NEW QUASI-OPTIMAL ALGORITHMS OF ANTENNA SELECTION WITH LOW COMPLEXITY

DOI: 10.36724/2072-8735-2023-17-7-47-56

Mikhail G. Bakulin,
Moscow Technical University of Communications and Informatics, Moscow, Russia, **m.g.bakulin@gmail.com**

Vitaly B. Kreyndelin,
Moscow Technical University of Communications and Informatics, Moscow, Russia, **vitkrend@gmail.com**

Mikhail L. Khazov,
Moscow Technical University of Communications and Informatics, Moscow, Russia, **mikekhazov@mail.ru**

Manuscript received 08 June 2023;
Accepted 07 July 2023

Keywords: *MIMO communication system, spectral efficiency, bit error-rate, antenna selection, channel capacity, radio path, selection criteria, computational complexity*

Classical MIMO system model without antenna selection and MIMO system model with antenna selection are presented. New quasi-optimal low complexity algorithms of antenna selection are proposed for MIMO communication systems. These algorithms allow to achieve high spectral efficiency without significant increase of complexity. The statistical modeling method is used to evaluate the efficiency of the proposed algorithms and to compare their characteristics with the characteristics of the known algorithms of full and partial combined selection. The computational complexity of the proposed algorithms is evaluated and been compared with the computational complexity of the well-known algorithms of full and partial combined selection in low-order and high-order MIMO system configurations. The possibility of practical application of new quasi-optimal algorithms in real communication systems is clearly demonstrated by comparative analysis of error-rate performance in conjunction with an assessment of computational complexity. These applications provide significantly improving of the energy performance of MIMO communication systems and it allows to improve quality characteristics of communications for subscribers or could be exchanged to the lower price of construction and maintenance of real communication systems.

Information about authors:

Mikhail G. Bakulin, *Moscow Technical University of Communications and Informatics, Associate Professor, Moscow, Russia*

Vitaly B. Kreyndelin, *Moscow Technical University of Communications and Informatics, chief of the Department, Moscow, Russia*

Mikhail L. Khazov, *Moscow Technical University of Communications and Informatics, post-graduate student, Moscow, Russia*

Для цитирования:
Бакулин М.Г., Крейнделин В.Б., Хазов М.Л. Новые квазиоптимальные алгоритмы автовыбора антенн с низкой вычислительной сложностью // T-Comm: Телекоммуникации и транспорт. 2023. Том 17. №7. С. 47-56.

For citation:
Bakulin M.G., Kreyndelin V.B., Khazov M.L. New quasi-optimal algorithms of antenna selection with low complexity. *T-Comm*, vol. 17, no.7, pp. 47-56.

Introduction

Wireless communication systems with many transmit and many receive antennas (Multiply-Input-Multiply-Output – MIMO) have recently attracted serious attention from developers of promising communication systems due to their advantages in capacity and spectral efficiency. The advantages of using MIMO technology communication systems increase with an addition of the number of receive and/or transmit antennas compared to traditional communication systems with one transmitting and one receiving antenna (Single-Input-Single-Output – SISO). However, the increasing at the same time hardware complexity is a key limiting factor. A large number of radio frequency paths are required in order to obtain good system performance, but at the same time there is a high cost and large size of communication systems equipment (user terminals, base stations).

The article proposes new algorithms of antenna selection at the transmitting and receiving sides which allows to reduce the complexity of the system while preserving the main advantages of MIMO technology. For a limited set number of radio frequency chains, receive and/or transmit antennas could be selected and optimally assigned. The proposed algorithms allow to achieve high spectral efficiency without significant increase of complexity, reduce the size of devices, increase of their energy efficiency by reducing the number of active elements.

A large number of antenna selection algorithms have known up to now [1], [2], [3]. Some of the known approaches are based on maximizing the signal–to-noise ratio, while others are based on maximizing of channel capacity.

Well-known works in this area include simple algorithms for antenna selection [4], as well as more complex algorithms [5], [6], [7] which have slightly improved characteristics, but at the same time significantly higher computational complexity. For the MIMO communication system new quasi-optimal low complexity algorithms of antenna selection compared to known algorithms, and with the characteristics are close to the characteristics of the optimal (full combined selection) algorithms are proposed.

1. Classical MIMO system model without antenna selection

Assume that there are *M* receive antennas and *N* transmit antennas in the MIMO communication system. Let's also assume that the number of receive radio chains is equal to *L*, and the number of transmit radio chains is equal to *P*.

Consider a situation with Rayleigh fadings and Gaussian noise in the communication channel. When all transmitting and receiving antennas ($L = M$ and $P =$ N) are involved, the model of the received signal in the MIMO communication system has the following form [9], [10]:

$$\mathbf{y} = \sqrt{\frac{\rho}{N}} \cdot \mathbf{H} \cdot \mathbf{s} + \boldsymbol{\eta}, \tag{1}$$

where $\boldsymbol{y}$ – is *M*-dimensional column-vector of complex counts of received signals; $\mathbf{s}$ – is *N*-dimensional vector of transmitted QAM-symbols; ρ – average signal-to-noise ratio (SNR) in each receive antenna; *N* – amount of transmit antennas; $\boldsymbol{\mu}$ – is *M*-dimensional column-vector of complex numbers with zero mathematical expectation of additive white Gaussian noise with a unit correlation matrix; $\mathbf{H}$ – is $M \times N$ – dimensional complex matrix of MIMO communication channel:

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N} \\ h_{21} & h_{22} & \dots & h_{2N} \\ \dots & \dots & h_{ij} & \dots \\ h_{M1} & h_{M2} & \dots & h_{MN} \end{bmatrix}, \tag{2}$$

where h_{ij} – is channel coefficient between *i*'s receive antenna and *j*'s transmit antenna. We will assume that the coefficients h_{ij} are uncorrelated complex Gaussian random variables with zero mathematical expectations and with equal to one variances. Let's here and further consider the MIMO system without spatial correlation of fading, as well as in the absence of direct sight between all transmit and receive antennas (only reflected signals are received) [9], [10].

2. MIMO system model with antenna selection

Consider MIMO system where selection of antennas is present both on the transmitting side ($P < N$) and on the receiving side ($L < M$). Follows that only *P* antennas uses from all set amount of *N* transmit antennas and *L* antennas uses from all set amount of *M* receive antennas. Therefore, instead of *N* active transmitting radio chains for antenna selection system uses only *P* of these radio chains, and instead of *M* active receiving radio chains uses only *L* of these chains.

Expression for the model of the received signal in the MIMO communication system has the following form [1], [8], [11], [12], [13]:

$$\tilde{\mathbf{y}} = \sqrt{\frac{\rho}{P}} \cdot \tilde{\mathbf{H}} \cdot \mathbf{s} + \tilde{\boldsymbol{\eta}}, \tag{3}$$

where $\tilde{\mathbf{y}}$ – is *L* – dimensional column-vector of receive signal which is contains complex samples of received signals from all selected antennas at receiver side; $\tilde{\mathbf{H}}$ – is $L \times P$ – dimensional complex submatrix of MIMO channel. $\tilde{\mathbf{H}}$ matrix – it is submatrix of full channel matrix $\mathbf{H}$. Matrix $\tilde{\mathbf{H}}$ consist of selected elements of matrix $\mathbf{H}$, corresponding to selection of some subset *P* from *N* available transmit antennas and of some subset *L* from *M* available receive antennas.

To select the matrix $\tilde{\mathbf{H}}$ from full matrix of the channel $\mathbf{H}$, it is necessary to use the selection criteria (criteria of optimality), which allows to select the best submatrix $\tilde{\mathbf{H}}$ according to this criteria. In fact, according to a given criteria of optimality, the selected submatrices $\tilde{\mathbf{H}}$ are compared. Finally we get best combination of subset *P* from *N* available transmit antennas and subset *L* from *M* available receive antennas, according to a given criteria of optimality.

A number criteria of optimality are known. These include the following: the maximum of capacity criteria, the maximum of SNR criteria, and the minimum trace of the correlation matrix of information symbols demodulation errors [4], [8].

The expression for the maximum of capacity criteria (MaxCapacityFull):

$$C_{\max} = \max_{\tilde{\mathbf{H}}} \log\det\left(\mathbf{1} + \frac{\rho}{P}\cdot\tilde{\mathbf{H}}\cdot\tilde{\mathbf{H}}'\right). \quad (4)$$

The expression for the maximum of the Frobenius norm criteria (the maximum of SNR criteria, FrobeniusFull):

$$\max_{\tilde{\mathbf{H}}} \left\|\tilde{\mathbf{H}}\right\|_F^2 = \max_{\tilde{\mathbf{H}}} \sum_{m=1}^{L}\sum_{n=1}^{P}\left|\tilde{h}_{mn}\right|^2. \quad (5)$$

The minimum trace of the correlation matrix of information symbols demodulation errors criteria (MinTrVmmse, MinTrVzf) is aimed at selection such a submatrix of the channel, in which the minimum summary variance of errors in the evaluation of demodulated information symbols is achieved.

$$\min_{\tilde{\mathbf{H}}} tr(\mathbf{R}) = \min_{\tilde{\mathbf{H}}} tr\left(\left(\frac{\rho}{P}\cdot\tilde{\mathbf{H}}'\cdot\tilde{\mathbf{H}}+\mathbf{1}\right)^{-1}\right). \quad (6)$$

3. Full combinations or optimal antenna selection algorithm

The optimal algorithm of antenna selection in the MIMO system assumes a complete reselection of all possible sets of submatrix $\tilde{\mathbf{H}}$ inside the matrix $\mathbf{H}$. The number of all variants of the submatrix $\tilde{\mathbf{H}}$ is [16]:

$$Q(N,P,M,L) = C_N^P C_M^L = \frac{N!}{(N-P)!\cdot P!}\cdot\frac{M!}{(M-L)!\cdot L!} \quad (7)$$

In

Table 1 is demonstrated the results of counting the number of all possible variants of submatrices $\tilde{\mathbf{H}}$ with a complete reselection for a various values of equal total number of transmit and receive antennas ($N = M$) and a various values of equal number of radio paths or in other words selected by the criteria of optimality of transmit and receive antennas ($L = P$).

Table 1

The number of submatrix $\tilde{\mathbf{H}}$ with an optimal antenna selection

N = M	8	12	16	24
L = P	4	6	8	12
Q(N, P, M, L)	$4{,}9\cdot10^3$	$8{,}5\cdot10^5$	$1{,}6\cdot10^8$	$7{,}3\cdot10^{12}$

From

Table 1, it is obvious that with an increase in the number of antennas, the number of all possible variants of submatrix $\tilde{\mathbf{H}}$ rises rapidly. So it is impossible to implement the optimal algorithm of antenna selection even with a relatively several number of antennas.

Therefore an approach of using an optimal antenna selection algorithm in real conditions, starting with MIMO 16(8)x16(8), is simply impossible due to the rapid growth in the volume of calculations (computational complexity).

Than consider some of the well-known antenna selection algorithms which do not require a complete selection of all the variants of the reselected submatrix.

4. Well-known quasi-optimal algorithms of antenna selection

NSA algorithm.

A simple quasi-optimal antenna selection algorithm is well-known. In the literature it is called NSA (Norm based Antenna Selection). Antenna in NSA are selected using criteria of the maximum Euclidean norm of the columns and then rows of the communication channel matrix [1], [4].

A submatrix $\hat{\tilde{\mathbf{H}}}$ which has a $M\times P$ dimension and are containing P columns with maximal Euclidean norms is selected from the full channel matrix $\mathbf{H}$, while matrix $\hat{\tilde{\mathbf{H}}}$ still having the same number of rows M as in the full channel matrix $\mathbf{H}$. Then, from the submatrix $\hat{\tilde{\mathbf{H}}}$, the target submatrix $\tilde{\mathbf{H}}$ is selected, which has a $L\times P$ dimension and contains L rows with maximal Euclidean norms.

So quasi-optimal antenna selection algorithm NSA uses Euclidean norm as a criteria of optimality. Algorithm NSA cannot use other criteria of optimality.

In addition to the mentioned simplest version of the NSA algorithm, iteration modifications of NSA algorithm are also well-known both with a decrease (Iteration Decrement) and with an increase (Iteration Increment) in the dimension of the reselected matrix [17], [19], [20].

IDNSA iterative algorithm

Initial conditions: $\tilde{\mathbf{H}}^0 = \mathbf{H}$.

Step 1. Euclidean norms are calculated for all columns of the matrix $\mathbf{H}$.

Step 2. Among $\mathbf{h}_j, j = 1\ldots N$ is selected one column with a minimal Euclidean norm $\left\|\mathbf{h}_{\min}\right\| = \min_{1\le j\le N}\left\|\mathbf{h}_j\right\|$ and it is excluded from matrix $\mathbf{H}$. So we obtain $\tilde{\mathbf{H}}^{(1)}$ matrix with $M\times(N-1)$ dimension.

Step 3. Euclidean norms are calculated for all rows of the matrix $\tilde{\mathbf{H}}^{(1)}$

Step 4. Among $\mathbf{h}_i, i = 1\ldots M$ is selected one row with a minimal Euclidean norm $\left\|\mathbf{h}_{\min}\right\| = \min_{1\le i\le M}\left\|\mathbf{h}_i\right\|$ and it is excluded from matrix $\tilde{\mathbf{H}}^{(1)}$. As a result we obtain $\tilde{\mathbf{H}}^{(2)}$ matrix with $(M-1)\times(N-1)$ dimension.

Repeat Steps 1-4, but using a matrix $\tilde{\mathbf{H}}^{(z)}$ instead of a matrix $\mathbf{H}$. The process of excluding rows and columns is repeated until we get an aimed matrix $\tilde{\mathbf{H}}$ of $L\times P$ dimension.

IINSA iterative algorithm

Initial conditions: equal amount of antennas at receive and at transmit sides. Initial matrix $\tilde{\mathbf{H}}^{(0)} = [\ ]$, so it is empty matrix without any of elements with 0×0 dimension.

Step by step the dimension of initial matrix is increased, while before the required aimed $\tilde{\mathbf{H}}$ submatrix with $L\times P$ dimension will be formed. Thus, a square matrix $\hat{\tilde{\mathbf{H}}}_{target}^{(k)}$ should be formed at the k's step.

Step 1. Pick the maximal by module element $h_{i(1)j(1)}$ from $\mathbf{H}$ matrix. In fact, this means selection of one transmit and one receive antenna with the maximal of transmission coefficient between them.

Matrix $\tilde{\mathbf{H}}^{(1)}$ consist of selected element $h_{i(1)j(1)}$, and has a dimension 1×1.

$$\tilde{\mathbf{H}}^{(1)}=\left[h_{i(1)j(1)}\right]=\left[\max_{1\le i\le M}\max_{1\le j\le N}\left|h_{ij}\right|\right]. \quad (8)$$

Step 2. Select from matrix $\mathbf{H}$ submatrix $\hat{\tilde{\mathbf{H}}}^{(2)}$, with 2×2 dimension. Submatrix $\hat{\tilde{\mathbf{H}}}^{(2)}=\begin{bmatrix} h_{i(1)j(1)} & h_{i(1)j(2)} \\ h_{i(2)j(1)} & \hat{h}_{i(2)j(2)} \end{bmatrix}$ includes selected at the first step element $h_{i(1)j(1)}$, which actually added by element $\hat{h}_{i(2)j(2)}$ selected at the second step from matrix $\mathbf{H}$ and bordered by elements $h_{i(1)j(2)}, h_{i(2)j(1)}$ of matrix $\mathbf{H}$. Submatrix $\tilde{\mathbf{H}}^{(2)}$ will be find by reselecting through all possible combinations of second-order submatrix $\hat{\tilde{\mathbf{H}}}^{(2)}$ from the full matrix of channel $\mathbf{H}$, each of it contains an element $h_{i(1)j(1)}$ and the Frobenius norm for it is maximal $\left\|\tilde{\mathbf{H}}^{(2)}\right\|_F=\max\left\|\hat{\tilde{\mathbf{H}}}^{(2)}\right\|_F$.

Thus, in Step 2, one more transmitting and one receiving antenna is selected. In Step 3, we use the logic described in Step 2. As a result, we select one more transmitting and one receiving antenna.

Next steps up to k's, where $k=L=P$, repeat iterative selection of elements from the matrix of channel $\mathbf{H}$. The selected matrix $\hat{\tilde{\mathbf{H}}}^{(k)}_{target}$ will be the formed required matrix $\tilde{\mathbf{H}}$ with $L\times P$ dimension, where $L=P$.

5. New quasi-optimal low complexity antenna selection algorithms

New quasi-optimal iterative algorithm IIZF

IIZF (Iterative Incremental Zero Forcing algorithm), an iterative algorithm with a step-by-step increase in the dimension of the formed matrix of channel and as a selection criterion minimum trace of the correlation matrix of errors of demodulation of information symbols.

Initial conditions: $\hat{\tilde{\mathbf{H}}}^{(0)}=[\ ]$, so it is empty (without any elements) matrix with 0×0 dimension.

Step-by-step increase the dimension of the initial matrix until the required submatrix $\tilde{\mathbf{H}}=\hat{\tilde{\mathbf{H}}}^{(k)}_{target}$ is formed with $L\times P$ dimension. Thus, a square matrix $\hat{\tilde{\mathbf{H}}}^{(k)}_{target}$ is formed at the k's step based on calculation and comparison the values of the antenna selection criterion of optimality for each of the available at current step submatrix.

First step of the algorithm coincides with the first step of well-known algorithm IINSA, represented in the section 4. From full matrix of channel $\mathbf{H}$ select maximal by module $h_{i(1)j(1)}$ element. In other words, will be selected pair of antennas on transmit and receive with a maximal transmission ratio. Element $h_{i(1)j(1)}$ is formed matrix $\tilde{\mathbf{H}}^{(1)}=\hat{\tilde{\mathbf{H}}}^{(1)}_{target}$ with 1×1 dimension.

At the second Step, taking into account criterion of optimality the submatrix $\hat{\tilde{\mathbf{H}}}^{(2)}=\begin{bmatrix} h_{i(1)j(1)} & h_{i(1)j(2)} \\ h_{i(2)j(1)} & \hat{h}_{i(2)j(2)} \end{bmatrix}$ with 2×2 dimension are sequentially reselected from the full matrix of channel and sorted. $\hat{\tilde{\mathbf{H}}}^{(2)}$ contains selected at the first step element $h_{\hat{i}(1)\hat{j}(1)}=\tilde{\mathbf{H}}^{(1)}$. Target submatrix $\tilde{\mathbf{H}}^{(2)}=\hat{\tilde{\mathbf{H}}}^{(2)}_{target}$ is find from full matrix of channel $\mathbf{H}$ by reselection through all existing combinations of second-order submatrix $\hat{\tilde{\mathbf{H}}}^{(2)}$, each of it contains element $h_{i(1)j(1)}$. Selection condition of submatrix $\tilde{\mathbf{H}}^{(2)}$ is:

$$\left\{i(2)j(2)\right\}=\arg\min_{\substack{1\le i\le M\\ i\ne i(1)}}\min_{\substack{1\le j\le N\\ j\ne j(1)}} f(\hat{\tilde{\mathbf{H}}}^{(2)}), \quad (9)$$

where $f(\hat{\tilde{\mathbf{H}}}^{(2)})$ – the trace of the correlation matrix of estimation errors $\hat{\tilde{\mathbf{R}}}^{(2)}_{\mathbf{H}}$, determined by the formula:

$$f(\hat{\tilde{\mathbf{H}}}^{(2)})=tr(\hat{\tilde{\mathbf{R}}}^{(2)}_{\mathbf{H}})=tr\left[\left(\hat{\tilde{\mathbf{H}}}'^{(2)}\hat{\tilde{\mathbf{H}}}^{(2)}+2\sigma_\eta^{\ 2}\cdot\mathbf{1}\right)^{-1}\right]. \quad (10)$$

As a result of the described actions, another transmits and receives antenna will be selected and a matrix $\tilde{\mathbf{H}}^{(2)}=\hat{\tilde{\mathbf{H}}}^{(2)}_{target}=\begin{bmatrix} h_{i(1)j(1)} & h_{i(1)j(2)} \\ h_{i(2)j(1)} & h_{i(2)j(2)} \end{bmatrix}$ will be formed.

According to the formulated rule, at the step $n-1$ will be formed submatrix

$$\tilde{\mathbf{H}}^{(n-1)}=\hat{\tilde{\mathbf{H}}}^{(n-1)}_{target}=\begin{bmatrix} h_{i(1)j(1)} & \dots & h_{i(1)j(n-1)} \\ \dots & \dots & \dots \\ h_{i(n-1)j(1)} & \dots & h_{i(n-1)j(n-1)} \end{bmatrix}.$$

Selection condition of element of matrix $\mathbf{H}$ at step n is:

$$\left\{i(n)j(n)\right\}=\arg\min_{\substack{1\le i\le M\\ i\ne i(1)\\ \dots\\ i\ne i(n-1)}}\min_{\substack{1\le j\le N\\ j\ne j(1)\\ \dots\\ j\ne j(n-1)}} f(\hat{\tilde{\mathbf{H}}}^{(n)}), \quad (11)$$

where $f(\hat{\tilde{\mathbf{H}}}^{(n)})$ – the trace of the correlation matrix of estimation errors $\hat{\tilde{\mathbf{R}}}^{(n)}_{\mathbf{H}}$, determined by the formula similar to (10):

After sorting through all possible combinations, the work of the IIZF algorithm will be completed and the target matrix $\tilde{\mathbf{H}}$ with $L\times P$ dimension, where $L=P$ will be formed.

New quasi-optimal iterative algorithm IDZF

IDZF (Iterative Decremental Zero Forcing algorithm), an iterative algorithm with a step-by-step decrease in the dimension of the matrix of channel until formed target submatrix started from full matrix of channel and with a selection criterion minimum trace of the correlation matrix of errors of demodulation of information symbols

Consider new antenna selection algorithm based on iteration decrement of dimension of matrix $\mathbf{H}$.

Initial conditions: $\hat{\tilde{\mathbf{H}}}^{(0)} = \mathbf{H}$. Inside of matrix $\mathbf{H}$ by turns exclude one row and one column at the same time, then calculate the values of the antenna selection criterion of optimality for each of the available submatrix $\hat{\tilde{\mathbf{H}}}^{(1)}$ with $(M-1)\times(N-1)$ dimension, remember the best of got selection.

After selection of target submatrix $\hat{\tilde{\mathbf{H}}}^{(1)}_{target}$ with a best calculated criterion of optimality value, necessary repeat all upper described actions for submatrix $\hat{\tilde{\mathbf{H}}}^{(1)}_{target}$ by turns exclude from analyzes one row and one column at the same time, after that to calculate values of the antenna selection criterion of optimality for each of the available submatrix $\hat{\tilde{\mathbf{H}}}^{(2)}$ with $(M-2)\times(N-2)$ dimension, putting into a memory the best selection $\hat{\tilde{\mathbf{H}}}^{(2)}_{target}$.

Excludes rows and columns in the matrix $\mathbf{H}$ and search for the submatrix with the best criterion of optimality value of the form (10) do until the dimension of the selected submatrix becomes equal $L\times P$, where $L = P$, and the matrix $\hat{\tilde{\mathbf{H}}}^{(n)}_{target}$ itself will actually be the matrix $\tilde{\mathbf{H}}$ that we are forming.

At the step n, iterate over the matrices $\hat{\tilde{\mathbf{H}}}^{(n)}$ that are obtained from the matrix $\hat{\tilde{\mathbf{H}}}^{(n-1)}_{target}$ by excluding the row $i(n)$ and column $j(n)$. The condition for choosing a matrix is as follows:

$$\{i(n)\,j(n)\} = \arg \min_{\substack{1\le i\le M \\ i(n)\ne i(1) \\ \dots \\ i(n)\ne i(n-1)}} \min_{\substack{1\le j\le N \\ j(n)\ne j(1) \\ \dots \\ j(n)\ne j(n-1)}} f(\hat{\tilde{\mathbf{H}}}^{(n)}[i(n), j(n)]) \qquad (12)$$

where $f(\hat{\tilde{\mathbf{H}}}^{(n)})$ – the trace of the correlation matrix of estimation errors $\hat{\tilde{\mathbf{R}}}^{(n)}_{\mathbf{H}}$, determined by the formula similar to (10).

Result of work of algorithm IDZF at the step n is the matrix $\tilde{\mathbf{H}} = \tilde{\mathbf{H}}^{(n)} = \hat{\tilde{\mathbf{H}}}^{(n)}_{target}$, with $(M-n)\times(M-n)$ dimension, where $1\le n\le M-L$.

6. Simulation results

Let's perform a comparative analysis of the known and proposed algorithms. The effectiveness of the algorithms was evaluated by statistical modeling method [14].

The simulation was carried out for two configurations of the selected and total number of antennas, the same values on the receive and transmit sides (4 of 8; 4 of 12) under the following general conditions:

- modulation method – 64-QAM;
- demodulation method– MMSE;
- type of noise-resistant coding – Turbo coding (speed – 1/2, number of decoding iterations – 4);
- simulated algorithms of antenna selection in their various combinations:
  - o optimal (full selection) with maximal capacity criterion (4) (MaxCapFull);
  - o optimal (full selection) with Frobenius norm criterion (5) (FrobeniusFull);
  - o quasi-optimal algorithm NSA (section 4);
  - o quasi-optimal algorithm IDNSA (section 4);
  - o proposed algorithm IIZF (11);
  - o proposed algorithm IDZF (12);
- channel matrix $\mathbf{H}$ is known on the receiving side;
- number of transmit antennas $N = 8$; $N = 12$;
- number of transmit radio chains $P = 4$;
- number of receive antennas $M = 8$; $M = 12$;
- number of receive radio chains $L = 4$;
- type of fading – uncorrelated Rayleigh;
- frame length – 573 bits:
- number of experiments – 100000.

Error rates curves for known optimal algorithms with selection criteria (4), (5) and the proposed optimal algorithm with a selection criterion (6) in a MIMO system 4(8)x4(8) are studied in [3], [12].

Figures 1 and 2 shows simulation results for well-known optimal algorithms (4), (5), well-known (section 4) and proposed quasi-optimal algorithms (11), (12) for MIMO configurations 4(8)x4(8) and 4(12)x4(12).

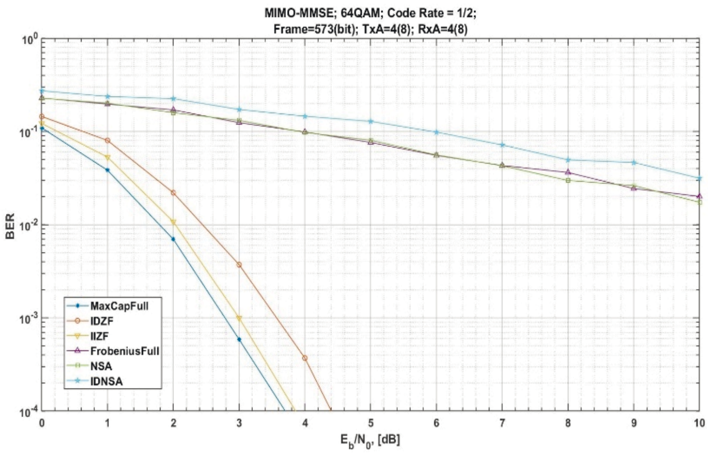

Fig. 1. Error rate of MIMO system in configuration 4(8)x4(8)

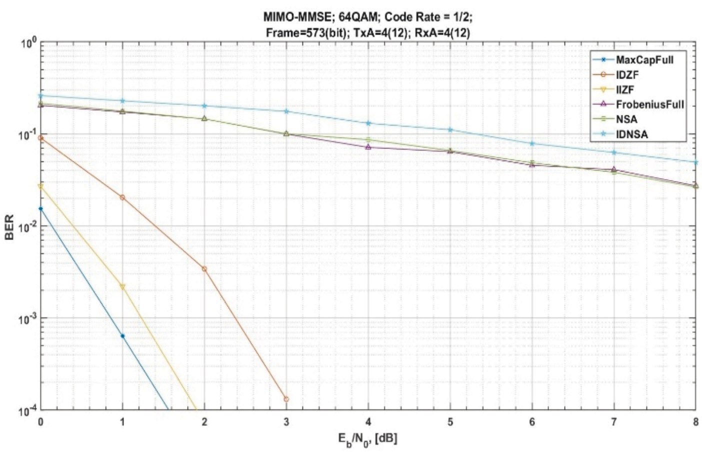

Fig. 2. Error rate of MIMO system in configuration 4(12)x4(12)

From quasi-optimal iterative algorithms (see Fig. 1, Fig. **2**) the best results, independently of the antenna configuration, are provided by algorithms using the minimum trace criterion of the correlation matrix of demodulation errors (6), noticeably exceeding the characteristics of the optimal algorithm with the maximum Frobenius norm criterion (5).

The proposed quasi–optimal IIZF algorithm (11) has small losses about 0.2 – 0.4 dB vs. the optimal (full selection) algorithm with a best of known maximal capacity criterion of optimality (4). At the same time, as will be shown below, the algorithm IIZF (11) has significantly less computational complexity. The proposed quasi–optimal IDZF algorithm (12) has additional 0.6 – 1.2 dB gain relatively of proposed IIZF algorithm (11). At the same time, as will be shown later, it has also a slightly higher computational complexity.

The well-known quasi-optimal iterative algorithms NSA and IDNSA (section 4) demonstrate low efficiency, being inferior to the worst-evaluated optimal (full selection) algorithm with the Frobenius norm criterion (5) and significantly inferior in characteristics to the new proposed quasi-optimal algorithms.

7. Computational complexity of algorithms

Now will calculate the computational complexity of the described antenna selection algorithms by estimating the total number of operations required to perform calculations. Such operations include operations of real addition ν_{Σ}^{add} and real multiplication operations ν_{Σ}^{mult}. Write's down the following expressions to calculate the computational complexity for optimal (full selection) algorithms:

$$\begin{aligned} \nu_{\Sigma}^{mult} &= Q \cdot \nu_{n}^{mult} \\ \nu_{\Sigma}^{add} &= Q \cdot \nu_{n}^{add} + Q \end{aligned}, \qquad (13)$$

where Q – is the number of all possible combinations of reselected active antennas on the receive and transmit sides for the exacted configuration of passive and active antennas, determined by the formula (7); ν_{n}^{mult} – is the number of arithmetic operations of real multiplications required to perform one combination; ν_{n}^{add} – is the number of arithmetic operations of real additions required to perform one combination.

Computational complexity of the optimal (full selection) algorithm with maximal capacity criterion (MaxCapacityFull) (4).

Find the number of arithmetic operations required for the processor to process the expression:

$$\log\det\left(\mathbf{1} + \frac{\rho}{P} \cdot \tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}'\right). \qquad (14)$$

The channel matrix $\tilde{\mathbf{H}}$ selected during the operation of this algorithm has a $L \times P$ dimension. Matrix $\tilde{\mathbf{T}} = \tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}'$ has a $L \times L$ dimension and includes elements $\tilde{\mathbf{T}}_{ij} = \sum_{k=1}^{P} h_{ik} h'_{kj}$, where $i, j = 1 \ldots L$.

To calculate one value $h_{ik} h'_{kj}$ require to perform one complex multiplication. To calculate one value $\tilde{\mathbf{T}}_{ij}$ require P of complex multiplications and $2 \cdot (P-1)$ of complex additions, which corresponds to $4P$ real multiplications and $4P-4$ real additions. For complete multiplication of matrix $\tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}'$ require to execute L^2 of similar operations. Taking into account the Hermitian nature of the matrix $\tilde{\mathbf{T}} = \tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}'$ value of $\tilde{\mathbf{T}}_{ij}$ necessary to perform about $L^2/2$ operations.

So to calculate $\tilde{\mathbf{T}} = \tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}'$ real operations will be required: $\nu_{1}^{mult} = 4 \cdot P \cdot \frac{L^2}{2}$ multiplications and $\nu_{1}^{add} = (4 \cdot P - 4) \cdot \frac{L^2}{2}$ additions.

Value $\frac{\rho}{P}$ from the expression (14) is known in advance (not in real time). Thus, to calculate complexity of matrix $\tilde{\mathbf{D}} = \left(\mathbf{1} + \frac{\rho}{P} \cdot \tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}'\right)$ from (14) requires the following values are the number of real multiplications and real additions:

$$\nu_{2}^{mult} = (4 \cdot P + 1) \cdot \frac{L^2}{2}. \qquad (15)$$

$$\nu_{2}^{add} = (4 \cdot P - 4) \cdot \frac{L^2}{2} + L. \qquad (16)$$

To understand the complexity of calculating the determinant of the matrix $\det\tilde{\mathbf{D}} = \det\left(\mathbf{1} + \frac{\rho}{P} \cdot \tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}'\right)$ we perform the following steps. The QR-decomposition of the matrix is known [5]. For the matrix $\tilde{\mathbf{D}}$ the record of its QR decomposition is: $\tilde{\mathbf{D}} = \mathbf{Q} \cdot \mathbf{R}$, where $\mathbf{Q}$ – is unitary matrix with $L \times L$ dimension, $\mathbf{R}$ – is upper triangular matrix.

Further take into account the following property of the determinant of the matrix $\mathbf{C} = \mathbf{A} \cdot \mathbf{B}$ [15], $\det\mathbf{C} = \det\mathbf{A} \cdot \det\mathbf{B}$. Apply this property to the matrix $\tilde{\mathbf{D}} = \mathbf{Q} \cdot \mathbf{R}$.

So the $\det\tilde{\mathbf{D}} = \det\mathbf{Q} \cdot \det\mathbf{R} = 1 \cdot \det\mathbf{R} = \det\mathbf{R}$. Determinant $\det\mathbf{R} = \prod_{i=1}^{L} \mathbf{R}_{ii}$ for matrix $\mathbf{R}$ require to perform $L-1$ of complex multiplications.

The computational complexity of the QR decomposition of the matrix is $\frac{2}{3}L^3 + L^2 + \frac{1}{3}L - 2$ complex multiplications and the same number of complex additions. A complex multiplication is equivalent to four real multiplications and two real additions. A complex addition consists of two real additions.

Thus, to calculate the determinant of the matrix, the following number of operations will be required:

$$\nu_{\det}^{mult} = 4 \cdot \left(\frac{2}{3}L^3 + L^2 + \frac{1}{3}L - 2\right). \qquad (17)$$

$$v_{\det}^{add} = 4 \cdot \left(\frac{2}{3} L^3 + L^2 + \frac{1}{3} L - 2 \right) \cdot \quad (18)$$

Accordingly, given (14), (15), (16), (17), (18), the following number of real operations is required to perform an optimal (full selection) algorithm with maximal capacity criterion (MaxCapacityFull) (4):

$$v_{\max CapFull}^{mult} = Q \cdot (v_2^{mult} + v_{\det}^{mult}) =$$
$$= Q \cdot \left[(4 \cdot P + 1) \cdot \frac{L^2}{2} + 4 \cdot \left(\frac{2}{3} L^3 + L^2 + \frac{1}{3} L - 2 \right) \right], \quad (19)$$
$$v_{\max CapFull}^{add} = Q \cdot (v_2^{add} + v_{\det}^{add}) + Q =$$
$$= Q \cdot \left[(4 \cdot P - 4) \cdot \frac{L^2}{2} + L + 4 \cdot \left(\frac{2}{3} L^3 + L^2 + \frac{1}{3} L - 2 \right) \right] + Q.$$

It is obvious from expression (19), that the algorithm optimal (full selection) with cruterion (4), has a third order of complexity.

Computational complexity of the optimal (full selection) algorithm with minimum trace of correlation matrix criterion (MinTrVmmse, MinTrVzf) (6).

Let 's turn to the criterion (6). For the matrix $\tilde{\mathbf{D}} = \left(\mathbf{1} + \frac{\rho}{P} \cdot \tilde{\mathbf{H}} \cdot \tilde{\mathbf{H}}' \right)$ got formulas (15) and (16) to calculate it computational complexity. Criterion (6) includes analogical matrix $\tilde{\mathbf{G}} = \frac{\rho}{P} \tilde{\mathbf{H}}' \tilde{\mathbf{H}} + \mathbf{1}$ to calculate the complexity of which it is not difficult to obtain the expression:

$$v_1^{mult} = (4 \cdot L + 1) \cdot \frac{P^2}{2}, \quad (20)$$

$$v_1^{add} = (4 \cdot L - 4) \cdot \frac{P^2}{2} + P \cdot \quad (21)$$

It is known that for the inversion of a complex Hermitian matrix with $P \times P$ dimension requires about $2P^3 - 2P^2$ of real multiplications, $2P^3 - 4P^2 + 2P$ of real additions and P divisions, which is about equal to $2P^3$ of real multiplications and $2P^3$ real additions [14], [15].

Calculating the trace of the matrix with $P \times P$ dimension requires $P - 1$ of real additions, since on the main diagonal of the matrix $\tilde{\mathbf{G}}$ are real numbers. Thus, taking into account (20) and (21) have the following expression for the computational complexity of the criterion (6):

$$v_2^{mult} = \left[2 \cdot P^3 + (4 \cdot L + 1) \cdot \frac{P^2}{2} \right], \quad . \quad (22)$$
$$v_2^{add} = \left[2 \cdot P^3 + (4 \cdot L - 4) \cdot \frac{P^2}{2} + P - 1 \right].$$

So for optimal (fill selection) algorithm with a criterion (6) requires to perform the following number of real operations:

$$v_{MinTrVzf}^{mult} = Q \cdot v_3^{mult} = Q \cdot \left[2 \cdot P^3 + (4 \cdot L + 1) \cdot \frac{P^2}{2} \right],$$
$$v_{MinTrVzf}^{add} = Q \cdot v_3^{add} + Q = Q \cdot \left[2 \cdot P^3 + (4 \cdot L - 4) \cdot \frac{P^2}{2} + P - 1 \right] + Q. \quad .(23)$$

Computational complexity of proposed new quasi-optimal algorithms using minimum trace of correlation matrix criterion.

At first estimate the computational complexity of the quasi-optimal partial (combined selection) algorithm of antenna selection IIZF (11).

Thus estimate the complexity of the algorithm at the first step. From full matrix of channel $\mathbf{H}$ the maximum by module of element $h_{\hat{i}(1)\hat{j}(1)}$ is selected. It's requires to calculate of modules and then comparing of all complex elements of matrix $\mathbf{H}$. Calculation of modules for all elements of matrix $\mathbf{H}$ require $2 \cdot N^2$ of real multiplications and N^2 of real additions (the operation of calculating the square root can be not taken into account, since it is performed by table), and comparison of values of all elements $h_{\tilde{i}\tilde{j}}$ require N^2 of real additions.

Further estimate the complexity of the algorithm at the second step. Here is doing reselection of submatrix with $(N-1)^2$ number of reselections. Taking into account of expression (23), where $Q = (N-1)^2$ and $L = P = 2$ get required number of operations for the second step:

$$v_2^{mult} = 34 \cdot (N-1)^2 \quad (24)$$
$$v_2^{add} = 25 \cdot (N-1)^2$$

At the n's step doing reselection of $(N-n+1)^2$ submatrices. Taking into account of expression (23), where $Q = (N-n+1)^2$ and $L = P = n$ get required amount of operation for the n's step:

$$v_n^{mult} = (N-n+1)^2 \cdot \left[2 \cdot n^3 + (4 \cdot n + 1) \cdot \frac{n^2}{2} \right], \quad (25)$$
$$v_n^{add} = (N-n+1)^2 \cdot \left[2 \cdot n^3 + (4 \cdot n - 4) \cdot \frac{n^2}{2} + n - 1 \right],$$

where $n = 1 \ldots L$.

To complete the estimation of computational complexity, it is necessary to sum up the values of computational complexity at all steps:

$$v_{IIZF}^{mult} = \sum_{n=1}^{L} v_n^{mult} = \sum_{n=1}^{L} \left[(N-n+1)^2 \cdot \left[2 \cdot n^3 + (4 \cdot n + 1) \cdot \frac{n^2}{2} \right] \right], \quad (26)$$
$$v_{IIZF}^{add} = \sum_{n=1}^{L} v_n^{add} = \sum_{n=1}^{L} \left[(N-n+1)^2 \cdot \left[2 \cdot n^3 + (4 \cdot n - 4) \cdot \frac{n^2}{2} + n - 1 \right] \right].$$

The computational complexity of the IDZF partial selection algorithm is performed similarly. As a result, we have the following expression:

$$v_{IDZF}^{mult} = \sum_{n=1}^{N-L} v_n^{mult} =$$

$$= \sum_{n=1}^{N-L}\left[2\cdot(N-n)^3 + (4\cdot(N-n)+1)\cdot\frac{(N-n)^2}{2}\right]\cdot(N-n+1)^2,$$

$$v_{IDZF}^{add} = \sum_{n=1}^{N-L} v_n^{add} =$$

$$= \sum_{n=1}^{N-L}\left[2\cdot(N-n)^3 + (4\cdot(N-n)-4)\cdot\frac{(N-n)^2}{2} + (N-n)-1\right]\cdot(N-n+1)^2. \quad (27)$$

8. Comparative analysis of computational complexity of algorithms

In Table 2 and

Table 3 present the results of the computational complexity estimation for optimal (full selection) algorithms with a best of known MaxCapFull (4) and MinTrVzf (6), and also for simplified quasi-optimal algorithms IIZF (11), IDZF (12). The estimates are given also for high-order MIMO system with the number of passive antennas equal to 64.

Table 2

Results of estimation of computational complexity for various antenna selection algorithms in the MIMO system

Number of real multiplication operations					
Path	Antennas	MaxCapFull	MinTrVzf	**IIZF**	IDZF
2	12	$2{,}18\cdot10^5$	$1{,}48\cdot10^5$	$4{,}76\cdot10^3$	$1{,}27\cdot10^6$
4	12	$9{,}02\cdot10^7$	$6{,}47\cdot10^7$	$3{,}74\cdot10^4$	$1{,}73\cdot10^6$
6	12	$9{,}99\cdot10^8$	$7{,}53\cdot10^8$	$1{,}13\cdot10^5$	$1{,}86\cdot10^6$
8	12	$6{,}57\cdot10^8$	$5{,}10\cdot10^8$	$2{,}16\cdot10^5$	$1{,}89\cdot10^6$
2	8	$3{,}92\cdot10^4$	$2{,}67\cdot10^4$	$1{,}95\cdot10^3$	$1{,}33\cdot10^5$
4	8	$1{,}80\cdot10^6$	$1{,}29\cdot10^6$	$1{,}26\cdot10^4$	$1{,}58\cdot10^5$
6	8	$9{,}17\cdot10^5$	$6{,}91\cdot10^5$	$2{,}87\cdot10^4$	$1{,}60\cdot10^5$
Number of real addition operations					
Path	Antennas	MaxCapFull	MinTrVzf	**IIZF**	IDZF
2	12	$1{,}87\cdot10^5$	$1{,}13\cdot10^5$	$3{,}31\cdot10^3$	$1{,}19\cdot10^6$
4	12	$8{,}16\cdot10^7$	$5{,}59\cdot10^7$	$3{,}09\cdot10^4$	$1{,}63\cdot10^6$
6	12	$9{,}28\cdot10^8$	$6{,}81\cdot10^8$	$9{,}90\cdot10^4$	$1{,}75\cdot10^6$
8	12	$6{,}20\cdot10^8$	$4{,}72\cdot10^8$	$1{,}93\cdot10^5$	$1{,}77\cdot10^6$
2	8	$3{,}37\cdot10^4$	$2{,}04\cdot10^4$	$1{,}35\cdot10^3$	$1{,}21\cdot10^5$
4	8	$1{,}63\cdot10^6$	$1{,}12\cdot10^6$	$1{,}03\cdot10^4$	$1{,}43\cdot10^5$
6	8	$8{,}52\cdot10^5$	$6{,}26\cdot10^5$	$2{,}48\cdot10^4$	$1{,}45\cdot10^5$

Table 3

Results of estimation of computational complexity for various antenna selection algorithms in the high-order MIMO system

Total operations for high-order MIMO					
Path	Antennas	MaxCapFull	MinTrVzf	**IIZF**	IDZF
8	64	$1{,}0\cdot10^{23}$	$7{,}9\cdot10^{22}$	$3{,}4\cdot10^7$	$5{,}0\cdot10^{10}$
16	64	$9{,}5\cdot10^{33}$	$7{,}7\cdot10^{33}$	$3{,}9\cdot10^8$	$7{,}4\cdot10^{10}$
32	64	$1{,}0\cdot10^{42}$	$8{,}8\cdot10^{41}$	$3{,}5\cdot10^9$	$8{,}9\cdot10^{10}$
40	64	$3{,}8\cdot10^{40}$	$3{,}2\cdot10^{40}$	$5{,}9\cdot10^9$	$9{,}0\cdot10^{10}$
48	64	$2{,}5\cdot10^{35}$	$2{,}1\cdot10^{35}$	$8{,}2\cdot10^9$	$9{,}1\cdot10^{10}$

Data in Table 2 and Table 3 demonstrate the possibility of practical application of the new quasi-optimal algorithm of partial selection IIZF (11) .

At Figure 3 the results of computational complexity estimation for various antenna selection algorithms in a high-order MIMO system are presented graphically.

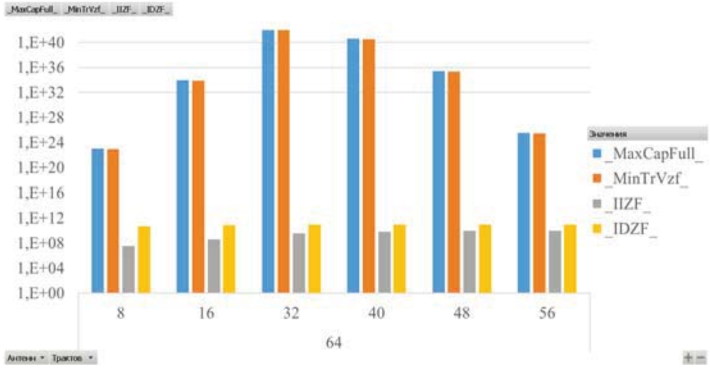

Fig. 3. The results of computational complexity estimation for various antenna selection algorithms in a high-order MIMO system

At Figure 3 obviously demonstrated the difference in computational complexity of the best of all represented algorithms for MIMO with a total of 64 antennas on the receive side and 64 on the transmit side. New quasi-optimal algorithms IIZF (11) и IDZF (12) demonstrate much less of computational complexity compared to the best algorithms.

Conclusions

The proposed quasi–optimal algorithm of partial combined selection which is step-by-step increase of dimension of forming matrix of channel IIZF (11) has about 0.2 – 0.4 dB loss vs. assigned to the optimal (full selection) algorithm with a best of known maximal capacity criterion of optimality (4).

At the same time new proposed algorithm IIZF (11) has significantly less computational complexity in comparison to the best algorithms in terms of error rates performance (6), (4) and demonstrates up to two-tree orders of magnitude lower computational complexity for low-order MIMO configurations and up to fifteen – thirty orders of magnitude for a high-order MIMO configuration with 64 passive antennas.

Optimal (full selection) algorithm with a criterion (6) also demonstrates slightly less computational complexity compared to the best of known optimal algorithms with a criterion (4), at the same time, it demonstrates the best error rates performance which are studied in [3], [12].

References

1. S. Sanayei and A. Nosratinia, "Antenna selection in MIMO systems," in *IEEE Communications Magazine*, vol. 42, no. 10, pp. 68-73, Oct. 2004, doi: 10.1109/MCOM.2004.1341263.

2. V. Kreyndelin, M. Khazov. Antenna selection algorithms in MIMO systems. *Elecrosvyaz*. 2017. No. 10, pp. 59-64.

3. V. Kreyndelin, M. Khazov Compare of MIMO systems with different antenna selection criteria. Materials of the XIII International Industrial Scientific and Technical Conference «Informational society technologies». Moscow: MTUCI. 20-21 march 2019.

4. P. J. Smith, T. W. King, L. M. Garth and M. Dohler, "An Analysis of Low Complexity Algorithms for MIMO Antenna Selection," *2006 IEEE International Conference on Communications,* Istanbul, Turkey, 2006, pp. 1380-1385, doi: 10.1109/ICC.2006.254941.

5. WH. Teukolsky, SA. Vetterling, WT. Flannery, BP (2007), "Section 2.10. QR Decomposition", Numerical Recipes: The Art of Scientific Computing (3rd ed.), New York: Cambridge University Press, ISBN 978-0-521-88068-8 - https://dev.abcdef.wiki/wiki/QR_decomposition.

6. M. I. As-Saafani, S. J. Sadi, E. F. Badran, D. A. E. Mohamed and S. Shaaban, "Antenna Selection Algorithms in Correlated Fading MIMO Channels," *Proceedings of the Twenty Third National Radio Science Conference (NRSC'2006)*, Menouf, Egypt, 2006, pp. 1-8, doi: 10.1109/NRSC.2006.386326.

7. X. Zhou, B. Bai and W. Chen, "Iterative Antenna Selection for Multi-Stream MIMO under a Holistic Power Model," in *IEEE Wireless Communications Letters*, vol. 3, no. 1, pp. 82-85, February 2014, doi: 10.1109/WCL.2013.111713.130754.

8. M. Bakulin, V. Kreyndelin, M. Khazov Antenna selection criteria at MIMO systems. *Electrosvyaz*. 2018. No. 10, pp. 78-81.

9. M. Bakulin, L. Varukina, V. Kreyndelin MIMO system technology: entity and algorithms. Moscow: Goryachaya liniya – Telecom, 2014. 272 p.

10. Emil Björnson, Jakob Hoydis and Luca Sanguinetti (2017), “Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency”, *Foundations and Trends in Signal Processing*. Vol. 11, No. 3-4, pp. 154-655.

11. Molisch A. F, Win M. Z. MIMO systems with antenna selection. *IEEE Microwave Magazine*, 2004, No. 5, pp. 46-56.

12. V. Kreyndelin, M. Khazov Investigation of antenna selection benefits in MIMO systems as compare to base MIMO system without antenna selection. *Tsifrovaya obrabotka signalov*. 2018. No.4, pp. 63-68.

13. V. Kreyndelin, M. Khazov Advantages and open questions of antenna selection in multi-antenna MIMO systems. *Materials of the International scientific and technical conference INTERMATIC-2015*. Vol. 5, 1-5 December 2015, pp. 236-238.

14. M. Bakulin, V. Kreyndelin, D. Pankratov. Radio communication technology on the way to 5G. Moscow: Goryachaya liniya – Telecom, 2018. 272 p.

15. E. Tyrtyshnikov. Matrix analysis and linear algebra. Moscow: Phizmatlit, 2007. 480 p.

16. Lin Yisong, Zhuang Mingjie, «The complexity analysis and performance comparison of MIMO systems based on antenna selection techniques», *Computer modelling & New technologies,* 2014, no. 18(11), pp. 1380-1386.

17. A. Gorokhov. Antenna selection algorithms for MEA transmission systems. *IEEE ICASSP*, 2002. Vol. 3, pp. 2857-2860.

18. Yang-Seok Choi, A. F. Molisch, M. Z. Win and J. H. Winters, "Fast algorithms for antenna selection in MIMO systems," *2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall* (IEEE Cat. No.03CH37484), Orlando, FL, USA, 2003, pp. 1733-1737 Vol.3, doi: 10.1109/VETECF.2003.1285322.

19. Hyunsub Kim, Hyukyeon Lee, Jihye Koo and Jaeseok Kim Low-complexity lattice reduction algorithm for MIMO detectors with tree searching, EURASIP Journal on Wireless Communications and Networking (2017) 2017:17.

20. Sudhanshu Gaur and Mary Ann Ingram. Transmit/Receive antenna selection for MIMO systems to improve error performance of linear receivers, School of ECE, Georgia Institute of Technology, Atlanta, GA 30332-0250 USA, Ph: 404-894-9482

НОВЫЕ КВАЗИОПТИМАЛЬНЫЕ АЛГОРИТМЫ АВТОВЫБОРА АНТЕНН С НИЗКОЙ ВЫЧИСЛИТЕЛЬНОЙ СЛОЖНОСТЬЮ

Бакулин Михаил Германович, *Московский технический университет связи и информатики, Москва, Россия,* **m.g.bakulin@gmail.com**

Крейнделин Виталий Борисович, *Московский технический университет связи и информатики, Москва, Россия,* **vitkrend@gmail.com**

Хазов Михаил Леонидович, *Московский технический университет связи и информатики, Москва, Россия,* **mikekhazov@mail.ru**

Аннотация

Для систем связи MIMO предлагаются новые квазиоптимальные алгоритмы переключения (автовыбора) антенн (алгоритмы неполного перебора), позволяющие достичь высокую спектральную эффективность без существенного увеличения аппаратной сложности. Методом статистического моделирования выполнены оценка эффективности предложенных алгоритмов и сравнение их характеристик с характеристиками известных алгоритмов полного и неполного перебора. Проведена оценка вычислительной сложности предложенных алгоритмов и ее сравнение с вычислительной сложностью известных алгоритмов полного и неполного перебора. Сравнительный анализ помехоустойчивости в совокупности с оценкой вычислительной сложности наглядно демонстрируют возможность практического применения новых квазиоптимальных алгоритмов в реальных системах связи, существенно улучшая энергетические характеристики систем связи MIMO.

Ключевые слова: *система связи MIMO, спектральная эффективность, помехоустойчивость, автовыбор (переключение) антенн, пропускная способность канала связи, радиотракт, критерий автовыбора, вычислительная сложность.*

Литература

1. *Sanayei S., Nosratinia A.* Antenna selection in MIMO systems // IEEE Communications Magazine, vol. 42, no. 10, pp. 68-73, Oct. 2004, doi: 10.1109/MCOM.2004.1341263.

2. *Крейнделин В.Б., Хазов М.Л.* Алгоритмы переключения антенн в системах MIMO // Электросвязь. 2017. № 10. С. 59-64.

3. *Крейнделин В.Б., Хазов М.Л.* Сравнение систем MIMO, использующих различные критерии автовыбора антенн // Материалы XIII международной отраслевой научно-технической конференции "Технологии информационного общества". М.: МТУСИ. 20-21 марта 2019 г.

4. *Smith P.J., King T.W., Garth L.M., Dohler M.* An Analysis of Low Complexity Algorithms for MIMO Antenna Selection // 2006 IEEE International Conference on Communications, Istanbul, Turkey, 2006, pp. 1380-1385, doi: 10.1109/ICC.2006.254941.

5. *Теукольский С.А.*, Феттерлинг, штат Вашингтон; Фланнери, Б.П. (2007), "Раздел 2.10. QR-разложение", Численные рецепты: Искусство научных вычислений (3-е изд.), Нью-Йорк: Cambridge University Press, ISBN. 978-0-521-88068-8. https://dev.abcdef.wiki/wiki/QR_decomposition.

6. *As-Saafani M.I., Sadi S.J., Badran E.F., Mohamed D.A.E., Shaaban S.* Antenna Selection Algorithms in Correlated Fading MIMO Channels // Proceedings of the Twenty Third National Radio Science Conference (NRSC'2006), Menouf, Egypt, 2006, pp. 1-8, doi: 10.1109/NRSC.2006.386326.

7. *Zhou X., Bai B., Chen W.* Iterative Antenna Selection for Multi-Stream MIMO under a Holistic Power Model // IEEE Wireless Communications Letters, vol. 3, no. 1, pp. 82-85, February 2014, doi: 10.1109/WCL.2013.111713.130754.

8. *Бакулин М.Г., Крейнделин В.Б., Хазов М.Л.* Критерии автовыбора антенн в системах MIMO // Электросвязь. 2018. № 10. С. 78-81.

9. *Бакулин М.Г., Варукина Л.А., Крейнделин В.Б.* Технология MIMO: принципы и алгоритмы. М.: Горячая линия – Телеком, 2014. 272 с.

10. *Emil Bjornson, Jakob Hoydis, Luca Sanguinetti*. Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency // Foundations and Trends in Signal Processing. 2017, Vol. 11, No. 3-4, pp. 154-655.

11. *Molisch A.F, Win M.Z.* MIMO systems with antenna selection // IEEE Microwave Magazine, 2004, № 5, pp. 46-56.

12. *Крейнделин В.Б., Хазов М.Л.* Исследование преимуществ автовыбора антенн в системах MIMO в сравнении с базовой системой MIMO без автовыбора антенн // Цифровая обработка сигналов. 2018. №4. С. 63-68.

13. *Крейнделин В.Б., Хазов М.Л.* Преимущества и открытые вопросы при переключении антенн в многоантенных системах MIMO. Материалы международной научно-технической конференции INTERMATIC-2015, Часть 5, 1-5 декабря 2015 г. С. 236-238.

14. *Бакулин М.Г., Крейнделин В.Б., Панкратов Д.Ю.* Технология радиосвязи на пути к 5G. М.: Горячая линия – Телеком, 2018. 272 с.

15. *Тыртышников Е.Е.* Матричный анализ и линейная алгебра. М.: Физматлит, 2007. 480 с.

16. *Lin Yisong, Zhuang Mingjie*. The complexity analysis and performance comparison of MIMO systems based on antenna selection techniques // Computer modelling & New technologies 2014 18(11), pp. 1380-1386.

17. *Gorokhov A.* Antenna selection algorithms for MEA transmission systems // IEEE ICASSP, 2002, Vol. 3, pp. 2857-2860

18. *Choi Yang-Seok, Molisch A.F., Win M.Z., Winters J.H.* Fast algorithms for antenna selection in MIMO systems // 2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No.03CH37484), Orlando, FL, USA, 2003, pp. 1733-1737 Vol.3, doi: 10.1109/VETECF.2003.1285322.

19. *Hyunsub Kim, Hyukyeon Lee, Jihye Koo, Jaeseok Kim.* Low-complexity lattice reduction algorithm for MIMO detectors with tree searching, EURASIP Journal on Wireless Communications and Networking (2017) 2017:17.

20. Sudhanshu Gaur and Mary Ann Ingram Transmit/Receive antenna selection for MIMO systems to improve error performance of linear receivers, School of ECE, Georgia Institute of Technology, Atlanta, GA 30332-0250 USA, Ph: 404-894-9482

Информация об авторах:

Бакулин Михаил Германович, *Московский технический университет связи и информатики, доцент кафедры ТЭЦ, к.т.н. Москва, Россия*

Крейнделин Виталий Борисович, *Московский технический университет связи и информатики, заведующий кафедрой ТЭЦ, профессор, д.т.н., Москва, Россия*

Хазов Михаил Леонидович, *Московский технический университет связи и информатики, соискатель, Москва, Россия*