

DOI: <https://doi.org/10.36910/6775-2524-0560-2026-62-38>

УДК 621.391.8:519.21

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METHODOLOGY OF EQUIVALENT TRANSFORMATIONS OF UNEQUAL-ENERGY COMPLEX SIGNAL ENSEMBLES IN CODE-DIVISION MULTIPLE ACCESS SYSTEMS

Zhuchenko O., Panchenko S., Lysechko V., Indyk S. Methodology of Equivalent Transformations of Unequal-Energy Complex Signal Ensembles in Code-Division Multiple Access Systems. The paper develops a methodology of equivalent transformations for ensembles of complex signals with unequal energies in code-division multiple access (CDMA) systems. The relevance of this study arises from the limited applicability of classical equal-energy ensemble models to the analysis of CDMA systems under conditions of user energy heterogeneity. The proposed approach is based on preserving the total ensemble energy and its correlation structure, while transferring the effect of non-uniform signal energy distribution into scalar equivalence parameters. Within this framework, structural and energy equivalent transformations are introduced, forming a dual pair of equivalent volumes that ensure a consistent reproduction of the level of multiple-access interference for unequal-energy ensembles. It is shown that the proposed equivalent volumes retain the physical meaning of well-known correlation-based performance criteria and enable the use of analytical relations derived for equal-energy models without modification. The results of experimental modelling confirm the validity of the equivalent transformations and the adequacy of interference reproduction for various scenarios of energy heterogeneity. The obtained results can be employed for the analysis, comparison, and optimisation of signal ensembles in CDMA systems under conditions of non-uniform user energy distribution.

Keywords: ensembles of complex signals; unequal-energy signals; equivalent transformations; CDMA; multiple-access interference.

Жученко О.С., Панченко С.В., Лисечко В.П., Індик С.В. Методологія еквівалентних перетворень ансамблів різноенергетичних складних сигналів систем множинного доступу з кодовим розділенням. В статті розроблено методологію еквівалентних перетворень ансамблів різноенергетичних складних сигналів у системах множинного доступу з кодовим розділенням. Актуальність дослідження зумовлена обмеженою застосовністю класичних моделей різноенергетичних ансамблів для аналізу систем CDMA в умовах енергетичної неоднорідності користувачів. Запропонований підхід ґрунтується на збереженні сумарної енергії та кореляційної структури ансамблю з перенесенням впливу нерівномірного розподілу енергій сигналів у скалярні параметри еквівалентності. У межах дослідження введено структурне та енергетичне еквівалентні перетворення, які формують дуальну пару еквівалентних об'ємів і забезпечують узгоджене відтворення рівня внутрішньосистемних завад множинного доступу для різноенергетичних ансамблів. Показано, що запропоновані еквівалентні об'єми зберігають фізичний зміст відомих кореляційних критеріїв ефективності та дозволяють застосовувати аналітичні співвідношення різноенергетичних моделей без їх модифікації. Результати експериментального моделювання підтвердили коректність еквівалентних перетворень і адекватність відтворення заводової обстановки для різних сценаріїв енергетичної неоднорідності. Отримані результати можуть бути використані для аналізу, порівняння та оптимізації ансамблів сигналів у системах множинного доступу з кодовим розділенням в умовах нерівномірного енергетичного розподілу користувачів.

Ключові слова: ансамблі складних сигналів; різноенергетичні сигнали; еквівалентні перетворення; CDMA; внутрішньосистемні завади.

Statement of a scientific problem.

In code-division multiple access (CDMA) systems, the efficiency of signal reception is determined by the combined effect of the correlation properties of the signal ensemble and the distribution of energy among users. In the classical formulation, the analysis of such systems is performed for equal-energy ensembles of complex signals, for which closed-form analytical relationships have been obtained between the correlation structure of the ensemble and the level of internal multiple-access interference (MAI). Within this framework, the structural characteristics of the ensemble are consistently linked to integral performance criteria, thereby ensuring an unambiguous interpretation of the analysis results.

The transition to unequal-energy signal ensembles fundamentally alters the conditions under which MAI is formed. For a fixed correlation structure, a non-uniform distribution of energy among user signals leads to a dominance effect, whereby the contributions of individual signals to multiple-access interference increase in proportion to their energies weighted by the squares of the mutual correlation coefficients. As a

result, higher-energy signals generate dominant MAI components, which has the most critical impact on users with lower useful signal energy. Consequently, energy non-uniformity constitutes a distinct class of ensemble parameters that cannot be reduced to correlation characteristics and cannot be adequately accounted for within standard equal-energy models.

The direct application of analytical relationships derived for equal-energy ensembles to unequal-energy cases, without additional coordination, leads to methodologically inconsistent estimates, since the known formulations lack a parameter that explicitly captures the effect of energy non-uniformity without altering the underlying dependencies. At the same time, non-uniform energy distribution gives rise to energy unfairness as an independent ensemble property, which cannot be correctly represented solely through structural correlation measures. In view of this, a scientific problem arises concerning the development of a coherent theoretical and methodological framework that would enable the transfer of established analytical relationships and performance criteria of equal-energy ensembles to unequal-energy and structurally heterogeneous ensembles without changing their physical meaning.

Research analysis.

An analysis of the literature indicates that the problem of the impact of non-uniform signal energy distribution in code-division multiple access (CDMA) systems has been addressed within several interrelated research directions. Classical studies on CDMA analysis, in particular the statistical-mechanics approach presented in [1, 2], are focused on large-system analysis, sequence optimisation, and multiuser detector design under the assumption of equal-energy or statistically homogeneous ensembles. Contemporary methods for forming ensembles of complex signals with prescribed structural properties enable control of the correlation structure at different levels of detail; however, in these studies energy heterogeneity is not generalised into scalar parameters suitable for analytical equivalencing [3]. While these works have established fundamental analytical techniques, they largely fail to disentangle the influence of correlation structure from that of energy non-uniformity.

The problem of unequal user powers is explicitly addressed in [4], where the concept of the “dirty user problem” is introduced for downlink DS-CDMA systems. The authors demonstrate that the dominance of higher-power signals leads to a severe degradation in reception quality for weaker users. At the same time, the proposed solutions are mainly confined to numerical analysis and power optimisation procedures, without a formalised alignment with classical correlation-based models.

A number of studies [5, 6] are devoted to energy-efficient power control and joint transmitter–receiver optimisation in CDMA systems. In these works, energy non-uniformity is treated as a controllable optimisation variable; however, it is not introduced as an independent structural characteristic of the signal ensemble. A similar approach can be observed in applied studies of CDMA-based communication channels [7], where the emphasis is placed on capacity and interference robustness, but without a unified invariant measure of energy heterogeneity.

Recent investigations of non-orthogonal multiple access (NOMA) systems [8–10] further confirm the relevance of energy non-uniformity and the dominance of higher-power users. Although these studies extend beyond the classical CDMA framework, they reveal a common trend: non-uniform energy distribution has a critical impact on internal system interference and requires dedicated descriptive methods. A limitation of these approaches lies in their strong dependence on specific scenarios and power allocation algorithms, which complicates the transfer of results across different models.

Thus, existing studies either focus on equal-energy models or consider unequal user powers solely within optimisation frameworks. A coherent methodological apparatus that would preserve the physical meaning of classical correlation-based performance criteria while consistently accounting for energy heterogeneity is still lacking. This logically substantiates the need for the development of a methodology of equivalent transformations for unequal-energy ensembles of complex signals, as proposed in this paper, which bridges the gap between classical analytical models and the practical conditions of energy unfairness in CDMA systems.

The purpose of this study is to develop a methodology of equivalent transformations for ensembles of unequal-energy complex signals, which makes it possible to reduce the multidimensional distribution of user signal energies to a set of consistent scalar equivalence parameters and to ensure the correct application of well-known correlation-based performance criteria in code-division multiple access (CDMA) systems.

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

Let us consider an ensemble of complex signals in a code-division multiple access system consisting of L user signals. Within a discrete-time model, each signal is represented by a normalised complex sequence with an individual energy $E_i, i = 1, 2, \dots, L, i = 1, 2, \dots, L$. The collection of signals forms an ensemble whose correlation structure is defined by the matrix of mutual correlations of the normalised signals. In the subsequent analysis, the correlation structure of the ensemble is assumed to be fixed, while the differences between ensembles are determined exclusively by the distribution of energies among the user signals.

To describe internal multiple-access interference (MAI), a quadratic correlation model is employed, within which the contribution of the i -th signal to the interference is determined by its energy and by the squares of the mutual correlation coefficients with the other signals of the ensemble.

Let a set of non-negative quantities be given $E_i, i = 1, \dots, L$, not all of which are zero. We define a scalar quantity that quantitatively characterises the non-uniformity of the distribution of these values and is invariant with respect to uniform scaling $E_i \mapsto cE_i$ for $c > 0$. Such a quantity is required as a mathematical carrier of the dominance effect among the individual components.

We construct measures of dispersion and concentration for the set E_i and establish their interrelation. Let μ_E denote the mean value of the quantities, σ_E^2 – their variance, and C_v^2 – the squared coefficient of variation. Then:

$$\mu_E = \frac{1}{L} \sum_{i=1}^L E_i, \sigma_E^2 = \frac{1}{L} \sum_{i=1}^L (E_i - \mu_E)^2, C_v^2 = \frac{\sigma_E^2}{\mu_E^2}. \quad (1)$$

Under this formulation, both the total and individual multiple-access interference depend not only on the correlation structure but also on the energy distribution E_i , which becomes critical in the case of unequal-energy ensembles. The squared coefficient of variation C_v^2 represents a dimensionless quadratic measure of non-uniformity of the set E_i , consistently linking the first moment E_Σ and the second moment $\sum_{i=1}^L E_i^2$.

In order to eliminate dependence on the energy scale under the transformation $E_i \mapsto cE_i$ for $c > 0$, normalisation by the total energy is performed and a quadratic measure of concentration of the normalised shares is introduced as the sum of the squares of the normalised energy fractions:

$$\kappa_E = \sum_{i=1}^L \left(\frac{E_i}{\sum_{j=1}^L E_j} \right)^2. \quad (2)$$

The admissible range of values of this quantity lies within the interval $\frac{1}{L} \leq \kappa_E \leq 1$.

The lower bound $\kappa_E = 1/L$ corresponds to the uniform energy distribution, whereas the upper bound $\kappa_E = 1$ represents the limiting case of complete dominance of a single component.

Let us fix the relationship between the variational and concentration-based representations of non-uniformity as

$$C_v^2 = L\kappa_E - 1. \quad (3)$$

This relationship shows that C_v^2 and κ_E are mutually one-to-one representations of the same non-uniformity property for a given L . The variational form C_v^2 is physically transparent for interpretation,

while the concentration form κ_E is more convenient for further transformations, as it is directly related to quadratic sums of the normalised energy fractions.

As the basic condition for equivalent transformations, we impose the requirement of invariance of the total energy of the signal ensembles, since it defines the overall energy resource, which must remain unchanged under equivalencing. Under this condition, the differences between the original ensemble and its conditional equivalent are determined solely by the redistribution of energy among the signals.

Let us now consider the original multiple-access interference model and the issue of structural consistency:

$$E_{I,i} = E \left\{ |I_i|^2 \right\} \approx \sum_{j=1, j \neq i}^L E_j |R_{ij}(\tau_{ij})|^2, \quad (4)$$

where, $E_{I,i}$ – the energy of multiple-access interference for the i -th user;

I_i – the interference component at the output of the correlation receiver matched to the i -th signal;

E_j – the energy of the j -th user;

$R_{ij}(\tau_{ij})$ – the mutual correlation coefficient between the normalised signals at a relative delay τ_{ij} ;

L – the number of signals in the ensemble.

Here, the relative delays τ_{ij} are assumed to be statistically independent and wide-sense stationary random variables, which ensures the validity of the averaged correlation-based interference representation.

For an unequal-energy ensemble, the expression for $E_{I,i}$ explicitly includes the weighting factors E_j . As a result, the structural correlation-based estimate of multiple-access interference can no longer be uniquely determined solely by the correlation matrix, since the energy distribution introduces an additional, independent degree of freedom.

We therefore introduce the structural equivalent volume of an unequal-energy ensemble, denoted by $L_{\text{eq}}^{(+)}$, as the conditional equivalent number of signals in an equal-energy ensemble. This quantity is defined through the dispersion of signal energies and serves as a scalar representation of energy non-uniformity.

$$L_{\text{eq}}^{(+)} = L(1 + C_v^2), \quad L_{\text{eq}}^{(+)} = L^2 \kappa. \quad (5)$$

As the degree of energy non-uniformity increases, the value of $L_{\text{eq}}^{(+)}$ also increases. Within the adopted quadratic interference model, this growth reflects an increase in the integral estimates of internal multiple-access interference, which is equivalent to an increase in the effective number of equal-energy interfering signals while preserving the total ensemble energy. For a conditional equal-energy ensemble consisting of $L_{\text{eq}}^{(+)}$ signals with identical energy $E_{\text{eq}}^{(+)} = \frac{E_{\Sigma}}{L_{\text{eq}}^{(+)}}$, equivalence in terms of total energy can be expressed as:

$$L_{\text{eq}}^{(+)} E_{\text{eq}}^{(+)} = L_{\text{eq}}^{(+)} \frac{E_{\Sigma}}{L_{\text{eq}}^{(+)}} = E_{\Sigma}. \quad (6)$$

Thus, the transition to an equivalent ensemble preserves the total energy of the original ensemble, while the non-uniformity of the energy distribution is transferred into the scalar parameter $L_{\text{eq}}^{(+)}$. To determine the bounds of the quantity $L_{\text{eq}}^{(+)}$, two limiting cases are considered:

– uniform distribution of signal energies:

$$E_1 = \dots = E_L, \text{ then } \frac{E_i}{E_{\Sigma}} = \frac{1}{L} \text{ and } \kappa_E = \sum_{i=1}^L \left(\frac{1}{L} \right)^2 = \frac{1}{L}, \text{ then } L_{\text{eq}}^{(+)} = L^2 \cdot \frac{1}{L} = L; \quad (7)$$

– concentration of the total ensemble energy in a single signal:

$$E_1 = E_\Sigma, E_2 = \dots = E_L = 0, \text{ тоді } \kappa_E = 1 \text{ та } L_{\text{eq}}^{(+)} = L^2. \quad (8)$$

Accordingly, the bounds of $L \leq L_{\text{eq}}^{(+)} \leq L^2$ are realised for two extreme energy distributions: the lower bound corresponds to a uniform distribution of signal energies (the best-case scenario), which is equivalent to an equal-energy ensemble, whereas the upper bound corresponds to the concentration of the total ensemble energy in a single signal (the worst-case scenario).

Thus, equivalent transformations are proposed as a formalised tool for reconciling different levels of description of signal ensembles, namely the structural and the energy-related levels. This approach enables unequal-energy ensembles to be analysed within the parameter space of conditional equal-energy objects, thereby establishing a unified basis for comparison, ranking, and optimisation of ensembles subject to constraints on internal multiple-access interference. The introduced equivalence conditions provide a methodological foundation for the subsequent development of specific implementations of equivalent transformations and corresponding scalar indicators suitable for the practical analysis of code-division multiple access systems.

Experimental modelling.

A comparison was carried out between the individual multiple-access interference (MAI) energies of the original unequal-energy ensemble of time-division complex signals with a periodic structure and those of its structural equal-energy equivalent. The analysis was performed for a representative set of signal energies using an exact calculation based on the matrix of squared maximum normalised mutual correlation coefficients.

The consistency of the exact calculation of individual MAI was evaluated by means of the relative difference $\Delta_{I,i}^{(+)}$ between the threshold value $E_{I,\text{thr}}^{(+)}$ and the corresponding interference energy $E_{I,i}$:

$$E_{I,\text{thr}}^{(+)} = \frac{L_{\text{eq}}^{(+)} (L_{\text{eq}}^{(+)} - 1)}{E_\Sigma}, \Delta_{I,i}^{(+)} = \frac{E_{I,\text{thr}}^{(+)} - E_{I,i}}{E_{I,i}}, E_{\text{thr}}^{(+)} = \frac{(L-1)E_\Sigma}{L_{\text{eq}}^{(+)} (L_{\text{eq}}^{(+)} - 1)}. \quad (9)$$

The analytical expression for the relative difference of the individual MAI $\Delta_{I,i}^{(+)}$ is obtained. It makes it possible to directly trace its dependence on energy non-uniformity through C_v^2 , provided that the threshold value $E_{I,\text{thr}}^{(+)}$ is expressed explicitly in terms of C_v^2 and that the exact expression for $E_{I,i}$, applicable to time-division signals is employed:

$$E_{I,\text{thr}}^{(+)} = \frac{L_{\text{eq}}^{(+)} (L_{\text{eq}}^{(+)} - 1)}{E_\Sigma} = \frac{(1 + C_v^2)(L(1 + C_v^2) - 1)}{\mu_E}, E_{I,i} = \frac{L-1}{E_i}, \quad (10)$$

$$\Delta_{I,i}^{(+)} = \frac{E_{I,\text{thr}}^{(+)} - E_{I,i}}{E_{I,i}} = \frac{E_i}{L-1} \cdot \frac{(1 + C_v^2)(L(1 + C_v^2) - 1)}{\mu_E} - 1. \quad (11)$$

Expressions (9) – (11) compare the interference levels in a threshold-based sense, which is typical for MAI analysis in CDMA systems and allows relative equivalence assessment of different signal ensembles.

The structural equivalent transformation technique, interpreted as a transition from a non-uniform to a uniform energy distribution under a fixed total energy resource, was validated for an ensemble specified by the set $\{2,3,5,7,11\}$.

Figure 1 illustrates the distribution of signal energies: (a) the original unequal-energy ensemble and (b) the equal-energy equivalent ensemble with $L_{\text{eq}}^{(+)}$ rounded up to the nearest integer. The figure demonstrates the preservation of the total energy E_Σ and the replacement of the non-uniform set E_i by the

uniform value $E_{eq}^{(+)}$. For the reference example, $E_{\Sigma} = 28$ and $L_{eq}^{(+)} = 6,63$, which yields $E_{eq}^{(+)} = 4,22$; after rounding, $L_{eq}^{(+)} = 7$.

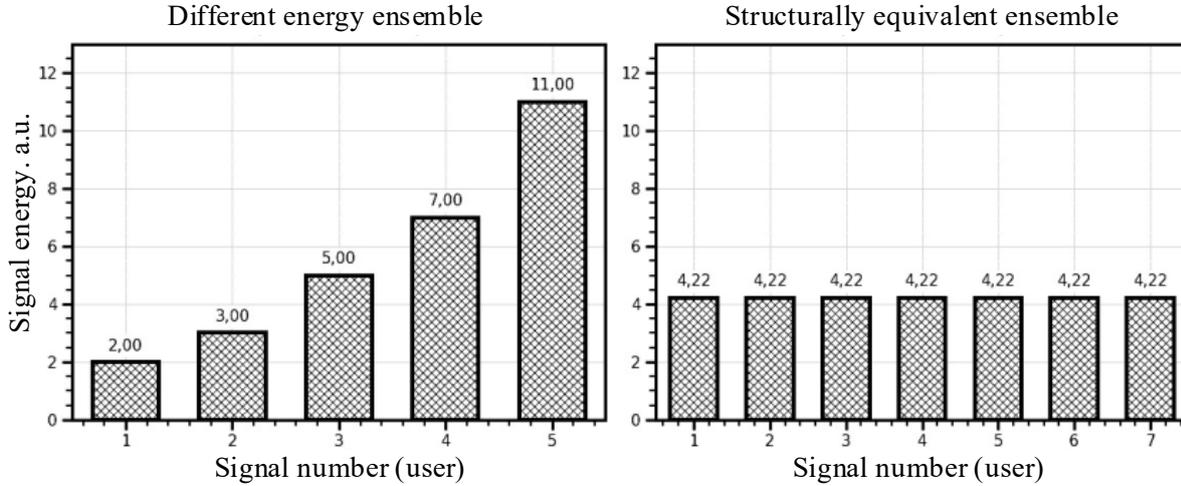


Fig. 1 – Signal energy distributions: (a) unequal-energy ensemble ($L=5$);
 (b) equal-energy equivalent ensemble ($L_{eq}^{(+)} = 7$)

Figure 2 presents the lower and upper bounds of the structural equivalent volume $L_{eq}^{(+)}$ and its values for a set of initial unequal-energy ensembles A1 – A10. The figure shows that the value of $L_{eq}^{(+)}$ for each ensemble lies within the admissible range defined by the bounds. For ensemble A7, a value of $L_{eq}^{(+)} = 6,63$ is observed, which exceeds L and reflects an increase in the structural parameter due to the presence of energy non-uniformity.

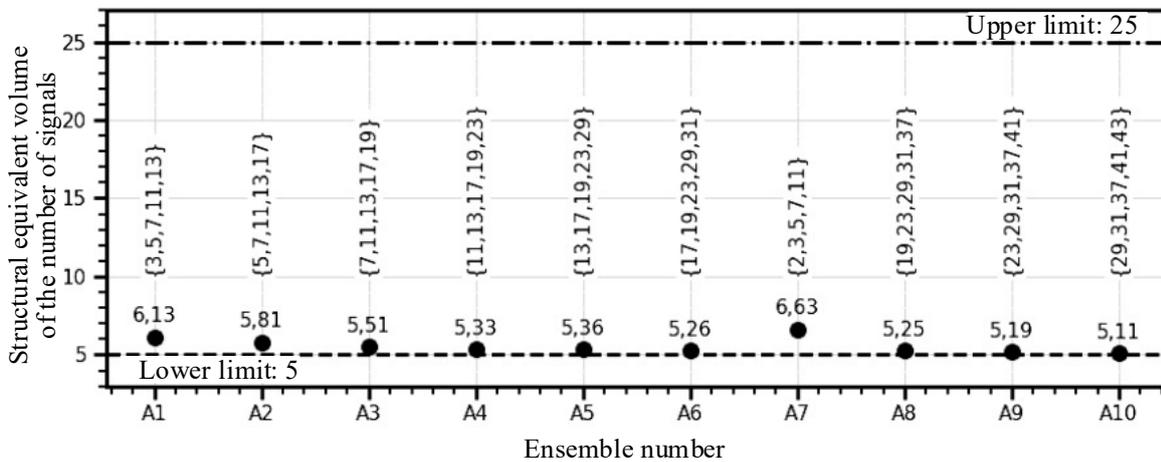


Fig. 2 – Bounds of the structural equivalent volume $L_{eq}^{(+)}$ for the set of initial unequal-energy ensembles A1 – A10 at $L=5$

Figure 3 illustrates the dependence of $L_{eq}^{(+)}$ on the squared coefficient of variation of the energies, C_v^2 for the set of ensembles A1 – A10 of equal size. The figure demonstrates a consistent relationship between the measure of energy dispersion C_v^2 and the structural parameter $L_{eq}^{(+)}$: as C_v^2 increases, $L_{eq}^{(+)}$ also increases. This provides a compact reconciliation of two descriptions of energy non-uniformity E_i and justifies the interpretation of $L_{eq}^{(+)}$ as a parameter that reflects the degree of energy heterogeneity without requiring a component-wise description of the set E_i .

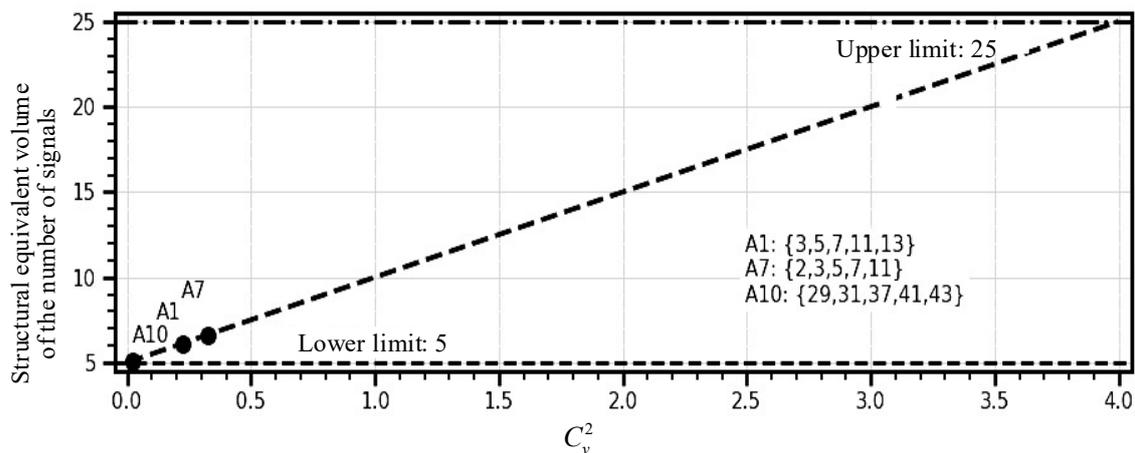


Fig. 3 – Dependence of the quantity $L_{eq}^{(+)}$ on C_v^2 for ensembles A1 – A10 ($L=5$)

The results of calculating the individual MAI energy for the original ensemble using the exact computation (Fig. 4) reveal a separation of users with respect to the threshold level: one signal produces MAI above the threshold, one is located close to the threshold, and the remaining signals lie below it. The normalised relative difference $\Delta_{I,i}^{(+)}$ provides a quantitative measure of the deviation of each user's MAI from the threshold. The obtained range of $\Delta_{I,i}^{(+)}$, from -33.3% to 267% , should be interpreted as a measure of individual MAI non-uniformity relative to the equal-energy representation: the sign indicates the side of the threshold, while the magnitude characterises the degree of deviation from it.

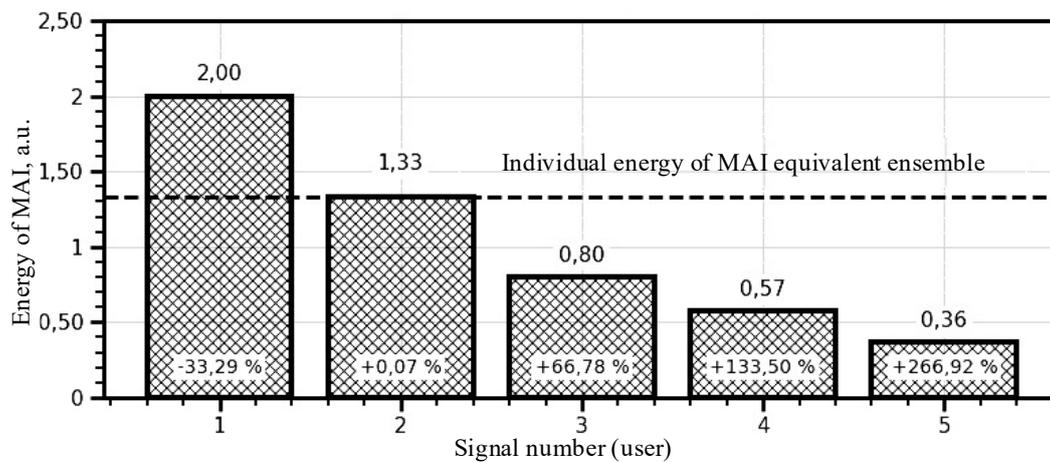


Fig. 4 – Individual MAI obtained by exact calculation using the full matrix of mutual correlations

It should be noted that, in the exact calculation, the individual MAI energy is a decreasing function of the energy of the corresponding signal. Consequently, the upper bound of the individual MAI is attained for the signal with the minimum energy in the set, whereas the lower bound corresponds to the signal with the maximum energy. In the approximate calculation, where the off-diagonal correlation coefficients are replaced by a single maximum value, the individual MAI becomes a linear function of the difference between the total ensemble energy and the signal energy. As a result, the upper bound again corresponds to the minimum signal energy, and the lower bound to the maximum signal energy. The difference from the exact case lies in the scaling of these bounds by a common factor determined by the adopted correlation approximation.

Figure 5 presents the individual MAI energy values for the original ensemble obtained under the approximate calculation (with a separate bar for each user), together with the level of the conditional equivalent user acting as a threshold in the MAI domain (shown by a horizontal dashed line). A narrowing of the range of relative differences with respect to the threshold is observed in comparison with the exact calculation, which is consistent with the change in the structure of the MAI dependence on signal energies

in the approximate model. For this example, the range of relative differences with respect to the threshold in the MAI domain extends from -8.62% to 39.76% .

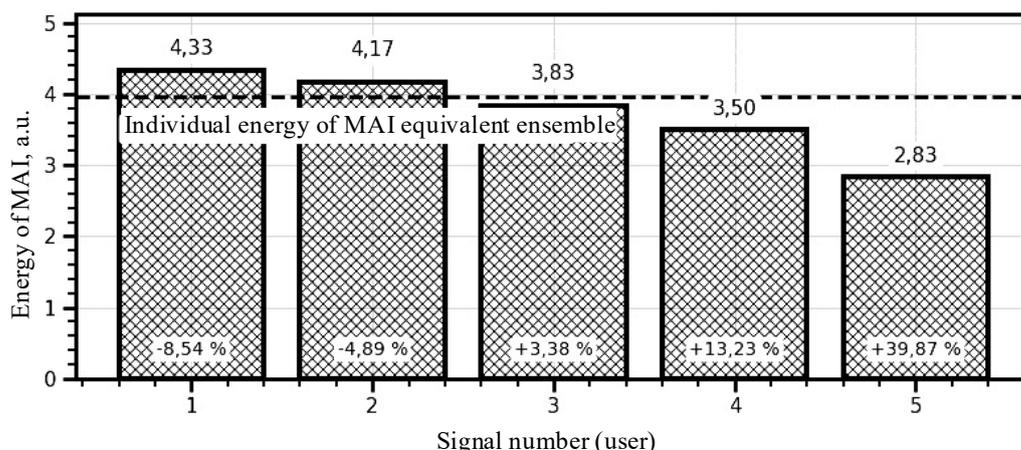


Fig. 5 – Individual MAI obtained by approximate calculation using the maximum mutual correlation value

The set of Figures 1–5 demonstrates that the structural parameter $L_{eq}^{(+)}$ consistently reflects the degree of energy non-uniformity, while threshold-based comparison in the MAI domain yields identical grouping and ranking for both the exact and approximate calculations in the reference example. This ensures an unambiguous interpretation of the numerical results.

At the same time, the obtained results indicate that the proposed methodology of equivalent transformations is applicable not only to the analysis of internal multiple-access interference, but also to the solution of energy balancing problems among users in unequal-energy ensembles. As the degree of energy non-uniformity increases, the contribution of the group of weaker signals to the total ensemble energy may become negligible, which leads to a degradation in their reception efficiency and to a violation of energy fairness within the system.

The use of the equivalent parameter $L_{eq}^{(-)}$, with $L_{eq}^{(-)} = \kappa^{-1}$, introduced within the framework of the $(-)$ criterion, makes it possible to replace the multidimensional energy distribution E_i with a single scalar parameter without loss of meaning in threshold-based MAI comparison. The difference between the exact and approximate evaluation modes manifests itself only in the numerical scale of deviations and does not affect the qualitative conclusions regarding the comparison and ranking of ensembles.

Thus, the proposed dual system of equivalent volumes establishes a unified parametric basis for the analysis, comparison, and optimisation of unequal-energy signal ensembles in code-division multiple access systems. It enables diverse scenarios of energy heterogeneity to be reduced to a consistent formalised description and ensures methodological continuity with classical models of equal-energy ensembles.

Conclusions and prospects for further research.

The paper develops and substantiates a methodology of equivalent transformations for ensembles of unequal-energy complex signals in code-division multiple access (CDMA) systems, which enables the consistent incorporation of non-uniform signal energy distribution without modifying the fundamental analytical relationships derived for equal-energy ensembles. The proposed approach is based on preserving the total ensemble energy and the correlation structure, while transferring the effect of energy heterogeneity into scalar parameters of equivalence.

Within the proposed methodology, structural and energy equivalent transformations are introduced, forming a dual pair of equivalent volumes $L_{eq}^{(+)}$ and $L_{eq}^{(-)}$. These provide alternative yet mutually consistent means of describing the impact of signal energy non-uniformity on the level of internal multiple-access interference. The results of experimental modelling confirm the validity of the equivalence concept and the adequacy of interference representation for various scenarios of energy heterogeneity.

The obtained results establish a foundation for the generalised analysis, comparison, and optimisation of signal ensembles in CDMA systems under conditions of energy unfairness. Future research directions include extending the proposed methodology to adaptive and multi-rate multiple-access systems,

accounting for the temporal variability of energy parameters, and integrating equivalent transformations into optimal power allocation procedures and signal ensemble synthesis.

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Історія статті:

Отримано: 21.01.2026 Доопрацьовано: 19.02.2026 Прийнято до друку: 23.03.2026 Опубліковано: 29.03.2026