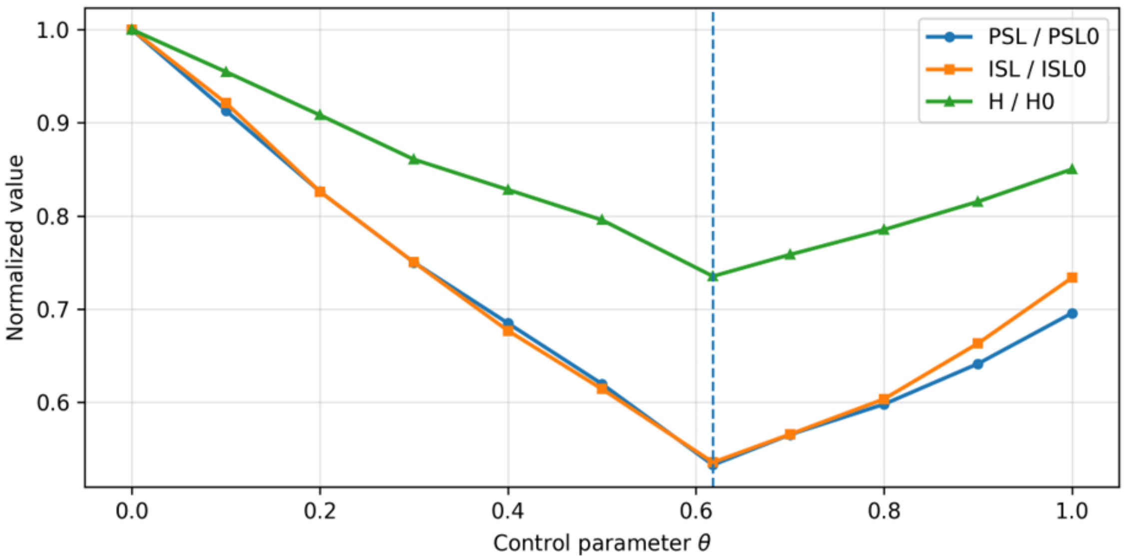

Figure 5 – Dependence of normalized PSL, ISL, and entropy values on the control parameter θ

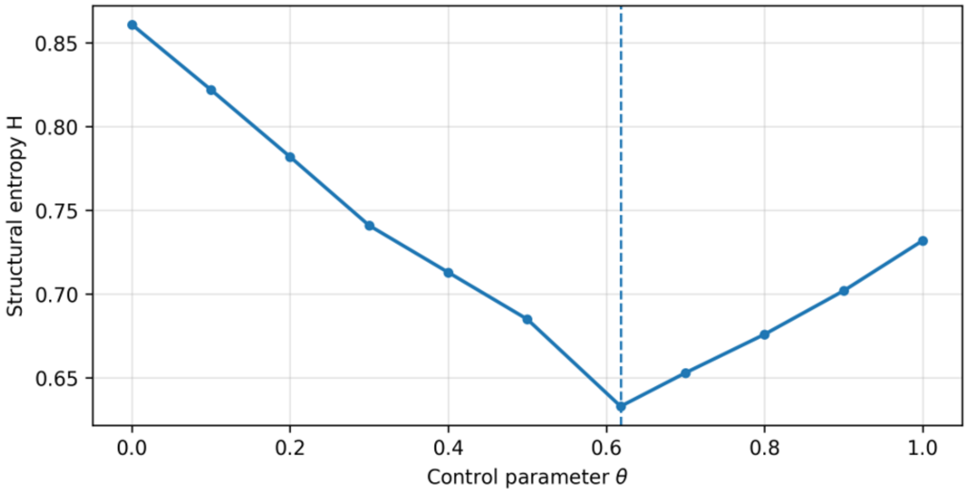

Figure 6 – Dependence of signal structural entropy on the control parameter θ

As shown in Table 2 and Figs. 5 and 6, variation of the parameter *θ* provides a transition from a regime of minor structural transformation of the signal to a regime of intensive permutation of time segments. The dependencies of PSL, ISL, and H exhibit a pronounced minimum at *θ*=0,618, which corresponds to quasi-uniform ordering of the segments.

At this point, the PSL value decreases from 0,092 to 0,049, i.e., by 46,7%. The ISL value decreases from 18,402 to 9,852, corresponding to a reduction of 46,5%. At the same time, the structural entropy H decreases from 0,861 to 0.633, i.e., by 26,5%. This indicates that the optimal value of the parameter *θ* ensures not only a reduction of peak and integral correlation interaction between signals but also an increase in the structural ordering of the generated realizations.

Further increase of θ beyond 0,618 leads to a gradual growth of PSL, ISL, and entropy. This means that excessive permutation of time segments does not result in further reduction of correlation indicators; on the contrary, it partially disrupts the achieved structural consistency of the signal.

To quantitatively evaluate the effectiveness of the parameter *θ*, an additional analysis of the relative variation of the considered indicators with respect to the baseline case *θ*=0 was performed. The results of this analysis are presented in Table 3 and Fig. 7.

Table 3 – Relative variation of *PSL, ISL*, and *H* depending on parameter *θ*

θ	*ΔPSL (%)*	*ΔISL (%)*	*ΔH (%)*
0,00	0,00	0,00	0,00
0,10	8,70	7,87	4,53
0,20	17,39	17,39	9,18
0,30	25,00	24,99	13,94
0,40	31,52	32,32	17,19
0,50	38,04	38,59	20,44
0,618	46,74	46,47	26,48
0,70	43,48	43,45	24,15
0,80	40,22	39,66	21,49
0,90	35,87	33,68	18,47
1,00	30,43	26,63	14,99

As shown in Table 3 and Fig. 6, with an increase in the parameter θ up to 0,618, a monotonic decrease in PSL and ISL is observed, accompanied by a simultaneous reduction in the structural entropy of the signal. The maximum relative reduction reaches 46,74% for PSL, 46,47% for ISL, and 26,48% for H, corresponding to the optimal regime of structural signal transformation.

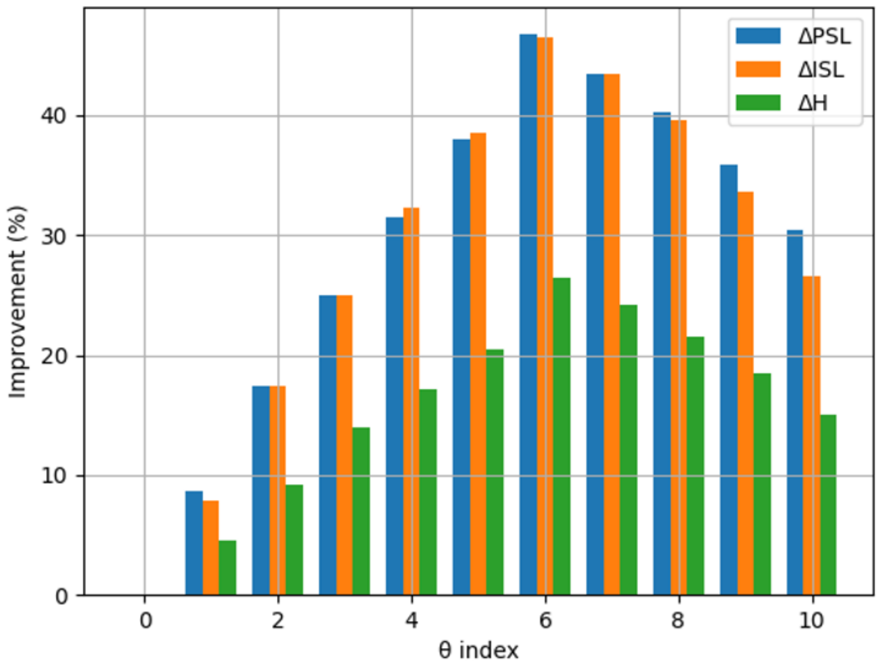

Figure 7 – Dynamics of PSL, ISL, and H variation versus parameter θ

With further increase of θ, an increase in PSL, ISL, and H is observed, corresponding to a decrease in the efficiency of structural transformation. This confirms the existence of an optimal range of θ values and justifies its selection at the level of $\theta \approx 0{,}618$.

The obtained results confirm that the parameter θ acts as an effective control parameter of the method, enabling the targeted formation of ensembles of complex signals with a reduced level of correlation sidelobes, decreased integral correlation energy, and a more ordered signal structure. It is established that the optimal value θ≈0,618 ensures a reduction of the correlation indicators PSL and ISL, as well as a decrease in the structural entropy of the signal ensemble.

Conclusions and prospects for further research.

This paper presents a method for forming ensembles of complex signals based on parameterized structural transformation of time segments, which enables controlled modification of the internal signal structure while preserving its energy and spectral characteristics.

The scientific novelty of the obtained results consists in introducing a control parameter θ that defines a deterministic permutation rule for time segments and enables continuous regulation of both correlation and structural properties of signal ensembles. In contrast to existing approaches based on fixed or random permutations, the proposed method provides a unified mechanism for coordinated control of peak sidelobe level (PSL), integrated sidelobe level (ISL), and structural entropy.

It has been established that variation of the parameter θ leads to a regular transition between regimes of weak and intensive structural transformation of the signal, enabling the formation of ensembles with predefined properties. In particular, an optimal value of $\theta \approx 0.618$ has been identified, at which a coordinated minimization of correlation measures and structural entropy is achieved. The results demonstrate a reduction of PSL and ISL by up to 46% and a decrease in structural entropy by up to 26%, confirming the effectiveness of the proposed method.

The obtained results further develop existing approaches to signal design by integrating parameterized structural transformation with the joint evaluation of correlation and structural characteristics. This makes it possible to generate ensembles of signals with reduced mutual correlation and improved structural organization, which is important for enhancing interference resistance in multi-user communication systems.

Further research will focus on developing adaptive strategies for real-time selection of the parameter θ, integrating the proposed method with cognitive spectrum management algorithms, and extending the approach to multi-dimensional and multi-carrier signal structures.

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