DOI: https://doi.org/10.36910/6775-2524-0560-2026-63-34
УДК 621.391.8:519.21
Zhuchenko Oleksandr[1] PhD, Associate Professor
https://orcid.org/0000-0003-3275-810X
Indyk Serhii[1] PhD, Associate Professor
https://orcid.org/0000-0003-3124-8722
Zablotskyi Valentyn[2], PhD, Associate Professor
https://orcid.org/0000-0002-2921-0031
[1]Ukrainian State University of Railway Transport, Kharkiv, Ukraine.
[2]Lutsk National Technical University, Lutsk, Ukraine.

STUDY OF PROPERTIES OF COMPLEX TIME-DIVISION SIGNAL ENSEMBLES WITH A PERIODIC STRUCTURE FOR ULTRA-WIDEBAND CODE-DIVISION MULTIPLE ACCESS SYSTEMS

Zhuchenko O., Indyk S., Zablotskyi V. Study of properties of complex time-division signal ensembles with a periodic structure for ultra-wideband code-division multiple access systems. This paper investigates unequal-energy ensembles of periodic complex time-division signals for ultra-wideband code-division multiple access (UWB CDMA) systems operating under interference-limited conditions. The study focuses on establishing analytical relationships between signal energy distribution, maximum mutual correlation, multiple-access interference (MAI), and achievable signal-to-interference-plus-noise ratio (SINR) characteristics for periodic impulse signal ensembles with minimum similarity properties. An analytical model of unequal-energy periodic signal ensembles is developed under the single-overlap condition, where no more than one pulse overlap can occur between arbitrary signal pairs for any temporal shift. Based on this model, analytical expressions for the maximum normalized mutual correlation, total MAI energy, normalized interference level, and interference-limited SINR are obtained. It is shown that, unlike conventional equal-energy ensembles, the interference characteristics of unequal-energy ensembles are determined jointly by correlation properties and by the internal energy distribution of the signals. The obtained results demonstrate that users employing lower-energy signals experience the most unfavorable interference conditions, whereas higher-energy users achieve significantly improved interference immunity and SINR performance. Additionally, the concept of structural equivalent ensemble size is applied to characterize ensemble-level interference behavior and to analyze the influence of ensemble size and signal energy distribution on system performance.
Keywords: ensembles of complex signals; unequal-energy signals; equivalent transformations; CDMA; multiple-access interference.

Жученко О.С., Індик С.В., Заблоцький В.Ю. Дослідження властивостей ансамблів складних часорозділювальних сигналів з періодичною структурою для надширокосмугових систем множинного доступу з кодовим розділенням. У статті досліджуються ансамблі різноенергетичних періодичних складних часорозділювальних сигналів для надширокосмугових систем множинного доступу з кодовим розділенням каналів (UWB CDMA), що функціонують в умовах домінування завад множинного доступу. Дослідження зосереджене на встановленні аналітичних залежностей між розподілом енергії сигналів, максимальною взаємною кореляцією, завадами множинного доступу (MAI) та характеристиками досяжного відношення сигнал/завада і шум (SINR) для ансамблів періодичних імпульсних сигналів з властивістю мінімальної подібності. Розроблено аналітичну модель різноенергетичних періодичних ансамблів сигналів за умови одиничного перекриття, коли для будь-якого часового зсуву між довільними парами сигналів може виникати не більше одного перекриття імпульсів. На основі цієї моделі отримано аналітичні вирази для максимальної нормованої взаємної кореляції, сумарної енергії завад множинного доступу, нормованого рівня завад та SINR в умовах обмеження завадами. Показано, що на відміну від традиційних рівноенергетичних ансамблів, характеристики завадостійкості різноенергетичних ансамблів визначаються спільним впливом кореляційних властивостей та внутрішнього енергетичного розподілу сигналів. Отримані результати демонструють, що користувачі з меншою енергією сигналу перебувають у найгірших умовах завад, тоді як сигнали з більшою енергією забезпечують суттєво кращу завадостійкість і характеристики SINR. Додатково використано поняття структурного еквівалентного розміру ансамблю для опису колективної завадової поведінки ансамблю та аналізу впливу розміру ансамблю й енергетичного розподілу сигналів на характеристики системи.
Ключові слова: ансамблі складних сигналів; різноенергетичні сигнали; еквівалентні перетворення; CDMA; внутрішньосистемні завади.

Statement of a scientific problem.

Modern ultra-wideband (UWB) communication systems are increasingly oriented toward supporting large numbers of users operating simultaneously within a shared spectral environment. In such systems, multiple-access interference becomes one of the key factors limiting communication reliability, spectral efficiency, and achievable user capacity. This problem is especially important for impulse-based code-division multiple access systems, where user separation is determined by the correlation properties of the employed signal ensembles.

Existing approaches to the design of CDMA signal ensembles are mainly focused on minimizing mutual correlation between signals and are commonly developed for equal-energy sequence structures.

However, in practical ultra-wideband systems based on periodic impulse signaling, different users may employ signals containing different numbers of pulses within equal signal duration. As a result, the ensemble naturally becomes unequal-energy, and the interference conditions for different users become nonuniform.

Under such conditions, classical correlation analysis becomes insufficient for accurate evaluation of ensemble performance. Even when signal pairs satisfy low-correlation or single-overlap conditions, the resulting multiple-access interference depends not only on correlation values themselves but also on the distribution of signal energies inside the ensemble. In particular, users with lower signal energy may experience substantially higher normalized interference levels compared with users employing higher-energy signals. Therefore, conventional correlation-based performance criteria cannot fully characterize the interference properties of unequal-energy periodic signal ensembles.

Another important limitation of existing studies is the absence of compact analytical relationships connecting ensemble structure, signal energy distribution, mutual correlation, multiple-access interference, and corresponding SINR characteristics. Most available results are based either on numerical simulation or on equal-energy assumptions that are not fully applicable to periodic time-division impulse ensembles.

Consequently, there is a need for analytical investigation of unequal-energy ensembles of complex time-division signals with periodic structure in order to establish the relationships between signal energy distribution, maximum mutual correlation, multiple-access interference, and interference-limited SINR indicators in ultra-wideband code-division multiple access systems.

Research analysis.

The development of ultra-wideband (UWB) communication systems and low-power wireless networks has intensified interest in signal ensembles with low mutual interference and improved spectral efficiency. The IEEE 802.15.4a and IEEE 802.15.4z standards introduced impulse-based physical layers for UWB communications and demonstrated the practical relevance of short-duration pulse signaling for ranging, localization, and multiple-access applications [1, 2]. In such systems, the efficiency of user separation is strongly influenced by the correlation properties of the employed signal ensembles.

Classical approaches to code-division multiple access (CDMA) systems are largely based on equal-energy spreading sequences and traditional correlation analysis. At the same time, modern communication environments increasingly require more flexible signal structures capable of supporting heterogeneous users and adaptive resource allocation. This has stimulated interest in low-correlation and zero-correlation-zone sequence families intended for asynchronous and interference-limited communication systems.

A considerable number of studies have been devoted to the synthesis of sequence ensembles with reduced cross-correlation. Hayashi proposed several classes of zero-correlation-zone sequence sets constructed from perfect sequences and pseudo-white-noise structures with optimal correlation properties [3, 4]. Feng et al. investigated complementary code constructions based on periodic cross-correlation constraints, demonstrating their applicability to interference-resistant communication systems [5]. Chiba and Hamamura analyzed multitone-hopping CDMA systems with decentralized access mechanisms and showed the importance of correlation control for reducing multiple-access interference under asynchronous operation conditions [6]. Despite significant progress in low-correlation sequence design, most existing approaches focus primarily on correlation minimization itself and commonly assume equal-energy signal ensembles. However, periodic impulse signal structures used in ultra-wideband systems naturally lead to unequal-energy ensembles because different signals may contain different numbers of pulses within the same signal duration. Under such conditions, conventional correlation analysis alone becomes insufficient for accurate performance estimation.

Previous studies by the authors considered the synthesis of complex signal ensembles with low interaction in the time domain and investigated generalized performance indicators for unequal-energy CDMA systems [7-10]. In particular, methods for constructing ensembles of complex time-division signals with periodic structure and approaches for equivalent transformation of unequal-energy signal ensembles were proposed. These studies demonstrated that interference conditions in unequal-energy systems are determined not only by correlation properties but also by the internal energy distribution within the ensemble.

At the same time, the influence of signal energy structure on maximum mutual correlation, multiple-access interference (MAI), and corresponding SINR characteristics for periodic time-division signal ensembles remains insufficiently investigated. Therefore, further research is needed to establish compact analytical relationships between correlation properties, signal energies, ensemble structure, and interference-limited performance indicators for ultra-wideband code-division multiple access systems.

The purpose of this study is to establish the properties of ensembles of complex time-division signals with periodic structure that influence their performance indicators.

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

Consider an ensemble of L equal-duration periodic pulse signals $s_i(t), i = 1, \dots, L$. The i-th signal contains n_i pulses uniformly distributed over the signal duration T, so that $n_i T_i = T$, where T_i is the pulse repetition period. For equal pulse amplitudes and durations, the signal energy is proportional to the number of pulses:

$$E_i = n_i E_u. \tag{1}$$

Therefore, if the values n_i differ, the ensemble becomes inherently unequal-energy. The signal parameters are chosen so that no more than one pulse overlap occurs between any signal pair for any temporal shift. This single-overlap condition provides the basis for analytical estimation of mutual correlation, MAI, and SINR.

The signal parameters are selected such that, for any temporal shift between arbitrary signal pairs, no more than one pulse overlap can occur. This condition defines the minimum similarity property of the ensemble:

$$\max_{\tau} R_{ij}(\tau) \le \frac{1}{\sqrt{n_i n_j}},\ 1 \le i < j \le L, \tag{2}$$

where $R_{ij}(\tau)$ is the normalized mutual correlation between the i-th and j-th signals for temporal shift τ.

Unlike conventional equal-energy spreading ensembles, the proposed periodic time-division structure allows the interference properties of the system to be analyzed jointly through correlation characteristics and signal energy distribution. This makes it possible to investigate how unequal signal energies influence multiple-access interference and interference-limited SINR characteristics.

As a representative example, the following ensemble of periodic pulse sequences is considered $\{n_1, n_2, n_3, n_4, n_5\} = \{2,3,5,7,11\}$. With normalized unit pulse energy, the signal energies numerically coincide with the corresponding pulse numbers:

$$\left\{\frac{E_1}{E_u}, \frac{E_2}{E_u}, \frac{E_3}{E_u}, \frac{E_4}{E_u}, \frac{E_5}{E_u}\right\} = \{2,3,5,7,11\}. \tag{3}$$

Figure 1 illustrates the ensemble structure. The key property of the considered ensemble is that, for any temporal shift, each signal pair can produce at most one pulse overlap. This property forms the basis for the subsequent analytical estimation of mutual correlation, multiple-access interference, and SINR characteristics for unequal-energy signal ensembles.

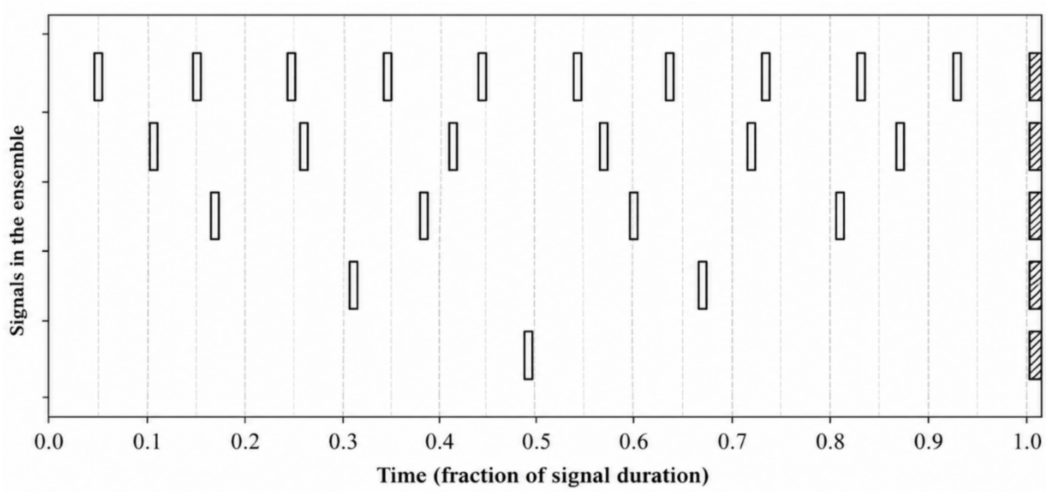


Figure 1 – Ensemble of complex time-division signals with periodic structure {2,3,5,7,11}

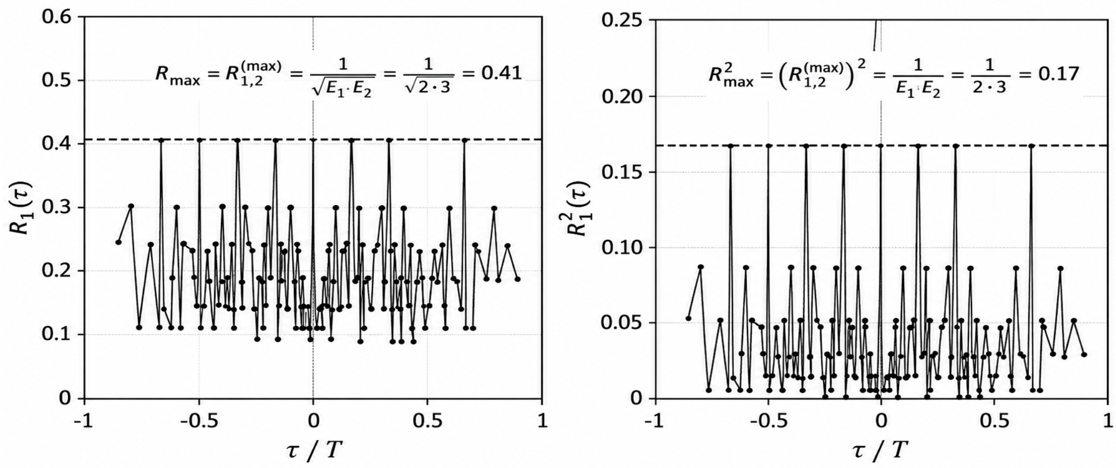
For periodic time-division signals, the mutual correlation at a discrete temporal shift is determined by the number of pulse overlaps $M_{ij}(\tau)$. Under the single-overlap condition $M_{ij}(\tau) \in \{0,1\}$, we have:

$$R_{ij}(\tau) = \frac{M_{ij}(\tau)}{\sqrt{E_i E_j}}. \quad (4)$$

Since the normalization is performed with respect to the geometric mean of the signal energies, the maximum correlation value becomes inversely proportional to $\sqrt{E_i E_j}$. Consequently, signal pairs with lower energies produce larger normalized correlation values and stronger relative interference effects. For the ensemble {2,3,5,7,11}, this gives $R_{max} = 1/\sqrt{2 \cdot 3} = 0.4082$.

An important property of periodic unequal-energy signal ensembles is that the maximum normalized mutual correlation for a given signal pair does not depend on the discrete temporal shift itself and is determined only by the energies of the corresponding signals. Variation of the temporal shift changes only the presence or absence of pulse overlap events. If no overlap occurs, the mutual correlation is zero; if a single overlap occurs, the correlation reaches its maximum value for that signal pair.

Consequently, the correlation levels shown in Figure 2. a) correspond to analytically determined maximum correlation values for individual signal pairs. This result demonstrates that, unlike equal-energy ensembles, the mutual correlation values in unequal-energy ensembles cannot be considered independently and must be analyzed jointly with the energies of interfering signals.



a) b)

Figure 2 – Mutual correlation for the signal ensemble {2,3,5,7,11}: a) maximum values; b) squares of the maximum values

Since the interference contribution is evaluated in the energy domain, the contribution of each interfering signal becomes proportional to the squared normalized correlation value. Physically, this corresponds to the portion of interfering signal energy coupled into the useful signal channel due to pulse overlap events.

Figure 2.b) shows the squared correlation values because the quantities $\left(R_{ij}^{(max)}\right)^2$, together with the energies of interfering signals E_j, determine the components of the total multiple-access interference (MAI) energy for the i-th user:

$$E_{I,i} = \sum_{j=1,\, j \neq i}^{L} E_j \left(R_{ij}^{(max)}\right)^2 \quad (5)$$

where $E_{I,i}$ is the total MAI energy for the i-th user,

E_j is the energy of the j-th interfering signal,

$R_{ij}^{(max)}$ is the maximum mutual correlation value between the i-th and j-th signals over all temporal shifts.

Thus, the contribution of each interfering signal to the total MAI energy is proportional to both the energy of the interfering signal and the squared maximum mutual correlation for the corresponding signal pair.

The contribution of the j-th interfering signal to the MAI energy of the i-th user is:

$$E_j R_{ij}^2(\tau) = \frac{M_{ij}(\tau)}{E_i}. \quad (6)$$

Thus, for the i-th user, the total MAI energy is:

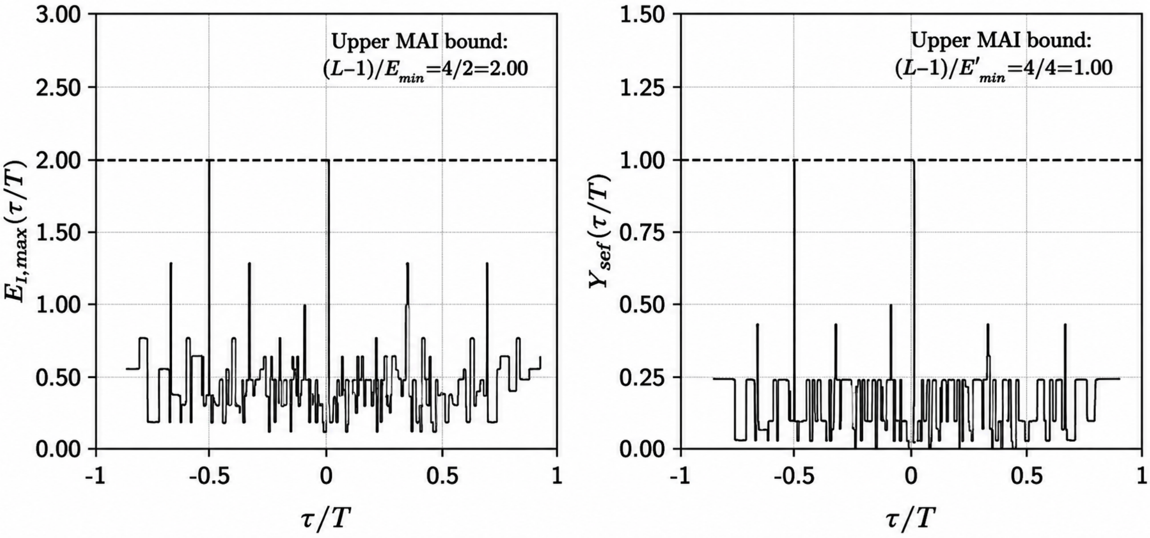
$$E_{I,i}(\tau) = \frac{1}{E_i} \sum_{j \neq i} M_{ij}(\tau), \quad (7)$$

and the normalized MAI energy is:

$$\gamma_{str,i}(\tau) = \frac{E_{I,i}(\tau)}{E_i} = \frac{1}{E_i^2} \sum_{j \neq i} M_{ij}(\tau). \quad (8)$$

These expressions show the main difference between equal-energy and unequal-energy ensembles: the interference level is governed by the energy of the useful signal and by the number of overlapping interfering signals.

Figure 3 presents the maximum total multiple-access interference (MAI) values among all users for the ensemble of periodic complex time-division signals $\{2,3,5,7,11\}$ as a function of the relative temporal shift τ/T. Figure 3. a) shows the maximum total MAI energy $E_{I,max}(\tau/T)$, while Figure 3. b) presents the maximum normalized total MAI energy $\gamma_{str}(\tau/T)$ among all users.



a) b)

Figure 3 – Maximum total multiple-access interference (MAI)

The maximum total MAI energy for the i-th user is achieved in the limiting case when all interfering signals simultaneously satisfy $M_{ij}(\tau) = 1, j \neq i$. In this case, the upper MAI bound is given by:

$$E_{I,i}^{(max)} = \frac{L-1}{E_i}. \quad (9)$$

Accordingly, the normalized upper interference bound becomes:

$$\gamma_{str,i}^{(max)} = \frac{L-1}{E_i^2}. \quad (10)$$

After normalization with respect to the useful signal energy, the normalized total MAI energy and the corresponding interference-limited SINR for the i-th user are defined as:

$$\gamma_{str,i}(\tau) = \frac{E_{I,i}(\tau)}{E_i}, \quad (11)$$

$$SINR_i^{(0)}(\tau) = \frac{1}{\gamma_{str,i}(\tau)}, \quad (12)$$

where $SINR_i^{(0)}(\tau)$ represents the ratio between the useful signal energy of the i-th user and the total multiple-access interference energy in the absence of noise.

These expressions demonstrate that the interference-limited performance of unequal-energy periodic ensembles is determined by the useful signal energy and by the number of simultaneous pulse overlaps. Consequently, higher-energy users exhibit substantially improved interference resistance compared with low-energy users.

For the ensemble $\{2,3,5,7,11\}$, the upper normalized interference bound for the user with the minimum signal energy is $\gamma_{str}^{(max)} = \frac{L-1}{E_{min}^2} = \frac{4}{2^2} = 1.00$, whereas for the user with the maximum signal energy it becomes $\gamma_{str}^{(min)} = \frac{L-1}{E_{max}^2} = \frac{4}{11^2} = 0.0331$.

Thus, the obtained results demonstrate that, for unequal-energy periodic signal ensembles, the achievable SINR is fundamentally determined by the square of the useful signal energy and by the number of simultaneously overlapping interfering signals. Consequently, higher-energy users exhibit substantially improved interference resistance, whereas low-energy users experience the most unfavorable interference conditions. This result highlights the dominant role of signal energy distribution in determining the interference-limited performance of unequal-energy periodic signal ensembles.

Therefore, the user with the maximum signal energy achieves:

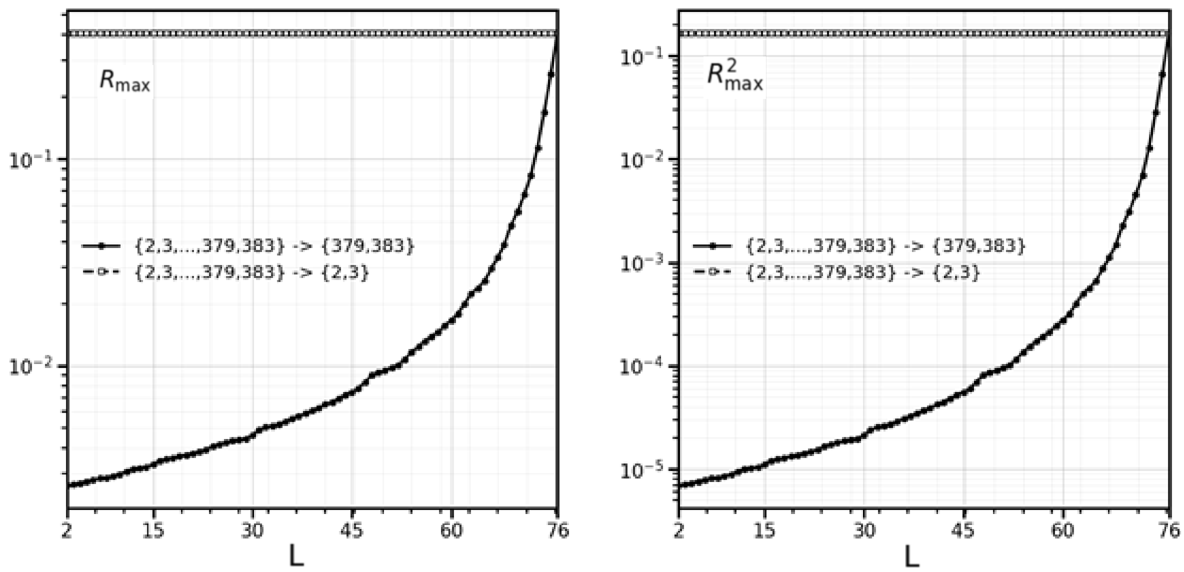
$$SINR_{max}^{(0)} = \frac{E_{max}^2}{L-1} = \frac{11^2}{4} = 30.25,$$

whereas for the user with the minimum signal energy:

$$SINR_{min}^{(0)} = \frac{E_{min}^2}{L-1} = \frac{2^2}{4} = 1.00.$$

These results clearly demonstrate the strong dependence of interference-limited SINR on the energy distribution within the ensemble. Users employing higher-energy signals achieve substantially better interference immunity, while low-energy users experience the most unfavorable interference conditions. Consequently, in unequal-energy periodic signal ensembles, the signal energy becomes one of the dominant factors determining achievable communication quality and interference resistance.

Figure 4 confirms that R_{max} is controlled by the two lowest-energy signals in the ensemble. If this pair remains $\{2,3\}$, the maximum correlation remains constant and equals 0.4082, regardless of ensemble size. If lower-energy signals are successively included in the ensemble, the minimum energy product decreases and R_{max} increases monotonically. Thus, the correlation behavior of unequal-energy periodic ensembles is determined not by the ensemble size alone but by the minimum energy pair.



a) b)

Figure 4 – Dependence of mutual correlation for ensembles of complex time-division signals: a) maximum values; b) squares of the maximum values.

Next, the dependence of the structural efficiency indicator $\gamma_{str}^{(+)}$ and the corresponding SINR value on the ensemble size and on the number of pulses in the highest-energy signal is investigated [9]:

$$\gamma_{str}^{(+)} = L_{eq}^{(+)} R_{max}^2, \tag{13}$$

where $L_{eq}^{(+)}$ is the structural equivalent ensemble size.

This parameter represents the size of an equivalent equal-energy signal ensemble having the same total signal energy and reflects the increase of multiple-access interference experienced by low-energy users due to the signal dominance effect caused by nonuniform energy distribution within the ensemble.

The structural equivalent ensemble size is defined as:

$$L_{eq}^{(+)} = \frac{L^2 \sum_{i=1}^{L} E_i^2}{\left(\sum_{i=1}^{L} E_i\right)^2}. \tag{14}$$

Figure 5 shows the dependence of the ensemble-level indicator $\gamma_{str}^{(+)}$ and the corresponding $SINR^{(0)}$ on the ensemble size and on the maximum signal energy. Since $R_{max}^2 = 1/(E_1 E_2)$, increasing the energies of the two lowest-energy signals reduces R_{max}^2, decreases $\gamma_{str}^{(+)}$, and increases $SINR^{(0)}$. At the same time, increasing the ensemble size increases $L_{eq}^{(+)}$, which strengthens the MAI effect. Therefore, larger ensembles require higher minimum signal energies to preserve the same SINR interval.

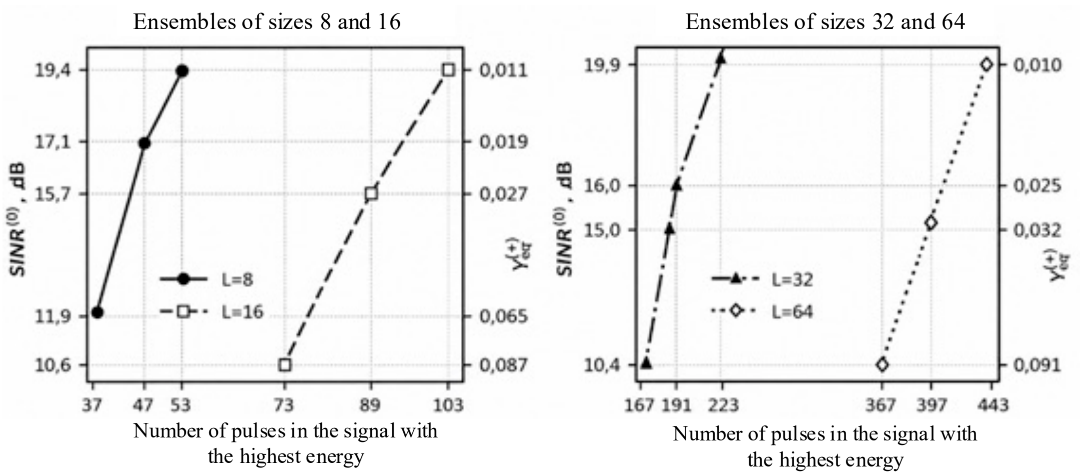


Figure 5 – Dependence of the ratio between the useful signal energy and the total multiple-access interference (MAI) energy for ensembles of complex time-division signals with periodic structure

Comparison of Figures 5. a) and 5. b) shows that, when the ensemble size increases, the same interval of $SINR^{(0)}$ values is achieved only for larger numbers of pulses in the highest-energy signal. For the upper part of the $SINR^{(0)}$ interval presented in Figure 5, the maximum number of pulses in the highest-energy signal equals 53 for $L = 8$, 103 for $L = 16$, 223 for $L = 32$, and 443 for $L = 64$.

Thus, when the ensemble size increases from $L = 8$ to $L = 64$, the maximum number of pulses in the highest-energy signal increases from 53 to 443, corresponding to an 8.36-fold increase.

These results demonstrate that preserving the same $SINR^{(0)}$ interval in larger ensembles requires correspondingly higher signal energies. Such behavior is governed by two competing factors:

– the reduction of the maximum mutual correlation value R_{max}^2 caused by increasing the energies of the lowest-energy signals;

– the increase of the structural equivalent ensemble size $L_{eq}^{(+)}$ with increasing ensemble size L.

An increase in $L_{eq}^{(+)}$ leads to higher values of the structural efficiency indicator $\gamma_{str}^{(+)}$, which corresponds to stronger multiple-access interference effects inside the ensemble. Therefore, maintaining similar $SINR^{(0)}$ levels in larger ensembles requires a more significant reduction of R_{max}^2. This reduction is achieved by increasing the energies of the two lowest-energy signals in the ensemble.

Consequently, the obtained results indicate that the interference resistance of unequal-energy periodic signal ensembles is determined not only by correlation properties but also by the balance between ensemble size and signal energy distribution. As the ensemble volume increases, maintaining stable interference-limited performance requires proportionally stronger growth of the minimum signal energies.

Conclusions.

This paper investigated unequal-energy ensembles of periodic complex time-division signals for ultra-wideband code-division multiple access systems. Analytical relationships between signal energy distribution, maximum mutual correlation, multiple-access interference, normalized interference energy, and interference-limited SINR were established.

It was shown that, unlike conventional equal-energy ensembles, the interference characteristics of unequal-energy periodic ensembles are determined jointly by correlation properties and by the internal signal energy distribution. The obtained results demonstrated that users employing lower-energy signals experience the most unfavorable interference conditions, whereas higher-energy users achieve substantially improved interference resistance and SINR performance.

The study also demonstrated that the maximum normalized correlation level is determined by the minimum energy product inside the ensemble rather than only by the ensemble size. Furthermore, the introduced structural equivalent ensemble size allows the interference behavior of unequal-energy ensembles to be characterized at the ensemble level.

The obtained analytical relationships may be useful for the synthesis and optimization of unequal-energy signal ensembles for ultra-wideband multiple-access communication systems operating under interference-limited conditions.

References

1. IEEE Standard for Information Technology. Local and Metropolitan Area Networks. Specific Requirements. Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs): Amendment 1: Add Alternate PHYs, IEEE Std 802.15.4a-2007, 2007.
2. IEEE Standard for Low-Rate Wireless Networks. Amendment 1: Enhanced Ultra-Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques, IEEE Std 802.15.4z-2020, 2020.
3. Hayashi T. A Novel Class of Zero-Correlation Zone Sequence Sets Constructed from a Perfect Sequence," IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, vol. E91-A, no. 4, pp. 1233-1237, 2008. DOI: https://doi.org/10.1093/ietfec/e91-a.4.1233
4. Hayashi T., Maeda T., Kanemoto S., Matsufuji S. Low-Peak-Factor Pseudo-White-Noise Sequence Set with Optimal Zero-Correlation Zone. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, vol. E97-A, no. 12, pp. 2343–2351, 2014. DOI: https://doi.org/10.1587/transfun.E97.A.2343
5. Feng L., Zhou X., Li X. A General Construction of Inter-Group Complementary Codes Based on Z-Complementary Codes and Perfect Periodic Cross-Correlation Codes. Wireless Personal Communications, vol. 71, no. 1, pp. 695-706, 2013. DOI: https://doi.org/10.1007/s11277-012-0837-6
6. Chiba K. Hamamura M. Multitone-Hopping CDMA Using Feedback-Controlled Hopping Pattern for Decentralized Multiple Access. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, vol. E91-A, no. 12, pp. 3723-3730, 2008. DOI: https://doi.org/10.1093/ietfec/e91-a.12.3723
7. 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, no. 4, pp. 7-14, 2020. DOI: https://doi.org/10.15588/1607-3274-2020-4-1
8. Lysechko V. P., Trubchaninova K. A., Zhuchenko O. S., Shubina H. V. Multi-Level Functional Model of Performance Indicators for a Code-Division Multiple Access System. Systems of Control, Navigation and Communication, no. 2(84), pp. 233-236, 2026. DOI: https://doi.org/10.26906/SUNZ.2026.2.233
9. Zhuchenko O., Panchenko S., Lysechko V., Indyk S. Methodology of Equivalent Transformations of Unequal-Energy Complex Signal Ensembles in Code-Division Multiple Access Systems. Computer-Integrated Technologies: Education, Science, Production, no. 62, pp. 337-345, 2026. DOI: https://doi.org/10.36910/6775-2524-0560-2026-62-38
10. Lysechko V. P., Zhuchenko O. S., Indyk S. V. System of Performance Indicators for Unequal-Energy Complex Signal Ensembles for Ultra-Wideband Code-Division Multiple Access Systems. Modern Directions for the Development of Information and Communication Technologies and Control Systems: Proceedings of the 16th International Scientific and Technical Conference, vol. 5, section 6, Baku; Kharkiv; Žilina, Apr. 29-30, 2026, pp. 65-68. DOI: https://doi.org/10.32620/ICT.26.t5

Історія статті:
Отримано: 06.05.2026 Доопрацьовано: 20.05.2026 Прийнято до друку: 23.05.2026 Опубліковано: 29.05.2026