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METHOD FOR FORMING ENSEMBLES OF COMPLEX SIGNALS BASED ON A LOCAL STRUCTURAL INSTABILITY INDICATOR

The article presents a method for forming ensembles of complex signals based on a local structural instability indicator. The proposed approach provides controlled determination of time-segmentation parameters through local structural analysis of nonstationary signals and adaptive adjustment of the segmentation scale to changes in their internal organization. The method enables alignment of the ensemble structure with the actual temporal organization of the signal, which leads to a reduction in mutual correlation between ensemble elements while preserving their structural and spectral characteristics. The effectiveness of the proposed approach is confirmed by experimental modeling for various scenarios of signal structural heterogeneity, demonstrating improved ensemble noise immunity under variable interference conditions.

Keywords: complex-signal ensembles, time segmentation, noise immunity, correlation reduction; spectral characteristics; telecommunication signal processing, frequency permutations, interference suppression.

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МЕТОД ФОРМУВАННЯ АНСАМБЛІВ СКЛАДНИХ СИГНАЛІВ НА ОСНОВІ ІНДИКАТОРА ЛОКАЛЬНОЇ СТРУКТУРНОЇ НЕСТАБІЛЬНОСТІ

У статті розроблено метод формування ансамблів складних сигналів на основі індикатора локальної структурної нестабільності, призначений для обробки нестационарних сигналів з вираженою часовою неоднорідністю. Метод ґрунтується на послідовному виконанні локального структурного аналізу часової реалізації сигналу, формуванні індикатора нестабільності на основі варіацій показника структурної складності та керованому визначенні параметрів часової сегментації. Такий підхід забезпечує узгодження масштабу сегментації до локальних змін внутрішньої організації сигналу та формування ансамблів із керованими кореляційними властивостями.

Особливістю запропонованого методу є здатність узгоджувати структуру сформованого ансамблю з реальною часовою організацією сигналу, що дозволяє зменшувати взаємну кореляцію між елементами ансамблю без порушення їх структурно-спектральних характеристик.

Проведено експериментальне моделювання за різними сценаріями. Зокрема квазістационарних, неоднорідних та сигналів з локальними деградаціями. Оцінювання ефективності методу виконано за показниками максимальної взаємної кореляції елементів ансамблю та спектральної близькості. Отримані результати підтверджують, що використання узгодженої часової сегментації на основі індикатора локальної нестабільності дозволяє суттєво знизити рівень міжканальних завад при збереженні спектральних властивостей сигналів.

Таким чином, запропонований метод забезпечує комплексне підвищення завадостійкості ансамблів складних сигналів та створює ефективну основу для їх застосування в сучасних когнітивних системах зв'язку в умовах складних завадових впливів.

Ключові слова: ансамблі складних сигналів; часова сегментація; завадостійкість; зменшення кореляції; спектральні характеристики; телекомунікаційна обробка сигналів; локальна структурна нестабільність; пригнічення завад.

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INTRODUCTION

In modern telecommunication systems, the increasing density of spectral resource utilization and the growing complexity of signal structures necessitate the improvement of methods for forming ensembles of complex signals. Under conditions of a complex interference environment, the efficiency of information transmission in telecommunication systems largely depends on the ensemble properties of signals, in particular on their correlation characteristics and interference immunity [1-15].

Practical experience in the application of multi-signal modes shows that as the ensemble size increases and signal structures become more complex, the mutual correlation between ensemble elements grows, which negatively affects interference immunity. Under such conditions, there arises a need to improve ensemble formation approaches by taking into account signal properties in the time domain and their influence on ensemble characteristics.

GENERAL STATEMENT OF THE PROBLEM

AND ITS CONNECTION WITH IMPORTANT SCIENTIFIC OR PRACTICAL TASKS

In the process of forming ensembles of complex signals, the parameters of signal segmentation in the time domain determine the mutual arrangement of ensemble elements and directly affect their correlation properties and the degree to which orthogonality conditions between signals are satisfied. The use of fixed segmentation parameters does not allow local signal properties in the time domain to be taken into account under nonstationary interference conditions, which leads to an increase in mutual correlation, violation of orthogonality conditions, and degradation of ensemble characteristics.

In this regard, a scientific problem arises in developing a method for forming ensembles of complex signals in which the selection of signal segmentation parameters in the time domain is performed with regard to local signal properties. Solving this problem is directly related to important practical tasks such as improving the interference immunity of telecommunication systems, reducing mutual correlation between ensemble elements, and bringing ensemble characteristics closer to orthogonality conditions when forming large-scale ensembles.

ANALYSIS OF RESEARCH AND PUBLICATIONS

In contemporary studies devoted to the formation of complex signal ensembles and the improvement of interference immunity in telecommunication systems, primary attention is focused on the optimization of individual spectral, correlation, or hardware-implementation characteristics of signals [1-15]. In particular, a number of works address issues related to coding techniques, filtering methods, and hardware-oriented optimization in the context of modern communication standards and cognitive radio systems [1,2,5,12,14]. However, these approaches do not analyze the influence of ensemble formation parameters in the time domain on correlation properties and orthogonality conditions.

A significant body of research is dedicated to methods for forming ensembles of complex signals based on spectral filtering, time-interval permutations, or multiscale processing of time segments [3,4,6,7,8]. These studies demonstrate the possibility of reducing mutual correlation between ensemble elements and improving certain ensemble characteristics. Nevertheless, the signal segmentation parameters in the time domain are typically fixed or selected empirically, without considering local signal properties under nonstationary interference conditions. This limitation restricts the ability to approach orthogonality conditions when forming large-scale ensembles.

A separate research direction concerns the synthesis and analysis of sequences with low or zero correlation zones, as well as interleaving and permutation-based techniques [9]. While such methods provide favorable correlation properties at the level of signal sequence construction, they do not take into account the effect of time-domain segmentation and local variations of signal properties during ensemble formation.

Methods based on multiscale, entropy-based, and fractal analysis of time series [10,13,15] offer effective tools for characterizing signal complexity and nonstationarity. However, in existing works these methods are primarily employed for analysis or evaluation purposes and are not used as a basis for the controlled selection of parameters for forming ensembles of complex signals.

In studies addressing parametric optimization of complex signal ensembles, the effectiveness of optimization approaches for improving selected ensemble characteristics has been demonstrated [11]. At the same time, these works do not consider the problem of coordinating time-domain signal segmentation parameters with local signal properties in order to bring ensemble characteristics closer to orthogonality conditions.

Thus, the analysis of existing research indicates the absence of a coordinated method for forming ensembles of complex signals that combines parametric optimization with the selection of time-domain segmentation parameters based on local signal properties while accounting for orthogonality conditions.

MATHEMATICAL FORMULATION OF THE PROBLEM

To justify the feasibility of local analysis of complex signals in the time domain, experimental modeling of a nonstationary signal characterized by pronounced structural nonuniformity over time was performed. Such signals contain segments with different degrees of regularity, interference levels, and spectral content, which makes effective processing impossible when using fixed segmentation parameters or uniform approaches to ensemble formation.

For this purpose, a sequence of local structural analysis operations was applied, enabling the detection of changes in the internal organization of the signal and the formation of informative control indicators for subsequent parameter selection and processing (Fig. 1).

Figure 1a shows the input nonstationary signal in the time domain, characterized by pronounced nonstationarity and the alternation of fragments with different degrees of regularity and interference levels. Figure 1b presents the structural component of the signal obtained by smoothing using a weighted moving average, which makes it possible to extract slow variations in the internal organization of the signal. Figure 1c illustrates a local structural complexity indicator calculated within sliding time windows, reflecting changes in signal behavior over time. Figure 1d shows the instability indicator $G(t)$, formed on the basis of variations in local structural complexity and intended for localizing time intervals associated with significant structural rearrangements of the signal.

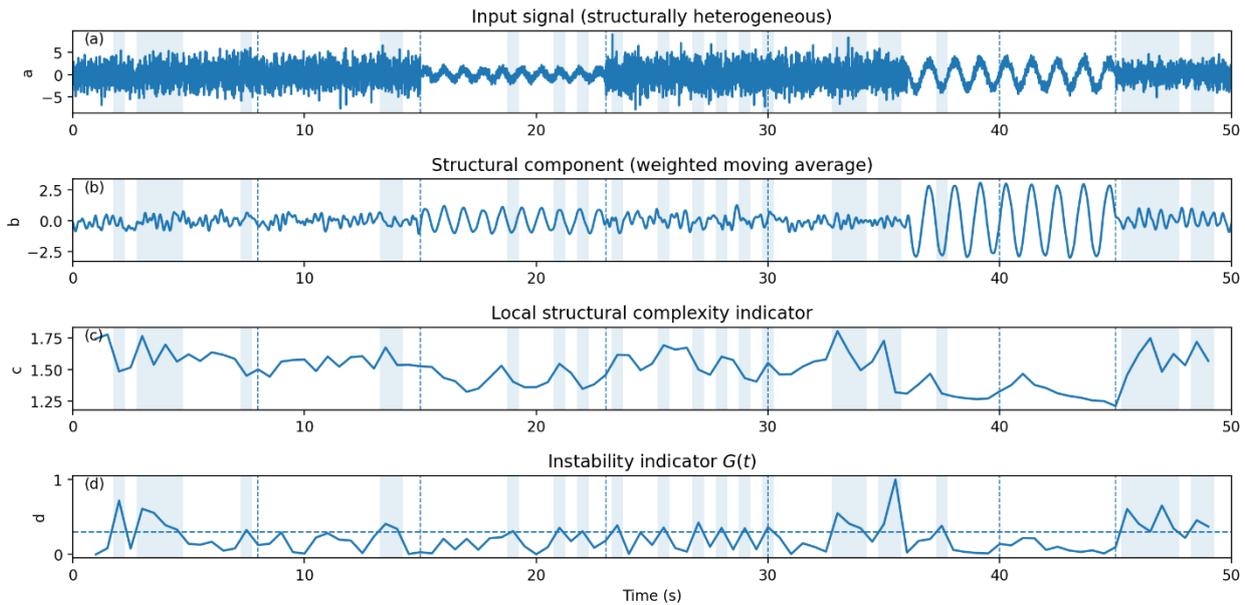


Fig. 1. Structural analysis of a nonstationary signal in the time domain

As can be seen from Fig. 1, intervals with increased values of the indicator $G(t)$ correspond to moments of substantial changes in the signal properties in the time domain and coincide with transitions between fragments exhibiting different statistical and spectral characteristics. This confirms the feasibility of using local structural indicators as a basis for controlled selection of subsequent signal processing parameters.

Taking into account the results of the conducted experiment, it is reasonable to develop a method in which the parameters of time-domain segmentation and structural ordering of signal elements are determined with regard to local changes in the internal signal properties. Accordingly, the method is implemented as a sequence of interconnected stages.

Stage 1. Local structural analysis of the signal.

At the first stage of the method, the input nonstationary signal is divided into a sequence of overlapping time windows of fixed duration, within which local signal properties in the time domain are evaluated. This approach enables signal analysis with regard to its internal nonstationarity and allows local changes in signal dynamics to be identified.

The evaluation of local structural complexity provides a quantitative measure of the degree of regularity or instability of the signal within each time window. In this study, the structural complexity indicator is based on the geometric properties of the signal time-domain representation and is invariant to amplitude scaling, which is important for the analysis of signals with varying energy.

The local structural complexity indicator is computed according to the following expression:

$$C_k = \frac{\log N}{\log N + \log \left(\frac{d_k}{L_k} \right)}, \quad (1)$$

where N is the number of samples within the time window, L_k is the total length of the polyline approximating the signal in the k -th window, and d_k is the maximum distance between the initial point of the window and the remaining samples within that window.

The use of this indicator makes it possible to detect local changes in signal properties in the time domain. An increase in the value of C_k corresponds to higher complexity and irregularity of the signal behavior, whereas a decrease in this indicator indicates more ordered and stable signal behavior.

At the second stage of the method, a local instability indicator is formed based on the sequence of local values of the structural complexity measure. This indicator reflects the intensity of changes in signal properties in the time domain. Since the rate of variation of structural complexity is an informative feature characterizing transitions between different signal behavior regimes, the instability indicator is defined as a measure of variation of the corresponding local indicator across adjacent time windows.

The local instability indicator is calculated according to the following expression:

$$G_k = |C_k - C_{k-1}|, \quad (2)$$

where C_k and C_{k-1} are the values of the structural complexity indicator in the current and the preceding time windows, respectively.

Increased values of the instability indicator G_k correspond to significant changes in signal properties in the time domain and are used to localize time intervals within which it is reasonable to modify the parameters of subsequent signal processing.

Stage 3. Determination of time-domain segmentation parameters and ensemble formation with regard to local signal nonstationarity.

The main objective of this stage is to adjust the scale of time-domain segmentation in accordance with local changes in signal properties in the time domain in order to increase the informativeness and interference immunity of the formed ensemble. For this purpose, based on the sequence of values of the local instability indicator G_k , the time windows are classified into unstable and stable ones, and the corresponding segmentation length is determined.

The threshold-based decision regarding the type of a local time interval is defined by the following condition:

$$\Omega_k = \begin{cases} 1, & G_k \geq \gamma \\ 0, & G_k < \gamma \end{cases} \quad (3)$$

where γ is the threshold level; $\Omega_k=1$ corresponds to intervals associated with structural changes of the signal, while $\Omega_k=0$ corresponds to stable intervals.

The segmentation length is defined as a function of Ω_k :

$$L_k = \begin{cases} L_{min}, & \Omega_k = 1 \\ L_{max}, & \Omega_k = 0 \end{cases} \quad (4)$$

where L_{min} and L_{max} are the minimum and maximum segment durations that define the admissible range of segmentation scales.

Thus, in time intervals characterized by significant values of G_k , shorter segments are applied to localize structural changes, whereas in stable intervals longer segments are used in order to preserve the structural and spectral characteristics of the signal.

The segments formed according to expressions (3) – (4) are used for ensemble construction. Let $\{s_m\}_{m=1}^M$ denote the set of obtained segments; then the ensemble is defined as a set of signals formed using a structural formation operator $F(\cdot)$:

$$\mathcal{E} = \{x^i(t) = F_i(\{s_m\}_{m=1}^M)\}_{i=1}^Q \quad (5)$$

where Q is the size of the complex signal ensemble, and the operator $F(\cdot)$ determines the method for forming the i -th ensemble element based on segments parameterized by L_k .

This ensures coordination between the ensemble structure and the signal properties in the time domain and creates prerequisites for improving the efficiency of subsequent signal processing.

Stage 4. Evaluation of the formed ensemble of complex signals

The purpose of this stage is to perform a quantitative analysis of ensemble properties and to verify the effectiveness of the selected time-domain segmentation parameters. The evaluation is carried out based on indicators that reflect the mutual consistency of ensemble elements and their structural and spectral properties.

Let $\mathcal{E} = \{x^i(t)\}_{i=1}^Q$ denote the formed ensemble of complex signals. For its evaluation, a vector of ensemble characteristics is introduced:

$$J = \Phi(\mathcal{E}), \quad (6)$$

where J is a set of ensemble metrics, and the operator $\Phi(\cdot)$ defines the procedure for their computation.

The vector J may include measures of mutual correlation between ensemble elements, spectral concentration metrics, and other characteristics reflecting the robustness of the ensemble to interference effects. The obtained values are used to analyze the effectiveness of the formed ensemble and to compare it with ensembles generated using fixed segmentation parameters.

Thus, the proposed method enables the selection of time-domain segmentation parameters and ensemble formation with regard to local signal nonstationarity, creating prerequisites for improving the efficiency of subsequent signal processing.

EXPERIMENTAL RESULTS

To verify the proposed method, experimental modeling was performed for various types of nonstationary signals with controlled structural nonstationarity and interference effects. The comparison is carried out with a baseline

approach based on fixed segmentation using indicators of mutual correlation between ensemble elements and spectral similarity. Additionally, the robustness of the results is analyzed with respect to variations in the window processing parameters and the threshold level γ .

The experimental parameters and the modeling results are presented in Tables 1 and 2, respectively.

Table 1

Experimental modeling parameters

Parameter	Value
Sampling frequency, f_s (Hz)	1000
Window length, N	256
Window overlap	50%
Minimum segment length, L_{\min}	64
Maximum segment length, L_{\max}	256
Gamma quantile, p	0,8
Ensemble size, Q	20

Table 2

Evaluation results of the formed ensembles

Signal scenario	Max corr (Fixed L)	Max corr (Adaptive L_k)	Spectral similarity (Fixed L)	Spectral similarity (Adaptive L_k)
S1: quasi-stationary	0,946	0,684	0,985	1,000
S2: piecewise-structural	0,948	0,682	0,990	1,000
S3: degraded fragments	0,907	0,712	0,990	1,000

As can be seen from Table 2, the use of time-domain segmentation based on the local instability indicator G_k provides a reduction of the maximum mutual correlation between ensemble elements by 21,5% compared to the fixed segmentation method. At the same time, the values of the spectral similarity metric remain close to unity, which indicates preservation of the structural and spectral characteristics of the signals. The obtained results confirm the effectiveness of the proposed method for forming ensembles of complex signals under conditions of structural nonstationarity.

Figures 2–4 present the results of local structural analysis for three modeled nonstationary signal scenarios (S1–S3), including:

- the time-domain signal representation with detected segmentation boundaries;
- the local structural complexity indicator C_k ;
- the local instability indicator G_k with the threshold level γ .

The presented dependencies demonstrate how the indicator G_k is used to localize regions of structural changes and to select the appropriate time-domain segmentation scale.

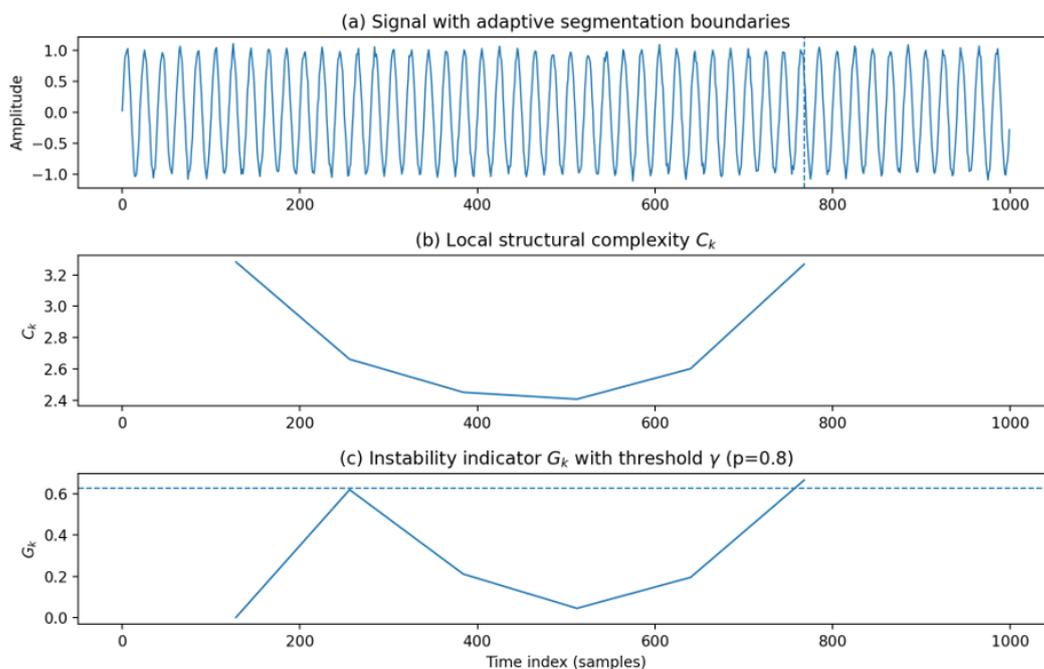


Fig. 2. Local analysis of a quasi-stationary signal

For scenario S1 (Fig. 2), variable time-domain segmentation is activated only in isolated regions of local instability (Fig. 2c), which results in a reduction of the maximum mutual correlation of the ensemble from 0,946 to 0,684, i.e., by approximately 27,7%, while preserving the spectral similarity at a level close to unity (Table 2). This confirms that the proposed method does not lead to excessive segmentation of stable signal fragments.

For scenario S2 (Fig. 3), the peaks of the indicator G_k (Fig. 3c) correspond to transitions between signal fragments with different degrees of regularity (Figs. 3a–b). This leads to a reduction of the maximum mutual correlation from 0,948 to 0,682 (approximately 28,1%), while preserving spectral similarity at a level close to unity (Table 2). Thus, variable selection of the segmentation scale enhances the localization of structural transitions without loss of spectral content.

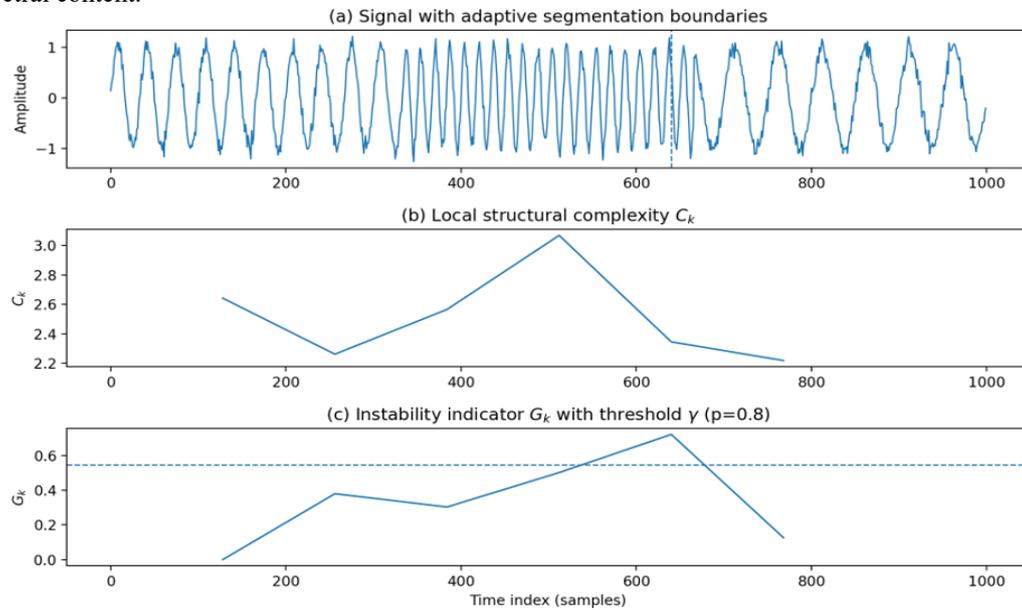


Fig. 3. Local analysis of a structurally nonstationary signal

For scenario S3 (Fig. 4), which contains a segment with an increased interference level, the indicator G_k forms a denser sequence of unstable intervals (Fig. 4c), providing more detailed localization of signal degradations. As a result, the maximum mutual correlation is reduced from 0,907 to 0,712 (approximately 21,5%), while the spectral similarity remains close to unity (Table 2). This demonstrates the robustness of the proposed method under interference conditions.

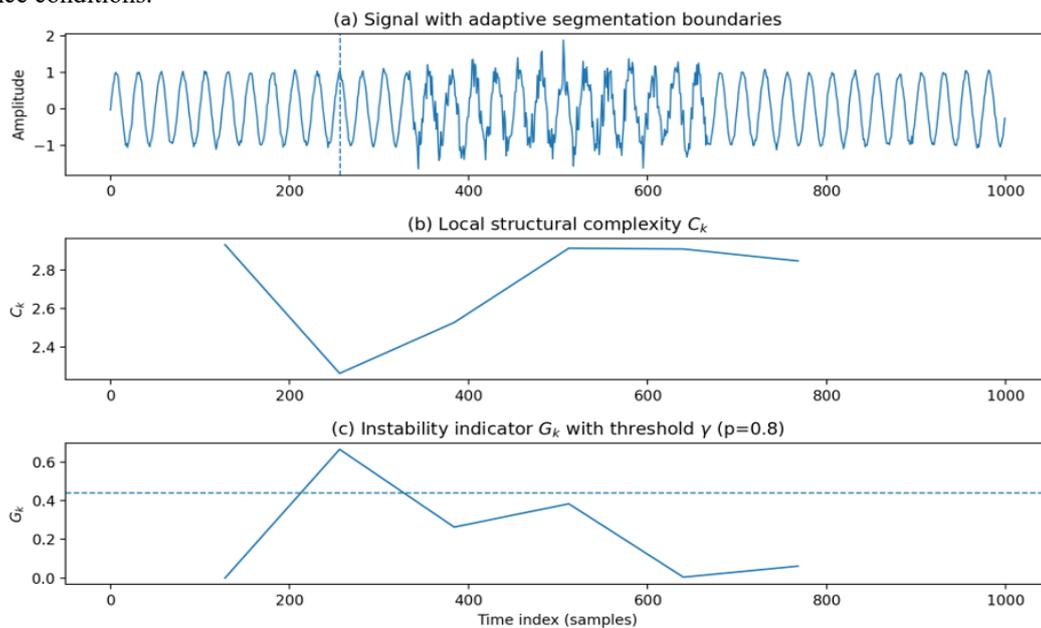


Fig. 4. Local analysis of a signal with degraded segments

Thus, the results presented in Figs. 2–4 and summarized in Table 2 demonstrate that the use of the local instability indicator G_k for coordinated control of time-domain segmentation makes it possible to balance the structure

of the formed ensemble with the actual signal behavior in the time domain. This ensures a reduction of mutual correlation between ensemble elements while preserving their structural and spectral characteristics.

CONCLUSIONS FROM THIS RESEARCH AND PROSPECTS FOR FURTHER RESEARCH IN THIS AREA

The article presents a method for forming ensembles of complex signals has been developed, in which the time-domain segmentation parameters are determined based on local signal analysis in the time domain using a local instability indicator. The proposed approach ensures coordination between the ensemble structure and the actual signal behavior in the time domain under conditions of structural nonstationarity.

The experimental results confirm the effectiveness of the proposed method compared to the baseline approach based on fixed segmentation. Simulation results obtained for various types of nonstationary signals show that the use of a variable time-domain segmentation scale reduces the maximum mutual correlation between ensemble elements by:

- 27,7% for a quasi-stationary signal (S1);
- 28,1% for a signal with piecewise structural nonstationarity (S2);
- 21,5% for a signal containing degraded fragments (S3).

It is shown that the reduction in mutual correlation is achieved without degradation of spectral characteristics. The values of the spectral similarity metric for the formed ensembles in all considered scenarios remain close to unity, indicating preservation of the structural and spectral content of the signals when using the proposed approach.

The use of the local instability indicator Gk provides correct localization of time intervals associated with structural changes in the signal and prevents excessive segmentation of stable fragments. This confirms the feasibility of using local structural indicators to control the parameters of complex signal ensemble formation.

The obtained results demonstrate an improvement in the interference immunity of ensemble characteristics, which makes the proposed method suitable for application in telecommunication systems operating under nonstationary interference conditions and variable signal behavior in the time domain.

Further research will focus on extending the proposed method to multi-channel and multi-band signal ensembles, as well as on investigating the influence of the instability indicator parameters and threshold selection on ensemble characteristics under different interference conditions.

References

1. Boiko, J., Druzhyin, V., Buchyk, S., Pyatin, I., Kulko, A. Methodology of FPGA Implementation and Performance Evaluation of Polar Coding for 5G Communications// CEUR Workshop Proceedings, 2024, 3654, P.P. 15–24, <https://doi.org/10.2478/tj-2024-0022>.
2. Бойко, Ю., Пятін, І., Срьоменко, О., Шаюк, Д. (2022). Оцінювання впливу зміщення несучих частот на завадостійкість телекомунікацій з OFDM. Measuring and computing devices in technological processes, (3), 19–26 <https://doi.org/10.31891/2219-9365-2022-71-3-3>
3. Indyk S. V., Lysechko V. P., Zhuchenko O. S., Kitov V. S. The Formation Method of Complex Signals Ensembles by Frequency Filtration of Pseudo-Random Sequences with Low Interaction in the Time Domain. Radio Electronics, Computer Science, Control., 2020, № 4 (55), С. 7-14. <https://doi.org/10.15588/1607-3274-2020-4-1>.
4. Bershov, V., Yakymchuk N. The method of forming ensembles of complex signals based on multi-scale decomposition of time intervals at different levels of detail. Науковий журнал «Комп'ютерно-інтегровані технології: освіта, наука, виробництво». Телекомунікації та радіотехніка, Луцьк, № 56, 2024. С. 325-334. <https://doi.org/10.36910/6775-2524-0560-2024-56-39>.
5. Knyazev, V., Kravchenko, V., Lazurenko, B., Serkov, O., Trubchaninova, K., & Panchenko, N. (2022). Development of methods and models to improve the noise immunity of wireless communication channels. Eastern-European Journal of Enterprise Technologies, 1(5(115)), 35–42, <https://doi.org/10.15587/1729-4061.2022.253458>.
6. Lysechko V., Bershov V. Justification of Filter Selection Methods for Enhancing the Efficiency of Multilevel Recurrent Time-Frequency Segmentation. SISIOT (Security of Infocommunication Systems and Internet of Things), vol. 2, no.1, p. 01006, 2024. P. 1-7. <https://doi.org/10.31861/sisiot2024.1.01006>.
7. Indyk S., Lysechko V. The study of ensemble properties of complex signals obtained by time interval permutation. Advanced Information Systems. 2020.-Vol. 4, № 3.-P. 85-88. <https://doi.org/10.20998/2522-9052.2020.3.11>.
8. Bershov, V., Zhuchenko, O. (2024). Adaptive method of forming complex signals ensembles based on multi-level recurrent time-frequency segment modeling. Science-Based Technologies, 63(3), 257–264. <https://doi.org/10.18372/2310-5461.63.18953>.
9. Hu H., Gong G. (2010) New Sets of Zero or Low Correlation Zone Sequences via Interleaving Techniques, in IEEE Transactions on Information Theory, vol. 56, no. 4, pp. 1702-1713, April 2010, <https://doi.org/10.1109/TIT.2010.2040887>.
10. Costa, M., Goldberger, A., Peng, C.-K. Multiscale entropy analysis of complex physiological time series. Physical Review Letters, 2002, Vol. 89, No. 6, 068102, <https://doi.org/10.1103/PhysRevLett.89.068102>.
11. Komar O., Lysechko V., Indyk S., Shevchenko O. (2025) Method of parametric optimization of complex-signal ensembles//Measuring and computing devices in technological processes. – Khmelnytskyi, Khmelnytskyi National University: 2025. – No. 84(4). – P. 362-369. <https://doi.org/10.31891/2219-9365-2025-84-4>.
12. Haykin S., "Cognitive radio: brain-empowered wireless communications," in IEEE Journal on Selected Areas in Communications, vol. 23, no. 2, pp. 201-220, Feb. 2005, <https://doi.org/10.1109/JSAC.2004.839380>.
13. Tulenko I., Shevchenko O. (2025) Entropy-based evaluation method of signal ensembles using LPT- τ permutations and Markov models// Computer-integrated technologies: education, science, production. Telecommunications and radio engineering / Lutsk National Technical University. – Lutsk. – 2025. (№61), P.P.300-310, <https://doi.org/10.36910/6775-2524-0560-2025-61-39>.
14. Kozlovskiy, V., Kozlovskiy, V., Boiko, J., Balanyuk, Y., Yakymchuk, N. Synthesis of Bandpass Filter as a Four-Pole Based on a Non-Homogeneous Line//Indonesian Journal of Electrical Engineering and Informatics, 2024, 12(3), P.P. 465–476, <https://doi.org/10.52549/ijeel.v12i3.5537>.
15. Higuchi T. (1988) Approach to an irregular time series on the basis of the fractal theory// Physica D: Nonlinear Phenomena, Volume 31, Issue 2, June 1988, Pages 277-283, [https://doi.org/10.1016/0167-2789\(88\)90081-4](https://doi.org/10.1016/0167-2789(88)90081-4).