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ANALYSIS OF IMPROVEMENT METHODS OF NOISE IMMUNITY OF MULTI-ANTENNA SYSTEMS OF MILITARY RADIOCOMMUNICATION

The experience of carrying out an antiterrorist operation on the territory of Donetsk and Lugansk oblasts shows, that the current level of noise immunity of multi-antenna systems of military radio communication does not meet the modern requirements put forward for their functioning. Most of the available publications describe only separate direction for increasing the noise immunity of multi-antenna systems of military radio communication, but this information is not systematized and does not create a generalized view on possible options for increasing the noise immunity of these systems. As a result of the research, the main methods of increasing the noise immunity of multi-antenna systems of military radio communication have been determined. It is established, that most of the theoretical achievements of known authors are aimed at developing optimal methods of space-time coding, frequency adaptation and creation (selection) of highly effective signal-code structures. This article uses the basic provisions of the theory of noise immunity, the theory of antennas, noise immunity coding, signal-code structures, and others. According to the results of the study, it is possible to say, that multi-antenna systems of military radio communication are multi-level spatial-frequency-time signal-code designs. Taking into account, that the devices of electronic warfare increase the level of their own technological perfection from multi-antennas of military radio communication, complex use mechanisms to increase the noise immunity at each level is required and significant improvement of existing models and methods of increasing the noise immunity of multi-antenna systems of military radio communication is required.

Keywords: *MIMO, system of radiocommunication, radioelectronic suppression, radio resource, pre-coding, signal-code designs, noise immunity.*

Introduction

Conducting an antiterrorist operation on the territory of Donetsk and Luhansk oblasts showed the imperfection of the existing system of control and communication, the basis of which are radiocommunication systems (RCS).

The main drawback of the existing system of communication of all units of the Armed Forces of Ukraine are [1–3]:

low mobility of communication nodes management points;

low productivity, reliability, dilution and noise protection;

low automation of installation, maintenance and maintenance of radio communication.

Therefore, ***aim of this work*** is an analysis of methods for increasing the noise immunity of multi-antenna systems of military radiocommunication.

Exposition of the main material of the research

In general, the noise immunity of multi-antenna systems (MIMO – Multiple-Input Multiple-Output), which are provided with impedance and secrecy from all classical systems of communication.

Concealment makes it difficult to detect the fact of the functioning of this communication system and to determine the characteristics of the signals emitted by it in order to create effective intentional interference or the destruction of the system. The noise immunity provides the normal functioning of the system under the influence of a certain set of unintentional and deliberate interference.

The analysis of known literature sources [1–6] allows us to determine the main ways to increase the noise immunity of multi-antenna communication systems, namely:

1. Selecting range of waves in which the effect of interference is minimal (range of decimetre or shorter waves).

2. Improving the energy of radio lines, that is, increasing the signal/noise ratio by increasing the power energy of the signal (increasing the power of the transmitter), which requires significant energy or material costs, and also complicates the electromagnetic compatibility of their radio equipment.

3. Application of noise-proof principles of space-time signal processing:

choosing of modulation type and principles of demodulation of the signal;

using of interference-free (corrective) codes;

using of several physically diverse communication channels (3–5 channels) transmitting the same information, or on a multiple transmission (3–5 times) of the same information from one communication channel. In the first case, essential material costs are required, while in the second, the bandwidth of the communication channel is significantly reduced (in 3–5 times). For

these reasons, using of these methods in military radio-communication systems is not always feasible;

using of channels with a different kind of feedback. The latter may be informational – some analogue of the majoritarian method with multiple information transmission and the decision on the correct transmission of the transmitter, or decisive feedback – by repeated transmission with the decision on the correct transmission on the part of the receiver.

As the analysis shows, in practice the following basic methods of increasing the energy and structural secrecy of the transmission system are used:

working with the minimum required power of radiation, sufficient to provide a given quality of communication. Using of radio systems adapted to the power of radiation;

application of optimal methods of reception of signals and devices of protection against certain types of interference;

application of broadband complex signals with a large base;

application of frequency-adaptive communication lines.

Let's consider more basic methods of increasing the noise immunity of multi-antenna systems of military radio communication.

Signal-code construction (SCC).

To increase the speed of information transmission without extending the occupied bandwidth (increasing the bandwidth of the communication system), using multi-positional M-signals. M-signals can be formed by multi-positional manipulation of carrier oscillation in amplitude, frequency or phase.

Using of SCC, which allow simultaneously to increase the reliability and speed of the transmission of information in the constraints on energy and the width of the band of operating frequencies and solve most of the contradictions, that arise. Combination of various ensembles of M-signals, noise immunity and manipulation codes generate many designs. However, only agreed variants of these designs provide an increasing in the frequency-energy efficiency of multi-antenna systems.

The SCC can be classified into three main features:

by type of noise immunity code,

by type of ensemble of signals,

by the way of agreeing modulation and encoding.

By type of jamming codes, all SCC can be divided into two major classes: on the basis of block codes and on the basis of continuous codes. In addition, a separate class includes SCC based on cascading codes, that use both block and continuous codes.

By type of ensemble of signals, the SCC is divided into designs with one-dimensional, two-dimensional and multi-dimensional signals.

Multi-dimensional signals consist of simpler (one-dimensional, two-dimensional) signals. When using two-dimensional signals, the number of positions M, corresponding to each N-dimensional signal is determined by the expression

$$M = m^{N/2},$$

where m – position of two-dimensional signal.

In tabl. 1 were used following marking $Q(x) = \dfrac{1}{\sqrt{2\pi}} \int\limits_{x}^{\infty} e^{-t^2/2} dt$ – integral of errors, M – number of positions for multi-position modulation types, $k = \log_2 M$, m – modulation index, $K_{\delta_{min}}$ – number of states with a minimum euclidean distance, $\sin c\,(x) = \sin(x)/x$, E_b – the energy, which is necessary to transmit one bit of information; N_0 – spectral density of white noise power in the channel.

Using of pre-coding methods.

Spatial multiplexing and spacing are contradictory to the geometry and probabilistic characteristics of the channel matrix. Theoretically proved [6–15], that if the channel information is available only to the receiver, then there is a fundamental trade-off between multiplexing and spacing, in which one can not increase one and not reduce another. The situation changes, if we assume, that some parameters of the communication channel are known on the transmitting side and can be used to construct the corresponding spatial signal-code structure.

In fact, such systems assume the presence of a reverse link, and the procedure for the formation of an optimal signal-code structure in these conditions is called spatial pre-coding.

In the authors' publications [1–13] it was noted, that using of information on the state of the communication channels on the transmitting side can significantly increase the power and frequency efficiency of multi-antenna radio-communication systems of a special purpose, to improve the coverage area and reduce the complexity of the implementation of the receiver of the system from using MIMO technology [9–13].

In the general case, the previous coding can be considered as one of the methods of spatial-temporal coding and as one of the types of signal-code structures.

It should be considered, that for the previous coding, the presence of feedback is mandatory, since the matrix of the previous coding is selected based on the status of the channel [9–13]. Physical nature of the pre-coding in MIMO radio systems is that the pre-coding allows you to reconcile the transmitted signal with the characteristics of the communication channel. This result in improved performance compared to the system without such an agreement.

In the case, where the complex matrix of channel **H** is accurately known on the transmitting side, one can make an optimal pre-coding, which is to transform the vector of symbols transmitted, using the unitary matrix **V**, which depends on the matrix **N**.

Table 1

Error probability for bit for different modulation types

Type of modulation	Bit error rate (BER)
BPSK (binary phase shift keying) (M=2)	$\text{BER} = Q\left(\sqrt{2E_b / N_0}\right)$
Incoherent DBPSK (differential phase shift keying) (M=2)	$\text{BER} = \dfrac{1}{2}\exp(-E_b/N_0)$
Coherent DBPSK (M=2)	$\text{BER} = 2Q\left(\sqrt{\dfrac{2E_b}{N_0}}\right)\left(1 - Q\left(\sqrt{\dfrac{2E_b}{N_0}}\right)\right)$
QPSK (Quadrature Phase Shift Keying) (M=4)	$\text{BER} = Q\left(\sqrt{2E_b/N_0}\right)$
Coherent DQPSK at $E_b/N_0 \gg 1$	$\text{BER} = 2Q\left(\sqrt{2E_b/N_0}\right)$
M-PSK	$\text{BER} = \dfrac{2}{\log_2 M}Q\left(\sqrt{\dfrac{2E_b\log_2 M}{N_0}\sin^2\left(\dfrac{\pi}{M}\right)}\right)$
FSK (frequency shift keying)	$\text{BER} = Q\left(\sqrt{\left[1 - \dfrac{\sin(2\pi\cdot m)}{2\pi\cdot m}\right]\dfrac{E_b}{N_o}}\right)$
MSK (minimum shift keying)	$\text{BER} = Q\left(\sqrt{E_b/N_0}\right)$
M-MSK	$\text{BER} = \dfrac{2(M-1)}{M\log_2 M}Q\left\{\sqrt{\log_2 M\dfrac{E_b}{N_0}}\right\}$
M-QAM (quadrature amplitude modulation)	For $k = \log_2 M$, k-pair; $\text{BER} = \dfrac{2P_0 - P_0^2}{\log_2 M}$, where $P_0 = \dfrac{2\sqrt{M}-1}{\sqrt{M}}Q\left(\sqrt{\dfrac{3\log_2 M}{M-1}\dfrac{E_b}{N_0}}\right)$ For odd k: $\text{BER} \le \dfrac{1}{\log_2 M}\left[1 - \left(1 - 2Q\left(\sqrt{\dfrac{3\log_2 M}{M-1}\dfrac{E_b}{N_0}}\right)\right)^2\right]$
CPFSK (Continuous-Phase Frequency-Shift Keying)	$\text{BER} \cong \dfrac{P_S}{k},\ P_S > K_{\delta_{min}}Q\left(\sqrt{\dfrac{E_b}{N_0}\delta^2_{min}}\right),$ $\delta^2_{min} = \min_{1\le i\le M-1}\left\{2k\left(1 - \sin c\left(2\pi im\right)\right)\right\}$

The matrix **V** is a part of the singular expansion of the matrix **H** [1–4]:

$$\mathbf{H} = \mathbf{U\Lambda V}',\qquad(1)$$

where $\mathbf{U}, \mathbf{V}$ – unitary dimension matrices $M\times M$ and $N\times N$ in accordance; $\Lambda = \text{diag}\{\lambda_1, \lambda_2, ..., \lambda_r\}$ – diagonal matrix with size $M\times N$, on the main diagonal of which has its own numbers $\lambda_i, i = 1,...,r$ matrix **H**; $r = \min\{N, M\}$.

With optimal pre-coding, the best characteristics of the MIMO radio system are achieved due to the fact, that the system in this case is decomposed into a plurality of parallel systems SISO (Single Input Single Out-put), the minimal complexity of the demodulation algorithm at the receiving side [1–18].

Unfortunately, in practice, the implementation of optimal pre-coding is quite problematic, since the matrix of the channel **H** is always evaluated with some error, especially in a situation, where channel parameters change rapidly, due to the high mobility of subscribers. Therefore, in modern radio systems in practice, various quasi-optimal algorithms of pre-coding are used [1–18]. In the quasi-optimal algorithms indicated on the transmitting side, instead of full information about the state of the channel contained in the matrix **H**, only partial information about the status of the communication channel is used. The indicated partial information may be in the

form of one or more parameters, that characterize the current state of the communication channel or only its statistics (the law of fading, the distribution of power between the direct and reflected beam in the channel).

To date, there are three main ways to get information about the state of the communication channel:

– using of the mutual linearity of the communication channel;

– using of the feedback line between the transmitter and the receiver;

– combination of the first and second methods.

The pre-coding procedure, based on the using of the communication channel status information available on the transmitting side, provides two functions:

– splitting the transmitted signal into independent spatial flows (rays);

– distribution of the power of emitted signals between these spatial flows (beams).

If spatial flows (rays) exactly correspond to the own (singular) vectors of the matrix **H** of the channel, then there are no interferences between these flows. The transmission of information through a communication channel in this case is carried out in parallel in several independent spatial channels, and for realization of such an ideal data transfer it is necessary that accurate information about the current state of the communication channel is available on the transmitting side.

If the transmission side information is only partially known, then the pre-coding spatial flows (rays) are formed in such a way as to minimize the level of interference between them.

Selection of demodulation method.

Improving the efficiency of the operation of multi-antenna radio communications is achieved through the using of Space-Time Processing (STC) techniques, that provide the transmission and reception of parallel streams of information. In theory, the bandwidth of the MIMO system with STC can be increased in proportion to the number of antennas on the transmitting side (provided, that the number of receiving antennas is not less, than the number of transmitting antennae) compared to traditional radio systems with one SISO transmission antenna. The analysis of the known systems of STC [25; 2–14] shows, that increasing the spectral efficiency of the MIMO system is usually due to the complication of the STC demodulator and the reduction of system impedance. Therefore, an important task is to choose a method of processing signals on the receiving side, which provides a given quality of information transmission and is characterized by moderate computational complexity.

We will conduct a comparative analysis of the demodulation of signals in the MIMO system with STC in terms of their efficiency and computational complexity.

Transmitted signals after the influence of the relay idle and white gaussian noise in the radio channel, come in M_r receiving tracks.

Counts of complex by-pass output M_r recievers on one interval can be described by a vector-matrix equation [5; 11]:

$$\mathbf{Z} = \mathbf{HA} + \mathbf{B}, \qquad (2)$$

where **Z** – vector, each component of which z_i, $i = \overline{1, M_r}$, is a countdown of a comprehensive by-pass on i-th demodulator input STC; **A** – vector, each component of which a_j, $j = \overline{1, M_t}$ – transmitted complex informational symbol belonging to a plurality $\{a^{(1)}, \ldots, a^{(K)}\}$, K – multiplicity of quadrature amplitude modulation (QAM); **H** – matrix, each component of which h_{ij} – complex transmission coefficient of the propagation path of the signal, that is emitted by j-th antenna and accepted by i-th antenna; **B** – vector, each component of which b_i – countdown of complex gaussian noise on i-th demodulator input STC, which has zero average and variance $2\sigma^2$.

On the transmission side, information symbols a_i split into blocks with L characters are appropriately processed and radiated through M_t transmitting antennas for a given number of time intervals K_{giv}. The spatial-temporal code can be presented as a generating matrix, in which the rows correspond to the transmit antennas, and the columns – the time intervals for the transmission of symbols:

$$\begin{vmatrix} s_{11} & s_{12} & \ldots & s_{1K_{зад}} \\ s_{21} & s_{22} & \ldots & s_{2K_{зад}} \\ \ldots & \ldots & \ldots & \ldots \\ s_{M_t 1} & s_{M_t 2} & \ldots & s_{M_t K_{зад}} \end{vmatrix}, \qquad (3)$$

where s_{jk}, $j = \overline{1, M_t}$, $k = \overline{1, K_{given}}$ – function from complex information symbols a_i, $i = 1, 2, \ldots$, which is emitted by 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 block L to the amount of time needed to transmit this block of time intervals K_{giv}: $R_{STC} = L/K_{giv}$. The higher symbolic speed R_{STC} spatial-temporal code, the higher the efficiency of the frequency resources using of the wireless communication 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 generating matrix has the form [23]:

$$G = \begin{vmatrix} a_1 & -a_2' \\ a_2 & a_1' \end{vmatrix}. \qquad (4)$$

The symbolic speed of the Alamouti code is $R_{STC} = 1$. In the matrix (4), the rows are orthogonal to each other, the same is valid for its columns. Due to this property on the receiving side, it is possible to calculate the estimates of maximum likelihood (ML) of the transmitted symbols using the algorithm of weighting the received signals. The energy gain from the using of

the Alamouti circuit with two transmitting and one receiving antennas compared to the usual SISO system is 7 dB for the probability of false reception $P_{error} = 10^{-2}$ when using four-phase phase modulation (QPSK).

Unfortunately, for systems with more, than two transmit antennas, QAM has no orthogonal codes at speeds $R_{STC} = 1$. 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.

Increasing the bandwidth of communication channels can be done using non-orthogonal spatial-temporal codes. The symbolic velocity for non-orthogonal coding can reach values corresponding to the number of transmitting antennas M_t, that is, behind the time intervals K_{giv} you can transfer unit with $L = K_{giv}M_t$ of information symbols. This condition satisfies Vertical Bell Labs Layered Space Time (V-BLAST) code [23; 25]. Another example of a non-orthogonal code is the double code of Alamouti.

The demodulation process of STC reduces to solve the equation (2) with respect to the unknown, but since there is a random component in Gaussian noise **B**, the traditional methods for solving linear equations do not provide the required precision. Different methods can be used to calculate the ratings of transmitted symbols: ZF – Zero Forcing, RMS, Successive Interference Cancellation (SIC), Maximum Likelihood Method (ML), spherical decoding method (SD), etc. [15].

Estimates of transmitted symbols by the ZF method are calculated as follows:

$$\hat{\theta} = (\mathbf{H'H})^{-1}\mathbf{H'Y} . \tag{5}$$

The expression for computing the estimation of MAQD has the form:

$$\hat{\theta} = (\mathbf{H'H} + 2\sigma^2\mathbf{I})^{-1}\mathbf{H'Y} . \tag{6}$$

The MAQD method allows for noise to consider the availability reduction and higher noise immunity compared to ZF. The computational complexity of both methods is proportional M_t^3 .

Significantly better characteristics, than the ZF and MAQD methods have an SIC algorithm, which reduces to the sequential exclusion of demodulated components from the received signal. For each iteration of this algorithm by the MAQD method, a rigorous evaluation of one of the components transferred to the i-th antenna is calculated, the replica of which is then subtracted from the received signal. The SIC method has a significant drawback – the effect of "multiplying errors". The number of arithmetic operations in this method is proportional M_t^4 .

The best practice among known demodulation methods is the MP method. The evaluation of information symbols by the MP method is carried out by checking all combinations of the vector θ from the set of possible values of the QAM symbol vector $\Theta = \left\{ \theta^{(1)},...,\theta^{\left(K_{given}^{M_t} \right)} \right\}$:

$$\hat{\theta} = \arg\min_{\theta} \|\mathbf{Y} - \mathbf{H}\theta\|^2 . \tag{7}$$

In this way, the best noise immunity among known demodulation methods has the maximum likelihood method. A promising direction for further research to increase the spectral and energy efficiency of MIMO systems is the development of efficient algorithms for demodulating signals with characteristics approaching the characteristics of the maximum probabilistic method with acceptable computational complexity.

Conclusion

As a result of the research, the main methods of increasing the noise immunity of multi-antenna systems of military radiocommunication have been determined.

According to the results of the research, it is possible to say, that multi-antenna systems of military radio communication are multi-level spatial-frequency-time signal-code construction.

Increasing of technological perfection of the devices of electronic warfare requires the comprehensive using of mechanisms for increasing noise immunity at each level and requires significant improvement of existing models, methods and techniques for increasing the noise immunity of multi-antenna systems of military radio communication.

Further research by the author will be aimed at developing effective methods of spatial-temporal coding and effective signal-code designs.

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АНАЛІЗ МЕТОДІВ ПІДВИЩЕННЯ ЗАВАДОЗАХИЩЕНОСТІ БАГАТОАНТЕННИХ СИСТЕМ ВІЙСЬКОВОГО РАДІОЗВ'ЯЗКУ

С.В. Калантаєвська

Досвід проведення антитерористичної операції на території Донецької та Луганської областей свідчить, що існуючий рівень завадозахищеності багатоантенних систем військового радіозв'язку не задовольняє сучасним вимогам, що висуваються до їх функціонування. Більшість наявних публікацій описують лише окремий напрямок підвищення завадозахищеності багатоантенних систем військового радіозв'язку, проте зазначена інформація не систематизована та не створює узагальненого уявлення щодо можливих варіантів підвищення завадозахищеності зазначених систем. В результаті проведеного дослідження визначено основні методи підвищення завадозахищеності багатоантенних систем військового радіозв'язку. Встановлено, що більшість теоретичних набутків відомих авторів спрямовані на розробку оптимальних методів просторово-часового кодування, частотної адаптації та створення (вибір) високоефективних сигнально-кодових конструкцій. В зазначеній статті використані основні положення теорії завадозахищеності, теорії антен, завадостійкого кодування, сигнально-кодових конструкцій та інш. За результатами проведеного дослідження можна сказати, що багатоантенні системи військового радіозв'язку представляють собою багаторівневі просторово-частотно-часові сигнально-кодові конструкції. Беручи до уваги те, що засоби радіоелектронної боротьби підвищують рівень власної технологічної досконалості від багатоантенних засобів військового радіозв'язку вимагається комплексне використання механізмів підвищення завадозахищеності на кожному з рівнів та необхідне істотне удосконалення існуючих моделей, методів та методик підвищення завадозахищеності багатоантенних систем військового радіозв'язку.

Ключові слова: *МІМО, системи радіозв'язку, радіоелектронне подавлення, радіоресурс, попереднє кодування, сигнально-кодові конструкції, завадозахищеність.*

АНАЛИЗ МЕТОДОВ ПОВЫШЕНИЯ ПОМЕХОЗАЩИЩЕННОСТИ МНОГОАНТЕННЫХ СИСТЕМ ВОЕННОЙ РАДИОСВЯЗИ

С.В. Калантаевская

Опыт проведения антитеррористической операции на территории Донецкой и Луганской областей свидетельствует, что существующий уровень помехозащищенности многоантенных систем военной радиосвязи не удовлетворяет современным требованиям, предъявляемым к их функционированию. Большинство имеющихся публикаций описывают лишь отдельные направление повышения помехозащищенности многоантенных систем военной радиосвязи, однако указанная информация не систематизирована и не создает обобщенного представления о возможных вариантах повышения помехозащищенности указанных систем. В результате проведенного исследования определены основные методы повышения помехозащищенности многоантенных систем военной радиосвязи. Установлено, что большинство теоретических достижений известных авторов направлены на разработку оптимальных методов пространственно-временного кодирования, частотной адаптации и создания (выбор) высокоэффективных сигнально-кодовых конструкций. В указанной статье использованы основные положения теории помехозащищенности, теории антенн, помехоустойчивого кодирования, сигнально-кодовых конструкций и др. По результатам проведенного исследования можно сказать, что многоантенные системы военной радиосвязи представляют собой многоуровневые пространственно-частотно-временные сигнально-кодовые конструкции. Принимая во внимание то, что средства радиоэлектронной борьбы повышают уровень своего технологического совершенства, поэтому от многоантенных средств военной радиосвязи требуется комплексное использование механизмов повышения помехозащищенности на каждом из уровней и необходимо существенное усовершенствование существующих моделей, методов и методик повышения помехозащищенности многоантенных систем военной радиосвязи.

Ключевые слова: *МІМО, системы радиосвязи, радиоэлектронное подавление, радиоресурс, предварительное кодирование, сигнально-кодовые конструкции, помехозащищенность.*