

PANCHENKO Serhii Volodymyrovych¹, Doctor of Technical Sciences, Professor

ZHUCHENKO Oleksandr Serhiiovych¹, Candidate of Technical Sciences, Associate Professor

LYSECHKO Volodymyr Petrovych², Doctor of Technical Sciences, Professor

INDYK Serhii Volodymyrovych¹, Candidate of Technical Sciences, Associate Professor

1 Ukrainian State University of Railway Transport, Kharkiv, Ukraine

2 Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Ukraine



Estimation of the Energy of Interfering Signals in a Code Division Multiple Access System Based on Unequal-Energy Complex Signals for Users Susceptible to Dominance by Other Users' Signals

In a code-division multiple access system, when a user's signal is received, the signals from the other users are treated as interfering signals and produce multiple-access interference. For unequal-energy complex signal ensembles, a nonuniform signal-energy distribution causes the total energy of interfering signals to differ among users and gives rise to the signal-dominance effect. This study aims to obtain an estimate of the energy of interfering signals for users susceptible to signal dominance from other users, to be used as a pessimistic estimate for the ensemble as a whole. To reduce the set of individual values to a single estimate, the unequal-energy complex signal ensemble is equivalently transformed into a hypothetical equal-energy complex signal ensemble while preserving the total signal energy. It is shown that the normalized total energy of interfering signals for users susceptible to signal dominance from other users is approximately equal to the structural equivalent size, which therefore provides a pessimistic estimate for the unequal-energy complex signal ensemble as a whole. For equal-energy complex signal ensembles, the structural equivalent size is equal to the actual ensemble size, corresponding to a uniform signal-energy distribution. As the degree of nonuniformity in the signal-energy distribution increases, the structural equivalent size increases monotonically toward an upper bound corresponding to concentration of the total ensemble energy in a single signal—the highest possible nonuniformity for a fixed total signal energy. Thus, the structural equivalent size of an unequal-energy complex signal ensemble represents the calculated number of equal-energy complex signals in an ensemble with the same total signal energy as the original ensemble. It increases with the degree of signal-energy nonuniformity, provides a pessimistic estimate of the normalized total energy of interfering signals for users susceptible to signal dominance from other users, and allows performance metrics developed for equal-energy complex signal ensembles to be extended to unequal-energy complex signal ensembles by substituting the structural equivalent size into the corresponding expressions for equal-energy complex signal ensembles.

Keywords: code-division multiple access system, multiple-access interference, energy of interfering signals, unequal-energy complex signal ensemble, structural equivalent size, dominance by other users' signals, cross-correlation.

Introduction.

In a code-division multiple access system, when a user's signal is received, the signals from the other users are treated as interfering signals. These interfering signals produce multiple-access interference (MAI), whose energy depends on the energies of the interfering signals and their cross-correlations. Computing cross-correlations for every pair of signals in the ensemble can be computationally demanding, so a common approximation is to replace the pairwise cross-correlations with the maximum cross-correlation value in the ensemble, which is assumed to be known in this study. Under this approximation, the multiple-access interference energy is

the product of the total energy of the interfering signals, obtained by summing the energies of all ensemble signals except the user's desired signal, and the square of the maximum cross-correlation value. For equal-energy complex signals, removing any desired signal from the ensemble leaves the same sum of signal energies, so the total energy of the interfering signals is the same for every user.

For an unequal-energy complex signal ensemble, removing signals with different energies produces different remaining energy sums; therefore, the total energy of interfering signals differs among users because of the nonuniform signal-energy distribution.

Direct calculation of the interfering-signal energy for each user yields a set of individual values. For performance evaluation, it is useful to have a single numerical estimate that reduces this set to one quantity while accounting for the nonuniform signal-energy distribution. This allows a relation similar to that for the equal-energy case, in which the multiple-access interference energy is calculated as the product of this estimate and the square of the maximum cross-correlation value.

A nonuniform energy distribution in an unequal-energy signal ensemble gives rise to the signal-dominance effect, which appears as an increase in the total multiple-access interference energy relative to the desired-signal energy of a user. Under the adopted approximation, in which the signal cross-correlations are replaced by a single ensemble-wide maximum value, the subsequent analysis can be based on the total energies of the interfering signals.

If a user's desired signal has lower energy than the signals of at least some other users, the multiple-access interference energy relative to that desired signal increases, making the user susceptible to signal dominance from other users. Conversely, if a user's signal has higher energy than the signals of at least some other users, it contributes more strongly to the total interfering-signal energy seen by those users, so the signal tends to dominate the signals of other users. These two manifestations of signal dominance correspond to two numerical estimates of the energy of interfering signals: an estimate for users susceptible to signal dominance from other users, used as a pessimistic estimate for the ensemble as a whole, and an estimate for signals that tend to dominate the signals of other users, used as an optimistic estimate for the ensemble as a whole.

The energy of interfering signals is therefore the basis for calculating multiple-access interference energy, with the maximum cross-correlation value for the ensemble treated as known. Hence, the energy of interfering signals must be estimated before the corresponding performance metrics are evaluated.

The basic principles of code-division multiple access relate intrasystem interference to user signal energies and ensemble cross-correlations [1 – 4]. Ensembles of pulse sequences with low signal interaction are used in pulse-based multiple-access systems [5, 6]. Such ensembles are treated as complex time-division signals with a periodic structure [6, 7]. Complex time-division signals with a periodic structure can be synthesized using either a correction-and-search method or an analytical method [7]. Different numbers of pulses at a fixed pulse duration produce an inherent unequal-energy structure [8]. For unequal-energy complex signal ensembles, the total multiple-access interference energy depends on both signal cross-correlations and the nonuniformity of the signal-energy distribution [9].

An equivalent transformation replaces an unequal-energy complex signal ensemble with a hypothetical equal-energy complex signal ensemble while preserving the total signal energy. The size of the

hypothetical ensemble is the calculated number of equal-energy signals and is numerically equal to an approximate estimate of the normalized total energy of interfering signals [10, 11]. This provides a common basis for two estimates of the energy of interfering signals: a pessimistic estimate for users susceptible to signal dominance from other users and an optimistic estimate for signals that tend to dominate the signals of other users.

The aim of this study is to obtain an estimate of the energy of interfering signals for users susceptible to signal dominance from other users, to be used as a pessimistic estimate for the ensemble as a whole.

Materials and methods.

For an equal-energy complex signal ensemble of size L , in which each signal has energy E , the total energy of interfering signals for the i -th user is obtained by summing the energies $E_j = E$ of the other $L - 1$ users, with $j = 1, \dots, L$ and $j \neq i$:

$$\sum_{j=1, j \neq i}^L E_j = \sum_{j=1}^{L-1} E = (L - 1)E.$$

After normalization by the signal energy E , this gives a value one less than the ensemble size. For $L \gg 1$, the approximation $L - 1 \approx L$ is acceptable:

$$\frac{\sum_{j=1}^{L-1} E}{E} = \frac{(L - 1)E}{E} = L - 1 \approx L.$$

Thus, $L - 1$ is the normalized total energy of interfering signals, while the ensemble size L provides its approximate estimate.

For an unequal-energy complex signal ensemble, the nonuniform signal energies cause the total energy of interfering signals to differ among users [8, 9].

To evaluate users susceptible to signal dominance from other users, consider the case in which the energy of the i -th user's signal is lower than the energy of the k -th user's signal.

Let E_i be the desired-signal energy of the i -th user, $i = 1, \dots, L$, and let E_k denote the signal energies of users $k = 1, \dots, L$, $k \neq i$, for which $E_i < E_k$. The total energies of the interfering signals for the i -th and k -th users are then given by, respectively:

$$\sum_{j=1, j \neq i}^L E_j = \sum_{j=1}^L E_j - E_i,$$

$$\sum_{j=1, j \neq k}^L E_j = \sum_{j=1}^L E_j - E_k.$$

The difference between the total energies of the interfering signals for the i -th and k -th users is:

$$\sum_{j=1, j \neq i}^L E_j - \sum_{j=1, j \neq k}^L E_j = \left(\sum_{j=1}^L E_j - E_i \right) - \left(\sum_{j=1}^L E_j - E_k \right) = E_k - E_i > 0.$$

Therefore, the total energy of interfering signals for the i -th user is greater than that for the k -th user:

$$\sum_{j=1, j \neq i}^L E_j > \sum_{j=1, j \neq k}^L E_j.$$

This relation characterizes the susceptibility of the i -th user to signal dominance from users k for which $E_i < E_k$.

To obtain a single numerical estimate of the energy of interfering signals, [10, 11] use a mathematical framework in which the nonuniformity of a finite set of nonnegative quantities is characterized through relationships among their sum, sum of squares, mean, and variance [12, 13], as well as through concentration measures [14 – 18]. The basic relation underlying the equivalent transformation is the Cauchy–Schwarz inequality [13], which, for a fixed total ensemble signal energy and a fixed ensemble size, relates the square of the total signal energy to the sum of squared signal energies. Dividing both sides of the Cauchy–Schwarz inequality by the square of the ensemble size converts the left-hand side into the square of the mean signal energy and the right-hand side into the mean squared signal energy; the difference between them is the signal-energy variance. Equality therefore corresponds to zero variance and thus to an ensemble of equal-energy signals, whereas strict inequality corresponds to a nonuniform signal-energy distribution and thus to an ensemble of unequal-energy signals. Normalizing the signal energies by the total ensemble signal energy produces dimensionless energy fractions, which is equivalent to dividing both sides of the Cauchy–Schwarz inequality by the square of the sum of signal energies.

If both sides of the resulting Cauchy–Schwarz inequality are additionally divided by the ensemble size, the left-hand side becomes the reciprocal of the ensemble size, while the right-hand side becomes the sum of squared signal-energy fractions. This sum is a concentration measure for a finite set of nonnegative quantities [14 – 18] and, for an equal-energy ensemble, is equal to the left-hand side of the inequality.

Normalizing the concentration measure by its value for an equal-energy ensemble gives a relative quantity equal to one for equal signal energies and greater than one for a nonuniform signal-energy distribution. A reciprocal quantity also exists, and the product of the concentration measure and its reciprocal is equal to one [15, 16]. Normalizing this reciprocal quantity by its equal-energy value gives a relative quantity equal to one for equal signal energies and less than one for a nonuniform signal-energy distribution. The resulting normalized

quantities are used as factors applied to the ensemble size [10, 11].

This paper uses the normalized concentration measure of signal energies. It equals one for an equal-energy ensemble and exceeds one when the signal-energy distribution is nonuniform, corresponding to an increased estimate of the energy of interfering signals for users susceptible to signal dominance from other users:

$$\kappa_E = \frac{\sum_{i=1}^L E_i^2}{(\sum_{i=1}^L E_i)^2},$$

$$\frac{\kappa_E}{1/L} = L\kappa_E = \frac{L \sum_{i=1}^L E_i^2}{(\sum_{i=1}^L E_i)^2} = 1 + C_v^2,$$

where κ_E is the concentration measure of signal energies;

C_v^2 is the squared coefficient of variation of signal energy.

The squared coefficient of variation of signal energy is defined in terms of the mean ensemble signal energy and the signal-energy variance:

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

where μ_E is the mean ensemble signal energy; σ_E^2 is the variance of the ensemble signal energies.

For an equal-energy complex signal ensemble, with $C_v^2 = 0$, the quantity $\kappa_E/(1/L)$ is equal to one. For a nonuniform energy distribution, with $C_v^2 > 0$, it exceeds one and increases with the degree of signal-energy nonuniformity. We therefore use this quantity as a factor applied to the ensemble size L to obtain the size $L_{eq}^{(+)}$ of an equivalent equal-energy complex signal ensemble, defined as the product of $\kappa_E/(1/L)$ and L :

$$L_{eq}^{(+)} = L \frac{\kappa_E}{1/L} = L(L\kappa_E) = L(1 + C_v^2) = L \frac{\sum_{i=1}^L E_i^2}{(\sum_{i=1}^L E_i)^2/L} = \frac{L^2 \sum_{i=1}^L E_i^2}{(\sum_{i=1}^L E_i)^2}.$$

The size $L_{eq}^{(+)}$ of the equivalent equal-energy complex signal ensemble is defined as the structural equivalent size of the unequal-energy complex signal ensemble. It represents the hypothetical calculated number of equal-energy complex signals in an ensemble having the same total signal energy as the original unequal-energy complex signal ensemble.

Under the approximation $L_{eq}^{(+)} - 1 \approx L_{eq}^{(+)}$, the structural equivalent size $L_{eq}^{(+)}$ is numerically equal to an approximate estimate of the normalized total energy of

interfering signals in the hypothetical equal-energy complex signal ensemble. Without this approximation, the normalized total energy of interfering signals is $\frac{L_{\text{eq}}^{(+)} - 1}{L}$.

The bounds on the structural equivalent size $L_{\text{eq}}^{(+)}$ follow from the bounds on the normalized concentration measure $\kappa_E/(1/L)$:

$$1 \leq \frac{\kappa_E}{1/L} \leq L.$$

Multiplying $\kappa_E/(1/L)$ by the ensemble size L gives the following bounds on the structural equivalent size:

$$L \leq L_{\text{eq}}^{(+)} \leq L^2.$$

Thus, the lower bound $L_{\text{eq}}^{(+)} = L$ corresponds to an equal-energy complex signal ensemble in which each i -th signal has energy E , so that $E_i = E$, $i = 1, \dots, L$. The upper bound $L_{\text{eq}}^{(+)} = L^2$ corresponds to concentration of the entire ensemble energy in a single i -th signal, $E_i = E_{\Sigma} = \sum_{r=1}^L E_r$, while all other signal energies are zero, $E_j = 0$, $j = 1, \dots, L$, $j \neq i$.

The analytical relationship between the squared coefficient of variation of signal energy C_v^2 and the structural equivalent size $L_{\text{eq}}^{(+)}$ for an ensemble of size L is:

$$\frac{L_{\text{eq}}^{(+)}}{L} = 1 + C_v^2,$$

which gives the following expression for C_v^2 :

$$C_v^2 = \frac{L_{\text{eq}}^{(+)} - L}{L} = \frac{L_{\text{eq}}^{(+)} - L}{L}.$$

This relation establishes a one-to-one correspondence between the squared coefficient of variation of signal energy C_v^2 and the structural equivalent size $L_{\text{eq}}^{(+)}$ for an ensemble of size L . A larger C_v^2 corresponds to a larger $L_{\text{eq}}^{(+)}$. When $C_v^2 = 0$, $L_{\text{eq}}^{(+)} = L$, so the structural equivalent size $L_{\text{eq}}^{(+)}$ equals the size L of the equal-energy complex signal ensemble.

The bounds on C_v^2 can therefore be obtained from the bounds on the structural equivalent size $L_{\text{eq}}^{(+)}$:

$$L \leq L_{\text{eq}}^{(+)} \leq L^2.$$

For $L_{\text{eq}}^{(+)} = L$, we obtain:

$$C_v^2 = \frac{L_{\text{eq}}^{(+)} - L}{L} = \frac{L - L}{L} = 0.$$

For $L_{\text{eq}}^{(+)} = L^2$:

$$C_v^2 = \frac{L_{\text{eq}}^{(+)} - L}{L} = \frac{L^2 - L}{L} = L - 1.$$

For an ensemble of size L , the squared coefficient of variation of signal energy C_v^2 therefore satisfies:

$$0 \leq C_v^2 \leq L - 1,$$

where $C_v^2 = 0$ is the lower bound corresponding to an equal-energy complex signal ensemble, for which the structural equivalent size $L_{\text{eq}}^{(+)}$ equals the original ensemble size L .

$C_v^2 = L - 1$ is the upper bound corresponding to concentration of the total ensemble signal energy in one signal, for which the structural equivalent size $L_{\text{eq}}^{(+)}$ equals L^2 .

Assuming that $L_{\text{eq}}^{(+)}$ is treated as an integer, the energy $E_{\text{eq}}^{(+)}$ of one signal in the hypothetical equal-energy complex signal ensemble is determined by preserving the total signal energy of the original unequal-energy ensemble:

$$E_{\Sigma} = \sum_{i=1}^L E_i = \sum_{q=1}^{L_{\text{eq}}^{(+)}} E_{\text{eq}}^{(+)}.$$

Because all signals in the equivalent ensemble have the same energy, the total signal energy of the equivalent ensemble can be written as:

$$E_{\Sigma} = \sum_{q=1}^{L_{\text{eq}}^{(+)}} E_{\text{eq}}^{(+)} = L_{\text{eq}}^{(+)} E_{\text{eq}}^{(+)}.$$

Hence, the energy $E_{\text{eq}}^{(+)}$ of one signal in the equivalent equal-energy complex signal ensemble is:

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

This relation preserves the total signal energy in the equivalent equal-energy complex signal ensemble. The structural equivalent size $L_{\text{eq}}^{(+)}$ and the single-signal energy $E_{\text{eq}}^{(+)}$ jointly specify the replacement of the original unequal-energy complex signal ensemble by a

hypothetical equal-energy complex signal ensemble while preserving the total signal energy.

To determine the change in total multiple-access interference energy under the equivalent transformation, consider the total multiple-access interference energy of the original ensemble of complex time-division signals with a periodic structure [5 – 8] and that of the equivalent equal-energy signal ensemble specified by the structural equivalent size $L_{eq}^{(+)}$.

Using the full set of ensemble cross-correlations, define the relative difference in total multiple-access interference energy under the equivalent transformation, $\Delta_{I,\Sigma}^{(+)}$, as:

$$\Delta_{I,\Sigma}^{(+)} = \frac{E_{I,\Sigma}^{(eq,+)} - E_{I,\Sigma}}{E_{I,\Sigma}},$$

where $E_{I,\Sigma}$ is the total multiple-access interference energy of the original ensemble;

$E_{I,\Sigma}^{(eq,+)}$ is the total multiple-access interference energy of the equivalent equal-energy complex signal ensemble specified by the structural equivalent size $L_{eq}^{(+)}$.

Define the total multiple-access interference energy $E_{I,\Sigma}$ of the original ensemble of complex time-division signals with a periodic structure as the sum of the individual multiple-access interference energies $E_{I,i}$ for all users i . For this ensemble, the number of pulse overlaps for each pair of the i -th and j -th signals, $[i \neq j]$, is limited to one for any relative time shift [5 – 8]:

$$(R_{ij}^{(max)})^2 = \frac{1}{E_i E_j},$$

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

$$E_{I,\Sigma} = \sum_{i=1}^L E_{I,i} = \sum_{i=1}^L \frac{L-1}{E_i} = (L-1) \sum_{i=1}^L \frac{1}{E_i}.$$

Define the total multiple-access interference energy $E_{I,\Sigma}^{(eq,+)}$ of the equivalent equal-energy complex signal ensemble as the sum of the individual multiple-access interference energies $E_{I,i}^{(eq,+)}$ for all hypothetical users. All signals in the equivalent ensemble have energy $E_{eq}^{(+)}$, so the sum of identical terms reduces to the number of terms multiplied by one term:

$$(R_{ij}^{(max)})^2 = (R^{(max)})^2 = \frac{1}{E_{eq}^{(+)} E_{eq}^{(+)}}$$

$$E_{I,i}^{(eq,+)} = \sum_{j=1, j \neq i}^{L_{eq}^{(+)}} E_{eq}^{(+)} (R_{ij}^{(max)})^2 = \sum_{j=1, j \neq i}^{L_{eq}^{(+)}} E_{eq}^{(+)} \frac{1}{(E_{eq}^{(+)})^2} = (L_{eq}^{(+)} - 1) \frac{1}{E_{eq}^{(+)}}$$

$$\begin{aligned} E_{I,\Sigma}^{(eq,+)} &= \sum_{i=1}^{L_{eq}^{(+)}} E_{I,i}^{(eq,+)} = L_{eq}^{(+)} E_{I,i}^{(eq,+)} = L_{eq}^{(+)} \frac{L_{eq}^{(+)} - 1}{E_{eq}^{(+)}} = \\ &= \frac{L_{eq}^{(+)} (L_{eq}^{(+)} - 1)}{E_{eq}^{(+)}} = \frac{(L_{eq}^{(+)})^2 (L_{eq}^{(+)} - 1)}{E_{eq}^{(+)}} \end{aligned}$$

For the hypothetical equal-energy complex signal ensemble equivalent to the original ensemble of complex time-division signals with a periodic structure, use the relation $(R_{ij}^{(max)})^2 = (R^{(max)})^2 = 1/(E_{eq}^{(+)} E_{eq}^{(+)})$. This relation preserves the property of the ensemble of complex time-division signals with a periodic structure: if at most one pulse overlap occurs for a pair of signals in the hypothetical equivalent ensemble, their squared maximum cross-correlation is the reciprocal of the product of the energies of that pair. In the hypothetical equivalent equal-energy complex signal ensemble, every signal has energy $E_{eq}^{(+)}$; therefore, every signal pair has the same energy product, and the squared maximum cross-correlation has the same value for all signal pairs, $(R^{(max)})^2 = 1/(E_{eq}^{(+)} E_{eq}^{(+)})$.

Using the full set of cross-correlations for the ensemble of complex time-division signals with a periodic structure, define the relative difference in individual multiple-access interference energy under the equivalent transformation, $\Delta_{I,i}^{(+)}$, as:

$$\Delta_{I,i}^{(+)} = \frac{E_{I,i}^{(thr)} - E_{I,i}}{E_{I,i}}$$

$$E_{I,i}^{(thr)} = E_{I,i}^{(eq,+)} = \frac{L_{eq}^{(+)} - 1}{E_{eq}^{(+)}}$$

$$\Delta_{I,i}^{(+)} = \frac{L_{eq}^{(+)} - 1}{E_{eq}^{(+)} E_{I,i}} - 1,$$

where $E_{I,i}$ is the individual multiple-access interference energy for the i -th user, corresponding to the i -th signal of the original ensemble of complex time-division signals with a periodic structure;

$E_{I,i}^{(thr)}$ is the individual multiple-access interference energy of a hypothetical user in the equivalent equal-energy complex signal ensemble; in this comparison it is used as the threshold at which the sign of the relative difference $\Delta_{I,i}^{(+)}$ changes.

The relative difference $\Delta_{I,i}^{(+)}$ is positive when $E_{I,i}$ is less than $E_{I,thr}^{(+)}$ and negative when $E_{I,i}$ is greater than $E_{I,thr}^{(+)}$.

$$E_{I,i} > E_{I,thr}^{(+)}, \Delta_{I,i}^{(+)} < 0,$$

$$E_{I,i} < E_{I,thr}^{(+)}, \Delta_{I,i}^{(+)} > 0,$$

$$E_{I,i} = E_{I,thr}^{(+)}, \Delta_{I,i}^{(+)} = 0.$$

The total energy of interfering signals for the i -th user is the sum of the signal energies of the other users:

$$\sum_{j=1, j \neq i}^L E_j.$$

This sum is used to calculate the individual multiple-access interference energy:

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

For complex time-division signals with a periodic structure, the number of pulse overlaps for each signal pair is limited to one for any relative time shift; therefore:

$$(R_{ij}^{(max)})^2 = \frac{1}{E_i E_j},$$

$$E_{I,i} = \sum_{j=1, j \neq i}^L E_j \frac{1}{E_i E_j} = \sum_{j=1, j \neq i}^L \frac{1}{E_i} = \frac{L-1}{E_i}.$$

The resulting expressions for the threshold $E_{I,thr}^{(+)}$ and the relative difference in individual multiple-access interference energy under the equivalent transformation, $\Delta_{I,i}^{(+)}$, make it possible to determine the effect of signal-energy nonuniformity represented by the squared coefficient of variation C_v^2 . To express $E_{I,thr}^{(+)}$ in terms of C_v^2 , use:

$$L_{eq}^{(+)} = L(1 + C_v^2), E_{\Sigma} = L\mu_E.$$

Substitution into the expression for $E_{I,thr}^{(+)}$ gives:

$$E_{I,thr}^{(+)} = \frac{L_{eq}^{(+)}(L_{eq}^{(+)} - 1)}{E_{\Sigma}} = \frac{L(1 + C_v^2)(L(1 + C_v^2) - 1)}{L\mu_E} = \frac{(1 + C_v^2)(L(1 + C_v^2) - 1)}{\mu_E}.$$

Consider the components of the resulting expression for the threshold level $E_{I,thr}^{(+)}$:

1) the factor $1 + C_v^2$ depends linearly on C_v^2 and has the initial value 1 at $C_v^2 = 0$;

2) the factor $L(1 + C_v^2) - 1$ depends linearly on C_v^2 and has the initial value $L - 1$ at $C_v^2 = 0$;

3) the product $(1 + C_v^2)(L(1 + C_v^2) - 1)$ depends quadratically on C_v^2 and is equal to $L - 1$ at $C_v^2 = 0$;

4) at $C_v^2 = 0$, the ratio of the product $(1 + C_v^2)(L(1 + C_v^2) - 1)$ to μ_E is $(L - 1)/\mu_E$.

For fixed L and μ_E , $E_{I,thr}^{(+)}$ depends quadratically on C_v^2 and increases as C_v^2 increases.

Results and discussion. Fig. 1 shows the individual multiple-access interference energy for an ensemble of complex time-division signals with a periodic structure and the threshold $E_{I,thr}^{(+)}$ as functions of the squared coefficient of variation of signal energy C_v^2 . Each point corresponds to a separate ensemble obtained by successively removing the highest-energy signals from an ensemble of size $L = 76$ with the set $\{2, \dots, 167, 173, 179, \dots, 379, 383\}$, followed by ordering the resulting ensembles by increasing C_v^2 . The individual multiple-access interference energy of the original ensemble is calculated as $E_{I,i} = (L - 1)/E_i$.

For the signal with energy 173, the individual multiple-access interference energy curve is initially above the threshold curve, then crosses it and remains below it over the rest of the shown range. For the signal with energy 383, the individual multiple-access interference energy curve remains below the threshold curve throughout the shown range.

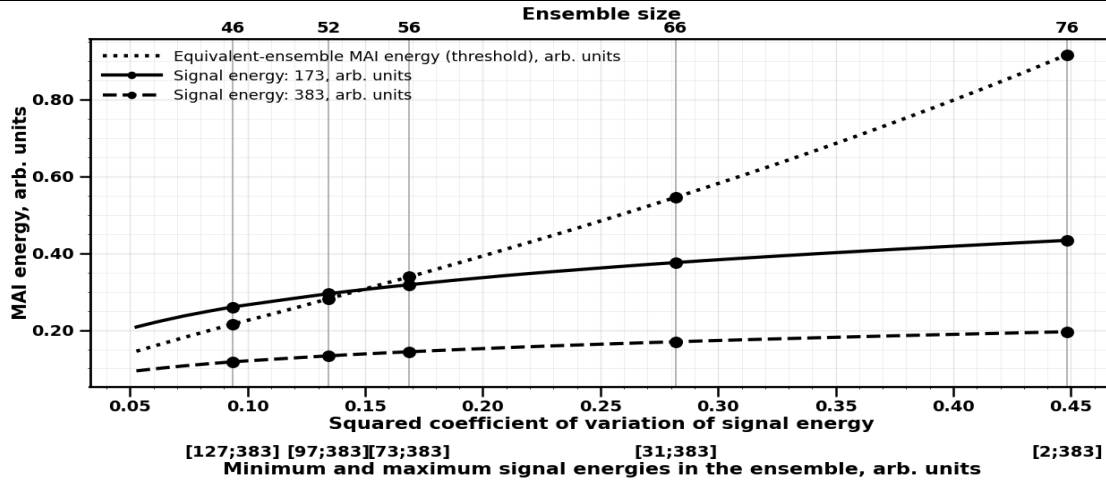


Fig. 1. Individual multiple-access interference energy of the original ensemble $\overline{E_{I,i}}$ and threshold $\overline{E_{I,thr}^{(+)}}$ versus the squared coefficient of variation of signal energy $\overline{C_v^2}$

In Fig. 1, the threshold curve at each value of the squared coefficient of variation $\overline{C_v^2}$ is obtained from the structural equivalent transformation, which reflects an increase in the hypothetical calculated number of equal-energy signals relative to the size of the original unequal-energy signal ensemble. For complex time-division signals with a periodic structure, the individual multiple-access interference energy is $\overline{E_{I,i}} = (L - 1)/E_i$; therefore, lower desired-signal energies correspond to higher individual multiple-access interference energies. Within the structural equivalent transformation, a user is considered susceptible to signal dominance from other users when $\overline{E_{I,i}} > \overline{E_{I,thr}^{(+)}}$. For the signal with energy 173, the individual multiple-access interference energy exceeds the threshold only over the part of the shown range preceding the intersection of the curves. Over this part of the ensemble sequence, the user with signal energy 173 can be considered susceptible to signal dominance from other users.

The results for signal energies 173 and 383 show different relative positions of the individual multiple-access interference energy curve $\overline{E_{I,i}}$ and the threshold curve $\overline{E_{I,thr}^{(+)}}$. For the signal with energy 173, the two curves change their relative positions by crossing, whereas for the signal with energy 383 the individual multiple-access interference energy remains below the threshold throughout the shown range.

Next, determine the bounds of the threshold $\overline{E_{I,thr}^{(+)}}$ and then the user signal energy $\overline{E_i}$ for which the individual multiple-access interference energy equals $\overline{E_{I,thr}^{(+)}}$.

Determine $\overline{E_{I,thr}^{(+)}}$ as the squared coefficient of variation changes from $\overline{C_v^2} = 0$ to $\overline{C_v^2} = L - 1$ for fixed total ensemble energy $\overline{E_\Sigma}$ and fixed ensemble size $\overline{L}$. The value $\overline{C_v^2} = 0$ corresponds to an equal-energy complex

signal ensemble, whereas $\overline{C_v^2} = L - 1$ corresponds to concentration of the total ensemble energy in a single signal. The mean signal energy $\overline{\mu_E} = \overline{E_\Sigma}/L$ remains constant, while changing $\overline{C_v^2}$ redistributes the energy among the ensemble signals.

For $\overline{C_v^2} = 0$:

$$\overline{E_{I,thr}^{(+)}} = \frac{(1 + \overline{C_v^2})(L(1 + \overline{C_v^2}) - 1)}{\overline{\mu_E}} = \frac{L - 1}{\overline{\mu_E}},$$

$$\overline{E_i} = \overline{\mu_E},$$

$$\overline{E_{I,i}} = \frac{L - 1}{\overline{E_i}} = \frac{L - 1}{\overline{\mu_E}} = \overline{E_{I,thr}^{(+)}}.$$

For $\overline{C_v^2} = L - 1$:

$$\overline{E_{I,thr}^{(+)}} = \frac{(1 + \overline{C_v^2})(L(1 + \overline{C_v^2}) - 1)}{\overline{\mu_E}} = \frac{L(L^2 - 1)}{\overline{\mu_E}}.$$

The threshold is bounded by:

$$\frac{L - 1}{\overline{\mu_E}} \leq \overline{E_{I,thr}^{(+)}} \leq \frac{L(L^2 - 1)}{\overline{\mu_E}},$$

for

$$0 \leq \overline{C_v^2} \leq L - 1, \overline{E_\Sigma} = \text{const}, L = \text{const}, \overline{\mu_E} = \frac{\overline{E_\Sigma}}{L} = \text{const}.$$

Now determine the user signal energy $\overline{E_i}$ for which the individual multiple-access interference energy equals the threshold $\overline{E_{I,thr}^{(+)}}$:

$$\overline{E_{I,i}} = \frac{L - 1}{\overline{E_i}},$$

$$E_{I,\text{thr}}^{(+)} = \frac{(1 + C_v^2)(L(1 + C_v^2) - 1)}{\mu_E},$$

$$\frac{L-1}{E_i} = \frac{(1 + C_v^2)(L(1 + C_v^2) - 1)}{\mu_E},$$

which gives the user signal energy:

$$E_i = \mu_E \frac{L-1}{(1 + C_v^2)(L(1 + C_v^2) - 1)}.$$

The ratio of the user signal energy E_i to the mean ensemble signal energy μ_E is:

$$\frac{E_i}{\mu_E} = \frac{L-1}{(1 + C_v^2)(L(1 + C_v^2) - 1)}.$$

For $C_v^2 = 0$:

$$\frac{E_i}{\mu_E} = 1,$$

$$E_i = \mu_E.$$

For $0 < C_v^2 < L-1$, the denominator satisfies

$$(1 + C_v^2)(L(1 + C_v^2) - 1) > L-1,$$

therefore:

$$\frac{E_i}{\mu_E} < 1,$$

$$E_i < \mu_E.$$

Thus, as C_v^2 increases, the threshold $E_{I,\text{thr}}^{(+)}$ corresponds to signal energies below the mean ensemble signal energy μ_E .

Accordingly, intermediate values of $E_{I,\text{thr}}^{(+)}$ correspond to the part of the original unequal-energy complex signal ensemble whose signal energies are below the mean signal energy μ_E of the original ensemble.

The threshold $E_{I,\text{thr}}^{(+)}$ can also be related to the arithmetic mean of the individual multiple-access interference energies by:

$$E_{I,\text{thr}}^{(+)} \geq \frac{1}{L} \sum_{i=1}^L E_{I,i},$$

where strict inequality applies to an unequal-energy complex signal ensemble, while equality holds only for an equal-energy complex signal ensemble.

Therefore, for an unequal-energy complex signal ensemble, the threshold $E_{I,\text{thr}}^{(+)}$ is greater than the arithmetic mean of the individual multiple-access interference energies of the original ensemble:

$$E_{I,\text{thr}}^{(+)} > \frac{1}{L} \sum_{i=1}^L E_{I,i}.$$

To quantify the deviation of the individual multiple-access interference energies $E_{I,i}$ of the original unequal-energy complex signal ensemble from the threshold $E_{I,\text{thr}}^{(+)}$, use the absolute relative difference $|\Delta_{I,i}^{(+)}|$:

$$|\Delta_{I,i}^{(+)}| = \left| \frac{E_{I,\text{thr}}^{(+)} - E_{I,i}}{E_{I,i}} \right| = \left| \frac{L_{\text{eq}}^{(+)} - 1}{E_{\text{eq}}^{(+)} E_{I,i}} - 1 \right|,$$

This quantity measures the relative magnitude of the deviation of $E_{I,i}$ from $E_{I,\text{thr}}^{(+)}$ regardless of its direction, allowing the deviations for different users to be compared.

Fig. 2 shows $|\Delta_{I,i}^{(+)}|$ versus C_v^2 under conditions analogous to those in Figure 1. For the signal with energy 173, the curve has a decreasing segment, a minimum region, and an increasing segment. This behavior is consistent with Fig. 1, where the individual multiple-access interference energy curve $E_{I,i}$ for the signal with energy 173 crosses the threshold curve $E_{I,\text{thr}}^{(+)}$. The smallest values of $|\Delta_{I,i}^{(+)}|$ correspond to the region in Figure 1 where the two curves intersect or come closest to each other.

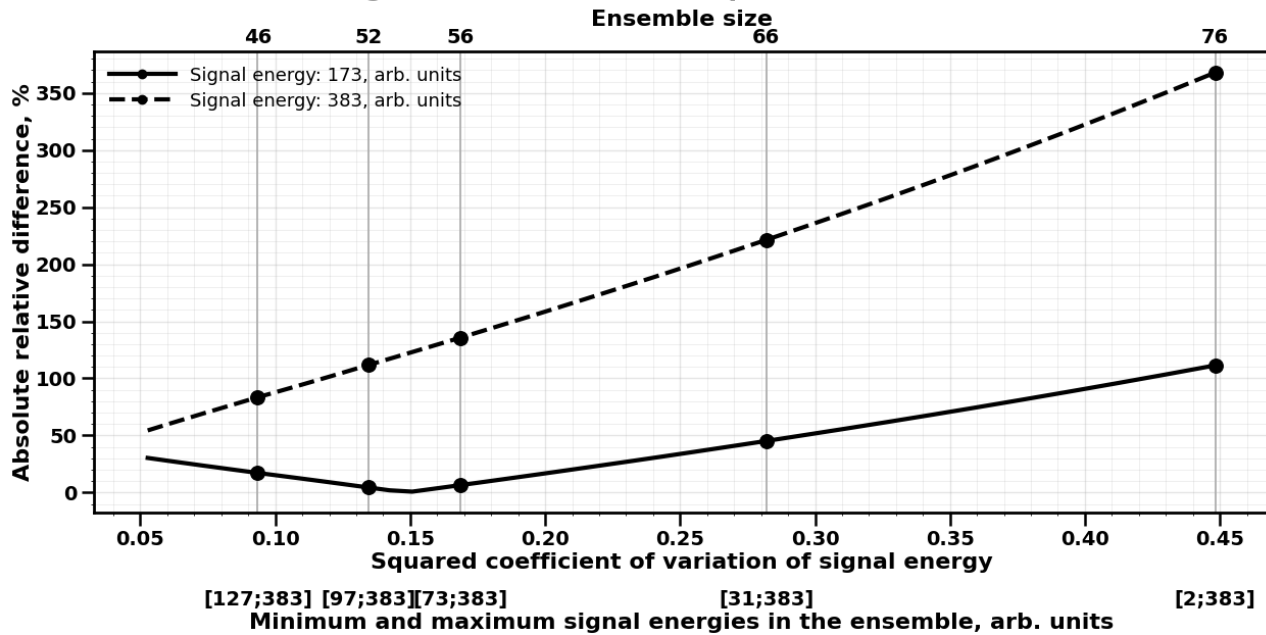


Fig. 2. Absolute relative difference between the individual multiple-access interference energy and the threshold $\Delta_{I,i}^{(+)}$ versus the squared coefficient of variation of signal energy C_v^2

For the signal with energy 383, the curve in Fig. 2 has no minimum region. This is consistent with Fig. 1, where the individual multiple-access interference energy $E_{I,i}$ for the signal with energy 383 remains below the threshold $E_{I,thr}^{(+)}$ throughout the shown range, so no minimum region appears on the curve.

Fig. 1 and 2 show two different aspects of the deviation of the individual multiple-access interference energy $E_{I,i}$ from the threshold $E_{I,thr}^{(+)}$. Fig. 1 indicates the sign of the relative difference through the relative positions of the $E_{I,i}$ and $E_{I,thr}^{(+)}$ curves. Fig. 2 shows the relative magnitude of the deviation through the absolute relative difference $|\Delta_{I,i}^{(+)}|$.

Conclusions.

It is shown that the normalized total energy of interfering signals for users susceptible to signal dominance from other users is approximately equal to the structural equivalent size and therefore provides a pessimistic estimate for the unequal-energy complex signal ensemble as a whole. For equal-energy complex signal ensembles, the structural equivalent size equals the original ensemble size, corresponding to a uniform signal-energy distribution. As the degree of signal-energy nonuniformity increases, the structural equivalent size increases monotonically toward an upper bound corresponding to concentration of the entire ensemble energy in a single signal, i.e., the highest possible nonuniformity for a fixed total signal energy. Thus, the structural equivalent size of an unequal-energy complex signal ensemble represents the calculated number of equal-energy complex signals in an ensemble with the same total signal energy as the original ensemble,

increases with the degree of signal-energy nonuniformity, provides a pessimistic estimate of the normalized total energy of interfering signals for users susceptible to signal dominance from other users, and allows performance metrics developed for equal-energy complex signal ensembles to be extended to unequal-energy complex signal ensembles by substituting the structural equivalent size into the corresponding expressions for equal-energy complex signal ensembles.

References

1. Sklar, B. (2001). Digital communications: Fundamentals and applications (2nd ed.). Prentice Hall PTR. <https://www.informit.com/store/digital-communications-fundamentals-and-applications-9780130847881>
2. Ipatov, V. P. (2005). Spread spectrum and CDMA: Principles and applications. John Wiley & Sons. <https://doi.org/10.1002/0470091800>
3. Viterbi, A. J. (1995). CDMA: Principles of spread spectrum communication. Addison-Wesley. <https://www.ece.ucsd.edu/faculty-research/books-by-faculty/cdma-principles-of-spread-spectrum-communication>
4. Verdú, S. (1998). Multiuser detection. Cambridge University Press. <https://www.cambridge.org/9780521593731>
5. Stepanenko, Yu. H., Prykhodko, S. I., & Lysechko, V. P. (2009). Metod vyznachennia periodu prokhodzhennia korotkykh videoimpulsiv v kodovykh poslidovnostiakh na osnovi aproksymatsii funktsii Khevisaida [Method for determining the passage period of short video pulses in code sequences based on approximation]

ІНФОРМАЦІЙНО-КЕРУЮЧІ СИСТЕМИ НА ЗАЛІЗНИЧНОМУ ТРАНСПОРТІ

- of the Heaviside function]. *Systemy ozbroiennia i viiskova tekhnika [Systems of Arms and Military Equipment]*, (4 (20)), 170–173. [in Ukrainian].
6. Indyk, S. V., Lysechko, V. P., Zhuchenko, O. S., & Kitov, V. S. (2020). 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*, (4), 7–14. <https://doi.org/10.15588/1607-3274-2020-4-1>
 7. Lysechko, V. P., Zhuchenko, O. S., & Indyk, S. V. (2026). Method for synthesis of ensembles of complex time-division signals with a periodic structure for ultra-wideband multiple access systems. In *Theory and practice of modern science in conditions of transformations: Proceedings of the scientific and practical conference*, 142–144. Molodyi Vchenyi Publishing House.
 8. Zhuchenko, O., Indyk, S., & Zablotskyi, V. (2026). Study of properties of complex time-division signal ensembles with a periodic structure for ultra-wideband code-division multiple access systems. *Kompiuterno-intehrovani tekhnologii: Osvita, nauka, vyrobnytstvo [Computer-Integrated Technologies: Education, Science, Production]*, (63), 310–317. <https://doi.org/10.36910/6775-2524-0560-2026-63-34>
 9. Zhuchenko, O. S., Lysechko, V. P., & Indyk, S. V. (2026). Justification of requirements for a structural efficiency indicator of unequal-energy complex signal ensembles in code division multiple access systems. *Zbirnyk naukovykh prats Ukrainського derzhavnoho universytetu zaliznychnoho transportu [Collected scientific works of Ukrainian State University of Railway Transport]*, (216), 187–198. <https://doi.org/10.18664/1994-7852.216.2026.362542>
 10. Zhuchenko, O., Panchenko, S., Lysechko, V., & Indyk, S. (2026). Methodology of equivalent transformations of unequal-energy complex signal ensembles in code-division multiple access systems. *Computer-Integrated Technologies: Education, Science, Production*, (62), 337–345. <https://doi.org/10.36910/6775-2524-0560-2026-62-38>
 11. Zhuchenko, O. S., & Shubina, H. V. (2026). Theoretical foundations of equivalent transformation of unequal-energy complex signal ensembles for code division multiple access systems. *Naukoemni tekhnologii [Science-based technologies]*, (2(70)), 205–211. <https://doi.org/10.18372/2310-5461.70.21196>
 12. Klenke, A. (2020). Probability theory: A comprehensive course (3rd ed.). Springer. <https://doi.org/10.1007/978-3-030-56402-5>
 13. Steele, J. M. (2004). The Cauchy-Schwarz master class: An introduction to the art of mathematical inequalities. Cambridge University Press. <https://doi.org/10.1017/CBO9780511817106>
 14. Simpson, E. H. (1949). Measurement of diversity. *Nature*, 163, 688. <https://doi.org/10.1038/163688a0>
 15. Hill, M. O. (1973). Diversity and evenness: A unifying notation and its consequences. *Ecology*, 54 (2), 427–432. <https://doi.org/10.2307/1934352>
 16. Jost, L. (2006). Entropy and diversity. *Oikos*, 113 (2), 363–375. <https://doi.org/10.1111/j.2006.0030-1299.14714.x>
 17. Chao, A., Chiu, C.-H., & Jost, L. (2010). Phylogenetic diversity measures based on Hill numbers. *Philosophical Transactions of the Royal Society B*, 365 (1558), 3599–3609. <https://doi.org/10.1098/rstb.2010.0272>
 18. Chiu, C.-H., & Chao, A. (2014). Distance-based functional diversity measures and their decomposition: A framework based on Hill numbers. *PLoS ONE*, 9 (7), Article e100014. <https://doi.org/10.1371/journal.pone.0100014>

Список використаних джерел

1. Sklar, B. (2001). Digital Communications: Fundamentals and Applications. 2nd ed. Upper Saddle River : Prentice Hall PTR, <https://www.informit.com/store/digital-communications-fundamentals-and-applications-9780130847881>
2. Ipatov, V. P. (2005). Spread Spectrum and CDMA: Principles and Applications. Chichester : John Wiley & Sons. <https://doi.org/10.1002/0470091800>
3. Viterbi, A. J. (1995). CDMA: Principles of Spread Spectrum Communication. Reading : Addison-Wesley. <https://www.ece.ucsd.edu/faculty-research/books-by-faculty/cdma-principles-of-spread-spectrum-communication>
4. Verdú, S. (1998). Multiuser Detection. Cambridge : Cambridge University Press, <https://www.cambridge.org/9780521593731>
5. Степаненко, Ю. Г., Приходько, С. І., & Лисечко, В. П. (2009). Метод визначення періоду проходження коротких відеоімпульсів в кодових послідовностях на основі апроксимації функції Хевісайда. *Системи озброєння і військова техніка*, 4 (20), 170–173.
6. Indyk, S. V., Lysechko, V. P., Zhuchenko, O. S., & Kitov, V. S. (2020). 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*, 4, 7–14. <https://doi.org/10.15588/1607-3274-2020-4-1>
7. Lysechko, V. P., Zhuchenko, O. S., & Indyk, S. V. (2026). Method for Synthesis of Ensembles of Complex Time-Division Signals with a Periodic Structure for Ultra-Wideband Multiple Access Systems. *Theory and Practice of Modern Science in Conditions of Transformations : Proceedings of*

- the Scientific and Practical Conference*, Poltava, April 24–25, 2026. Odesa : Molodyi Vchenyi Publishing House, 142–144.
8. Zhuchenko, O., Indyk, S., & Zablotskyi, V. (2026). Study of properties of complex time-division signal ensembles with a periodic structure for ultra-wideband code-division multiple access systems. *Комп'ютерно-інтегровані технології: освіта, наука, виробництво*. Луцьк, 63, 310–317. <https://doi.org/10.36910/6775-2524-0560-2026-63-34>
 9. Zhuchenko, O. S., Lysechko, V. P., & Indyk, S. V. (2026). Justification of requirements for a structural efficiency indicator of unequal-energy complex signal ensembles in code division multiple access systems. *Зб. наук. праць Укр. Держ. ун-ту залізнич. трансп.*, 216, 187–198. <https://doi.org/10.18664/1994-7852.216.2026.362542>
 10. Zhuchenko, O., Panchenko, S., Lysechko, V., & Indyk, S. (2026). Methodology of Equivalent Transformations of Unequal-Energy Complex Signal Ensembles in Code-Division Multiple Access Systems. *Computer-Integrated Technologies: Education, Science, Production*, 62, 337–345. <https://doi.org/10.36910/6775-2524-0560-2026-62-38>
 11. Zhuchenko, O. S., & Shubina, H. V. (2026). Theoretical foundations of equivalent transformation of unequal-energy complex signal ensembles for code division multiple access systems. *Наукові технології*, 2 (70), 205–211. <https://doi.org/10.18372/2310-5461.70.21196>
 12. Klenke, A. (2020). Probability Theory: A Comprehensive Course. 3rd ed. Universitext. Cham : Springer, <https://doi.org/10.1007/978-3-030-56402-5>
 13. Steele, J. M. (2004). The Cauchy-Schwarz Master Class: An Introduction to the Art of Mathematical Inequalities. Cambridge: Cambridge University Press, 318. <https://doi.org/10.1017/CBO9780511817106>
 14. Simpson, E. H. (1949). Measurement of diversity. *Nature*, 163, 688. <https://doi.org/10.1038/163688a0>
 15. Hill, M. O. (1973). Diversity and evenness: A unifying notation and its consequences. *Ecology*, 54 (2), 427–432. <https://doi.org/10.2307/1934352>
 16. Jost, L. (2006). Entropy and diversity. *Oikos*, 113 (2), 363–375. <https://doi.org/10.1111/j.2006.0030-1299.14714.x>
 17. Chao, A., Chiu, C.-H., & Jost, L. (2010). Phylogenetic diversity measures based on Hill numbers. *Philosophical Transactions of the Royal Society B*, 365, 1558, 3599–3609. <https://doi.org/10.1098/rstb.2010.0272>
 18. Chiu, C.-H., & Chao, A. (2014). Distance-based functional diversity measures and their decomposition: A framework based on Hill numbers. *PLoS ONE*, 9, 7. Article e100014. <https://doi.org/10.1371/journal.pone.0100014>

Оцінювання енергії заважаючих сигналів у системі множинного доступу з кодовим розділенням на основі різноенергетичних складних сигналів для користувачів, схильних до впливу на них ефекту домінування сигналів із боку інших користувачів

У системі множинного доступу з кодовим розділенням під час приймання сигналу користувачем сигнали інших користувачів вважають для нього такими, що заважають і створюють завади множинного доступу. Для ансамблів різноенергетичних складних сигналів нерівномірність розподілу енергії зумовлює відмінність сумарної енергії заважаючих сигналів для різних користувачів і прояв ефекту домінування. Користувачі з меншими енергіями корисних сигналів можуть бути схильними до впливу домінування сигналів із боку інших користувачів. Метою дослідження є оцінювання енергії заважаючих сигналів для користувачів, схильних до впливу на них ефекту домінування сигналів із боку інших користувачів як песимістичної оцінки для ансамблю в цілому. Для зведення сукупності індивідуальних значень до однієї оцінки застосовано еквівалентне перетворення ансамблю різноенергетичних складних сигналів в умовний ансамбль сигналів з однаковими енергіями зі збереженням сумарної енергії. Установлено, що оцінка нормованої сумарної енергії заважаючих сигналів для користувачів, схильних до впливу на них ефекту домінування сигналів із боку інших користувачів, наближено відповідає структурному еквівалентному об'єму та є песимістичною оцінкою для ансамблю різноенергетичних складних сигналів у цілому. Для ансамблів рівноенергетичних складних сигналів структурний еквівалентний об'єм збігається з об'ємом вихідного ансамблю, що відповідає відсутності нерівномірності розподілу енергії сигналів. Із зростанням ступеня нерівномірності розподілу енергії сигналів ансамблю структурний еквівалентний об'єм монотонно збільшується до верхньої межі, яка відповідає зосередженню сумарної енергії ансамблю в одному сигналі, тобто найбільшій нерівномірності розподілу енергії за сталої сумарної енергії сигналів. Отже, структурний еквівалентний об'єм ансамблю різноенергетичних складних сигналів, який є розрахунковою кількістю рівноенергетичних складних сигналів в ансамблі, еквівалентному вихідному за сумарною енергією сигналів, збільшується зі зростанням ступеня нерівномірності розподілу енергій сигналів, відповідає песимістичній оцінці нормованої сумарної енергії заважаючих сигналів для користувачів, схильних до впливу домінування сигналів із боку інших користувачів, і дає змогу поширити показники ефективності, призначені для ансамблів рівноенергетичних складних сигналів, на ансамблі різноенергетичних складних сигналів через

ІНФОРМАЦІЙНО–КЕРУЮЧІ СИСТЕМИ НА ЗАЛІЗНИЧНОМУ ТРАНСПОРТІ

підстановку величини структурного еквівалентного об'єму у відповідні співвідношення для ансамблів рівноенергетичних складних сигналів.

Ключові слова: система множинного доступу з кодовим розділенням, завади множинного доступу, енергія заважаючих сигналів, ансамбль різноенергетичних складних сигналів, структурний еквівалентний об'єм, вплив домінування сигналів із боку інших користувачів, взаємна кореляція сигналів.

Panchenko Serhii Volodymyrovych, Doctor of Technical Sciences, Professor, Professor of Department of Transport Communication, Ukrainian State University of Railway Transport, Kharkiv, Ukraine. ORCID ID: 0009-0002-2833-4347.

Zhuchenko Oleksandr Serhiiovych, Candidate of Technical Sciences, Associate Professor, Associate Professor of Department of Transport Communication, Ukrainian State University of Railway Transport, Kharkiv, Ukraine. Tel.: +38 (063) 779-44-12. E-mail: n030201@gmail.com. ORCID ID: 0000-0003-3275-810X.

Lysechko Volodymyr Petrovych, Doctor of Technical Sciences, Professor, Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Ukraine. E-mail: lysechko@kart.edu.ua. ORCID ID: 0000-0002-1520-9515.

Indyk Serhii Volodymyrovych, Candidate of Technical Sciences, Associate Professor, Associate Professor of Department of Transport Communication, Ukrainian State University of Railway Transport, Kharkiv, Ukraine. E-mail: indyk.serhii@kart.edu.ua. ORCID ID: 0000-0003-3124-8722.

Панченко Сергій Володимирович, доктор технічних наук, професор, професор кафедри транспортного зв'язку, Український державний університет залізничного транспорту, Харків, Україна. ORCID ID: 0009-0002-2833-4347.

Жученко Олександр Сергійович, кандидат технічних наук, доцент, доцент кафедри транспортного зв'язку, Український державний університет залізничного транспорту, Харків, Україна. Тел.: +38 (063) 779-44-12. E-mail: n030201@gmail.com. ORCID ID: 0000-0003-3275-810X.

Лисечко Володимир Петрович, доктор технічних наук, професор, Харківський національний університет Повітряних Сил імені Івана Кожедуба, Харків, Україна. E-mail: lysechko@kart.edu.ua. ORCID ID: 0000-0002-1520-9515.

Індик Сергій Володимирович, кандидат технічних наук, доцент, доцент кафедри транспортного зв'язку, Український державний університет залізничного транспорту, Харків, Україна. E-mail: indyk.serhii@kart.edu.ua. ORCID ID: 0000-0003-3124-8722.

Стаття надійшла 10.08.26

Стаття прийнята до друку після рецензування 18.09.26

Стаття опублікована (оприлюднена) 06.10.26

Стаття поширюється на умовах ліцензії Creative Commons Attribution License International CC-BY.