UDC 521.391
**doi: 10.20998/2522-9052.2018.3.15**

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# ANALYSIS OF SIGNAL PROCESSING METHODS IN MIMO SYSTEMS

Conflicts of the last decades (the Chechen war (Russian Federation), armed confrontation in the countries of the Middle East and North Africa, anti-terrorist operation in the territory of Donetsk and Lugansk regions (Operation of the United Nations)) go beyond the existing (traditional) forms and methods of warfare, conducted on the background of information and psychological operations and the active using of electronic emitters. Therefore, provision of sustainable communication is one of the priority directions of scientific research. One of the directions of increasing the noise immunity of radio communication devices is using of the multi-antenna radio communication systems. However, they are complex technical systems. There are many approaches to increase the impedance of multi-antenna systems, but the authors of this article limited themselves to considering only the methods of signal processing, namely orthogonal spatial-temporal codes. During the study, the authors used the basic provisions of the theory of communication, the theory of antennas, the theory of noise protection and signal-code structures. In the course of the analysis, the authors found, that the computational complexity of the orthogonal codes used in MIMO systems is directly proportional to the number of transmitting antennas in the system, which leads to a linear increase in the number of computational operations in the processing of signals was using mentioned spatio-temporal codes. However, this type of spatial-temporal codes has high energy efficiency in MIMO systems with a small number of antennas. The authors propose to develop a method of space-time coding of signals in multi-antenna radio systems with high energy and spectral efficiency, when the proposed method had an acceptable computational complexity.

**Keywords:** signal-interfering environment; information transfer speed; bit error probability; spatial-temporal processing; MIMO system; parallel channels.

## Introduction

Conflicts of the last decades (the Chechen war (Russian Federation), armed confrontation in the countries of the Middle East and North Africa, anti-terrorist operation in the territory of Donetsk and Lugansk regions (Operation of the United Nations)) go beyond the existing (traditional) forms and methods of warfare, conducted on the background of information and psychological operations and the active use of electronic emitters. Therefore, provision of sustainable communication is one of the priority directions of scientific research. One of the directions to increase the noise immunity of radio communication devices is using of the multi-antenna radio communication systems.

MIMO (Multiple Input Multiple Output) technology has been found to be practical in many modern telecommunication systems, in particular wireless LANs of the IEEE 802.11n standard, as well as WIMAX and LTE mobile wireless networks, and others [1-5].

The essence of MIMO technology is similar to the method of spaced reception, when several uncorrelated copies of the signal created on the receiving side due to the diversity of antennas in space, in polarization, in the distribution of signals at frequency or in time. Spatial multiplexing was implemented in MIMO radio systems: the data stream on the transmission was split into two or more sub-streams, each of which was transmitted and received using various antennas [1-6, 10-12].

The transmission of signals in the MIMO system results in inter-symbol interference (ISI) on the receiving side and may cause errors in the receiver output. In order to compensate for these distortions, channel alignment or evaluation of its impulse response must be performed, which will allow the most faithfully recovered symbols.

***The purpose of this article*** is analysis of signal processing methods in MIMO systems.

## Presentation of main material research

Let's formalize the work of the MIMO system. In general, the structure of the MIMO system has in its composition $M_t$ transmitters (transmit antennas) and $M_r$ receivers (receiving antennas) (Fig. 1). Transmitted signals after the influence of the relay fading and white Gaussian noise (WGN) in the radio channel, arrive at the $M_r$ receiving tracks [1-10].

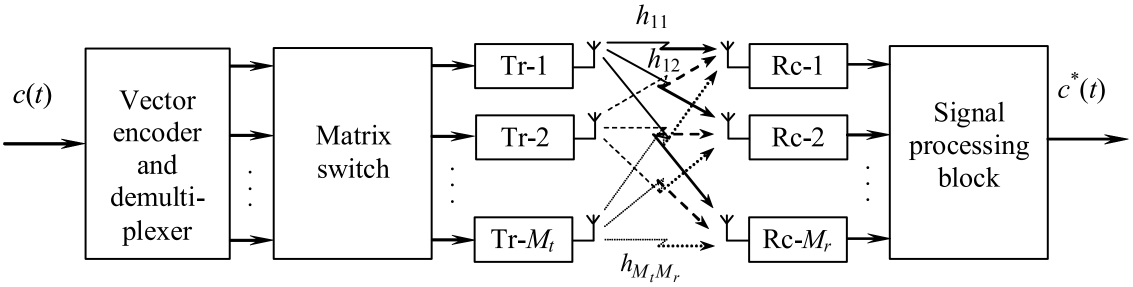

**Fig. 1.** The block diagram of the MIMO system

Consider the MIMO system $M_t \times M_r$, depicted in Fig. 1. High-speed data flow was divided into $M_t$ independent sequences at $1/M_t$, which was then transmitted simultaneously from several antennas, respectively, using only $1/M_t$ of their primary band.

The data flow converter at the transmitter end of the communication line converts the serial stream into parallel, and at the receiving terminal it performs the inverse transformation.

In such a system, signals on the transmitting side were emitted simultaneously and in the same band of frequencies through the $M_t$ transmit antennas. The transmitted signals, after the effect of the fading of the signal and the additive white Gaussian noise, arrive in the $M_r$ of the receiving paths. Each additive tract receives an additive mixture of transmitted signals.

Due to the multidirectional effect in the path of radio waves propagation, each of the transmitted signals is repeatedly diverted from various objects, thus forming independent trajectories of radio waves passing between each transmitting and receiving antennas. In this way, MIMO technology can benefit from the multipath effect. In addition, due to the spacing of the antennas, both the transmitting and the receiving side significantly reduces the correlation between the complex transmission coefficients of all paths of signal propagation from transmitting to receiving antennas, which increases the efficiency of signal processing on the receiving side (Table 1).

*Table 1* – **Characteristics of communication systems using MIMO technology**

| **Generation** | **3G** | **3,5G** | **4G** | **5G** |
|---|---|---|---|---|
| Beginning of developments | 1990 | < 2000 | 2000 | 2014 |
| Realization | 2002 | 2006-2007 | 2008-2010 | planned to 2020 |
| Services | even more capacity, up to 2 Mbit/s | increase the speed of third-generation networks | high capacity, IP-oriented network, multimedia support, speeds up to hundreds of megabits per second | high capacity, IP-oriented network, multimedia support, speeds up to tens of megabits per second |
| Transfer rate | to 3,6 Mbit/s | to 42 Mbit/s | 100 Mbit/s - 1 Gbit/s | 10 Gbit/s - 100 Gbit/s |
| Modulation | BPSK-64QAM | BPSK-64QAM | BPSK-256QAM | BPSK-1024QAM |
| Standarts | WCDMA, CDMA2000, UMTS | HSDPA, HSUPA, HSPA, HSPA+ | LTE-Advanced, WiMax Release 2 (IEEE 802.16m), WirelessMAN-Advanced | На базі технологій WiMAX 2, LTE-Advanced і Wi-Fi. |
| Technologies | TDD, FDD WCDMA, EV-DO, OFDM | TDD, FDD, CDMA, MIMO, OFDMA | TDD, FDD, MC-CDMA, SC-FDMA, MIMO-BF, OFDM, MIMO-OFDM | MIMO, OFDM, MIMO-OFDM, SDN |

Spatio-temporal encoding started using in communication systems starting from the 3G standard.

On the transmission side, the information symbols $a_i$ are divided into blocks of $W$ symbols, respectively processed and radiated through S transmit antennas for a given number of time intervals $K_{\text{giv}}$. The spatial-temporal code can be presented as a generating matrix, in which the rows correspond to the transmit antennas, and the columns are the time intervals for the transmission of symbols:

$$\begin{vmatrix} s_{11} & s_{12} & \dots & s_{1K_{given}} \\ s_{21} & s_{22} & \dots & s_{2K_{given}} \\ \dots & \dots & \dots & \dots \\ s_{M_t 1} & s_{M_t 2} & \dots & s_{M_t K_{given}} \end{vmatrix}, \tag{1}$$

where $s_{jk}$, $j = \overline{1, S}$, $k = \overline{1, K_{given}}$ is function from complex information symbols $a_i$, $i$ = 1, 2, ..., which is emitted $j$-th antenna on $k$-th time interval.

The symbolic speed of the MIMO system is defined as the ratio of the length of the information symbol $W$ to the amount of time required for transmitting this block of time $K_{\text{giv}}$: $R_{\text{STC}} = W/K_{\text{giv}}$. The higher the $R_{STC}$ symbolic spatial-temporal code, the higher the efficiency of using the frequency resources of the radio channel.

Spatial-time codes are divided into two classes: orthogonal and non-orthogonal. Among the orthogonal codes, it is necessary to allocate the code of Alamouti, whose generative matrix has the form [2-7]:

$$G = \begin{vmatrix} a_1 & -a_2' \\ a_2 & a_1' \end{vmatrix}. \tag{2}$$

Alamouti character code speed $R_{STC} = 1$. In the matrix (2) the rows are orthogonal to each other, the same is valid for its columns.

In this research, we confine ourselves to consideration of only orthogonal spatial-temporal codes.

If, in a complex, the transmission coefficients of the first and second transmitting antennas $h_1$ and $h_2$ to the receiving antennas, respectively, one can record the system of equations for the signals received in two time intervals $k_1$ and $k_2$

$$\begin{cases} y_1 = h_1\alpha_1 + h_2\alpha_2 + \eta_1; \\ y_2 = -h_1\alpha_2' + h_2\alpha_1' + \eta_2, \end{cases} \tag{3}$$

where $y_i, i = 1,2$ is the counting of the complex bending in the receiving tract on the $i$ -th time interval; $\eta_i$ is the countdown of the complex Gaussian noise in the receiving path at the $i$ -th time interval.

It is believed, that the system carries out a coherent reception, that is, the complex coefficients of transmission of paths of propagation of signals between each pair of transmitting and receiving antennas are known.

System (3) can be rewritten in the following form:

$$\begin{cases} h_1' y_1 + h_2 y_2' = \left(|h_1|^2 + |h_2|^2\right) a_1 + h_1' \eta_1 + h_2 \eta_2'; \\ h_2' y_1 - h_1 y_2' = \left(|h_1|^2 + |h_2|^2\right) a_2 + h_1' \eta_2 + h_2 \eta_1. \end{cases} \tag{4}$$

After conversion we get:

$$\begin{cases} \alpha_1 = \dfrac{h_1' y_1 + h_2 y_2'}{\left(|h_1|^2 + |h_2|^2\right)} - \dfrac{h_1' \eta_1 + h_2 \eta_2'}{\left(|h_1|^2 + |h_2|^2\right)}; \\ \alpha_2 = \dfrac{\left(h_2' y_1 - h_1 y_2'\right)}{\left(|h_1|^2 + |h_2|^2\right)} - \dfrac{h_1' \eta_2' - h_2 \eta_1}{\left(|h_1|^2 + |h_2|^2\right)}. \end{cases} \tag{5}$$

In order to calculate the estimates of the transmitted symbols in the demodulator in accordance with the criterion of maximum likelihood, it is necessary to minimize the squares of the norms of the vowels of resignation

$$\left\| \alpha_1 - \frac{h_1' y_1 + h_2 y_2'}{\left(|h_1|^2 + |h_2|^2\right)} \right\|^2 \left\| \alpha_2 - \frac{\left(h_2' y_1 - h_1 y_2'\right)}{\left(|h_1|^2 + |h_2|^2\right)} \right\|^2 . \tag{6}$$

Thus, demodulation on the receiving side is reduced first to the calculation of soft ratings

$$\begin{cases} \hat{\alpha}_1 = \dfrac{h_1' y_1 + h_2 y_2'}{\left(|h_1|^2 + |h_2|^2\right)}; \\ \hat{\alpha}_2 = \dfrac{\left(h_2' y_1 - h_1 y_2'\right)}{\left(|h_1|^2 + |h_2|^2\right)}. \end{cases} \tag{7}$$

System (5) consists of two equations, each containing only one unknown variable, that is, one unknown information symbol, it is possible to calculate the estimates of symbols, that are optimal by the criterion of maximum likelihood. It should be noted, that while the number of arithmetic operations for calculation is directly proportional to the number of transmitting antennas, that is, the demodulation algorithm according to the maximum probability criterion has a linear computational complexity.

The separation of the two transmitted signals becomes possible due to the orthogonality properties of the matrix (2), which satisfies the following condition:

$$\mathbf{G}'\mathbf{G} = \left(|a_1|^2 + |a_2|^2\right) 1. \tag{8}$$

In the general case, the matrix (2) of the space-time code of dimension $M \times K_t$ satisfies a certain condition

$$\mathbf{G}'\mathbf{G} = k1, \tag{9}$$

where $k$ is a certain constant, then this code is orthogonal; when it is used demodulation of symbols is based on the criterion of maximum probability with linear computational complexity, directly proportional to the number of transmitting antennas.

Unfortunately, for systems with more than two transmit antennas, QAM has no orthogonal codes at speeds $R_{\text{STC}} = 1$. When switching to more transmit antennas, for example, 3 and 4, the symbolic speed of the corresponding orthogonal codes does not exceed 3/4. The symbol speed of the codes for five or more transmitting antennas does not exceed 1/2.

## Conclusions

In this article, the authors analyzed the parameters of orthogonal spatial-temporal codes used for signal processing in MIMO systems.

In the course of the analysis, the authors found, that the computational complexity of the orthogonal codes used in MIMO systems is directly proportional to the number of transmitting antennas in the system, which leads to a linear increase in the number of computational operations in the processing of signals using the mentioned spatial-temporal codes.

However, this type of spatial-temporal codes has high energy efficiency in MIMO systems with a small number of antennas.

Consequently, an urgent scientific problem arises, which was solved in further studies by the authors, which consists in developing spatial-temporal signal processing methods with acceptable computational complexity and high energy and spectral efficiency.

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Received 15.05.2018
Accepted for publication 22.07.2018

## Аналіз методів обробки сигналів в системах MIMO

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Конфлікти останніх десятиліть (Чеченська війна (Російська Федерація), збройні протистояння в країнах Близького Сходу та Північної Африки, Антитерористична операція на території Донецької та Луганської областей (Операція Об’єднаних Сил)) виходять за рамки існуючих (традиційних) форм та способів ведення бойових дій, проводяться на фоні інформаційно-психологічних операцій та активного використання засобів радіоелектронного подавлення. Отже забезпечення стійкого зв’язку є одним з пріоритетних напрямків наукових досліджень. Одним з напрямків підвищення завадозахищеності засобів радіозв’язку є використання багатоантенних систем радіозв’язку. Проте вони є складними технічними системами. Існує багато підходів до підвищення завадозахищеності багатоантенних систем, проте автори зазначеної статті обмежилися розглядом лише методів обробки сигналів, а саме ортогональних просторово-часових кодів. В ході дослідження авторами були використані базові положення теорії зв’язку, теорії антен, теорії завадозахищеності та сигнально-кодових конструкцій. В ході проведеного аналізу авторами з’ясовано, що обчислювальна складність ортогональних кодів що використовується в системах MIMO прямо пропорційна кількості передавальних антен в системі, що призводить до лінійного зростання кількості обчислювальних операцій при обробці сигналів з застосуванням зазначених просторово-часових кодів. Проте зазначений вид просторово-часових кодів має високу енергетичну ефективність в системах MIMO з малою кількістю антен. Авторами запропоновано провести розробку методу просторово-часового кодування сигналів в багатоантенних системах радіозв’язку з високою енергетичною та спектральною ефективності, при цьому, щоб запропонований метод мав прийнятну обчислювальну складність.

**Ключові слова:** сигнально-завадова обстановка; швидкість передачі інформації; ймовірність бітової помилки; просторово-часова обробка; система MIMO; паралельні канали.

## Анализ методов обработки сигналов в системах MIMO

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Конфликты последних десятилетий (Чеченская война (Российская Федерация), вооруженные противостояния в странах Ближнего Востока и Северной Африки, Антитеррористическая операция на территории Донецкой та Луганской областей (Операция Объединенных Сил)) выходят за рамки существующих (традиционных) форм та способов ведение боевых действий, проводятся на фоне информационно-психологических операций та активного использование средств радиоэлектронного подавления. Поэтому вопрос обеспечение стойкой связи есть одним из приоритетных направлений научных исследований. Одним из направлений повышения помехозащищённости средств радиосвязи есть использование многоантенных систем радиосвязи. Они являются сложными техническими системами. Существует много подходов к повышению помехозащищённости многоантенных систем, тем не менее, авторы указанной статьи ограничились рассмотрением лишь методов обработки сигналов, а именно ортогональных пространственно-временных кодов. В ходе исследования авторами были использованные базовые положения теории связи, теории антенн, теории помехозащищённости и сигнально-кодовых конструкций. В ходе проведенного анализа авторами выяснено, что вычислительная сложность ортогональных кодов, что используется в системах MIMO прямо пропорциональная количеству передающих антенн в системе, которая приводит к линейному росту количества вычислительных операций при обработке сигналов с применением указанных пространственно-временных кодов. Тем не менее, указанный вид пространственно-временных кодов имеет высокую энергетическую эффективность в системах MIMO с малым количеством антенн. Авторами предложено провести разработку метода пространственно-временного кодирования сигналов в многоантенных системах радиосвязи с высокой энергетической и спектральной эффективности, при этом, чтобы предложенный метод имел приемлемую вычислительную сложность.

**Ключевые слова:** сигнально-помеховая обстановка; скорость передачи информации; вероятность битовой ошибки; пространственно-временная обработка; система MIMO; параллельные каналы.