

Hryhorii Radzivilov

PhD in Technical Sciences, Associate Professor
Kruty Heroes Military Institute of Telecommunications and Information Technology
01011, 45/1 Knyaziv Ostrozkykh Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-6047-1897>

Dmytro Pavliuk*

Adjunct
Kruty Heroes Military Institute of Telecommunications and Information Technology
01011, 45/1 Knyaziv Ostrozkykh Str., Kyiv, Ukraine
<https://orcid.org/0000-0001-8461-3899>

Mathematical model of the functioning of a mobile radio communication system built on software-defined means

Abstract. The purpose of the study was to develop a generalised mathematical model of the functioning of multi-antenna radio communication systems under the influence of random and intentional interference and to analytically describe the influence of interference-noise and non-stationary factors on the security and reliability of information transmission. The work used a matrix channel model, space-time block coding, orthonormal representation of signals in a common signal space and statistical modelling of noise and interference in the coordinates of the basis. The results of the study showed that under quasi-stationarity of the channel on the interval of block transmission and orthogonality of the space-time structure, an inverse channel operator was formed. Under such conditions, linear recovery of the transmitted symbol vector and coherent summation of the useful component were ensured with statistical independence of noise components at the decoder output. The desired signal, fluctuating noise, and intentional interference had a consistent coordinate structure in the same orthonormal signal space. As a result, the quality of each antenna channel was determined by the energy balance between the desired energy and the spectral parameters of noise and interference, which determined the distance of signal points from the regions of false decision. The constellation degradation was described by the composition of geometric transformations (rotation, scaling, quadrature deformation) and stochastic perturbations (phase jitter, interference, additive noise), and the parameters of these distortions were identified by the mathematical expectation, dispersion, and covariance of the coordinates of the received symbols. The temporal nonstationarity of the channel was determined by the Doppler shift and the correlation structure of the transmission coefficient, and the elliptical geometric scattering model related the delays of multipath components to the spatial configuration of the scatterers. The practical significance of the results lay in the possibility of using the proposed model for analysis and optimisation of multi-antenna radio systems on software-defined devices in conditions of noise, interference and non-stationary channel. Its application contributed to the justification of modulation and coding parameters, as well as to increasing the reliability and interference immunity of radio communications

Keywords: space-time coding; additive noise; intentional interference; MIMO; software-defined radio; Doppler effect

INTRODUCTION

Mathematical modelling of a radio channel in multi-antenna communication systems occupies a key place in modern radio engineering and telecommunications, since it is aimed not so much at describing individual implementations

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*Corresponding author



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of the signal as at establishing the structural properties of the channel, its statistical stability, sensitivity to parameters, correctness of channel state estimation and prediction of reception errors in real electromagnetic conditions. Unlike simplified models focused on idealised conditions, the applied approach for mobile Software-Defined Radio (SDR) systems requires simultaneous consideration of spatial correlation between antennas, non-stationarity due to the movement of the transmitter and receiver, Doppler shift, multipath propagation, intersymbol interference, phase shifts and phase jitter, as well as intentional interference of various types, which directly determine noise immunity and Multiple Input Multiple Output (MIMO).

In modern research, more and more attention is paid to models and methods that combine a realistic description of spatially correlated MIMO channels with mechanisms for channel estimation, interference detection, and decision support for software-defined radio systems. In particular, the work of H. Khudov *et al.* (2023) showed the practical value of SDR receivers for the tasks of determining the coordinates of low-visibility aerial objects. According to the conclusions, the accuracy of signal processing in such systems significantly depends on an adequate description of the radio channel and its coordination with signal processing algorithms under conditions of signal degradation. In the next work, H. Khudov *et al.* (2021) proposed a method for determining the coordinates of aerial objects using Automatic Dependent Surveillance-Broadcast (ADS-B) receivers. Such hybrid surveillance systems increase the requirements for mathematical models of the radio channel, which must correctly take into account the influence of noise, interference, and uncertainties in the signal propagation environment. The influence of the interference environment on the efficiency of signal processing has also been confirmed by experimental studies of radar systems. V.P. Riabukha *et al.* (2022) compared adaptive and non-adaptive Moving Target Indication (MTI) systems in pulsed radar stations of various applications and ranges, showing the dependence of signal processing efficiency on the characteristics of the interference and channel environment.

Similar problems arise in modern communication systems with massive MIMO. In particular, the tasks of detecting intentional jamming and channel estimation have become significant precisely for spatially correlated configurations. P. Du *et al.* (2026) considered the joint formulation of jamming detection and channel estimation for beamspace massive MIMO, thereby fixing the need for models that include interference as an integral element of the channel state, rather than as an external “superstructure”. Similarly, J. Amadid *et al.* (2022) investigated the features of channel parameter estimation and spectral efficiency in cell-free massive MIMO with multichannel access points taking into account spatial correlation. The authors showed that the channel correlation structure can limit the gain from multi-antenna, so it must be explicitly taken into account in the mathematical model.

The universality of the spatial correlation problem is also confirmed by studies in other multichannel communication technologies. For example, L. Zhao *et al.* (2024) demonstrated the criticality of correlation for visible light massive MIMO systems with “antenna” selection based on the Pearson coefficient. Further development of resource management methods in massive MIMO for spatially correlated channels is reflected in the study of A. de la Fuente *et al.* (2022), where user subgrouping and power control for multicast are directly related to the channel correlation structure and its impact on the coherence of spatial multiplexing.

A separate line of modern work is formed by approaches using Reconfigurable Intelligent Surfaces (RIS), in which the channel model must take into account not only propagation statistics, but also controlled reflection as an element of the system architecture. In particular, E. Shi *et al.* (2022) analysed cell-free massive MIMO systems with RIS support in spatially correlated channels, showing that correlation determines both the efficiency of signal matching and the limits of gain from additional reflective degrees of freedom. In the work of Z. Sui *et al.* (2025), RIS-assisted cell-free massive MIMO with modulation of reflection patterns is considered, where the controlled reflective contour actually changes the structure of the effective channel and requires models that can correctly describe the “switching” of reflective configurations in space and time. Further, A. Papazafeiropoulos *et al.* (2024) investigated the achievable speed in massive MIMO Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface (STAR-RIS) for spatially correlated channels, emphasising that the correctness of the throughput prediction depends on the consistent consideration of correlation and parameters of the guided wave transmission/reflection.

Despite the presence of a significant number of studies devoted to the modelling of MIMO systems, in the modern scientific literature there is a need to develop a generalised mathematical model capable of simultaneously taking into account spatial correlation, transmitter and receiver motion, Doppler non-stationarity, noise effects, intentional interference and other signal degradation factors with moderate computational complexity. Existing approaches are mainly focused on individual aspects of channel operation and do not provide a holistic description of the interaction of destabilising factors within a single analytical scheme. This necessitates the development of a model that would allow for a more adequate description of the operating conditions of multi-antenna radio communication systems and create a basis for further analysis of the interference immunity and reliability.

The purpose of the study was to develop a consistent analytical scheme for the operation of multi-antenna radio communication systems under the influence of random and intentional interference, as well as to establish the influence of interference-noise and non-stationary factors on the security and reliability of information transmission. To achieve the goal of the study, the following tasks were set: to form a

generalised model of the channel state of a multi-antenna radio communication system taking into account spatial correlation, transmitter and receiver motion, and Doppler non-stationarity; to formalise a model of interference-noise influence, which includes additive white Gaussian noise, intentional interference, intersymbol interference, phase distortions, and other signal degradation factors.

MATERIALS AND METHODS

The study was of a theoretical-analytical nature and was based on analytical-statistical modelling of multi-antenna radio communication systems. The work used matrix relations for the MIMO channel, stochastic noise and interference models, statistical fading models (Rayleigh, Rice, Nakagami, Rice-Nakagami), as well as parameterised models of non-stationary multipath propagation, suitable for consistent consideration of the motion of the transmitter and receiver and changes in the correlation structure of the channel in time.

The basic relationship between the transmitted and received signals was given by the matrix model of the MIMO channel in the form:

$$X(t) = H(t)A(t) + n(t) + j(t), \quad (1)$$

where $A(t)$ – the vector (or matrix) of transmitted complex symbols at time t ; $X(t)$ – the vector (or matrix) of received complex symbols; $H(t)$ – the channel matrix (complex matrix of transmission coefficients); $n(t)$ – the additive noise (in particular, the thermal noise of the receiver); $j(t)$ – the intentional interference; t – the time.

The matrix of the multipath channel was given in the form of formula:

$$H(t) = \begin{bmatrix} h_{11}(t) & h_{12}(t) & \dots & h_{1J}(t) \\ h_{21}(t) & h_{22}(t) & \dots & h_{2J}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{I1}(t) & h_{I2}(t) & \dots & h_{IJ}(t) \end{bmatrix}, \quad (2)$$

where $h_{ij}(t)$ – the complex transmission coefficient between the i -th transmitting antenna and the j -th receiving antenna; I – the number of transmitting antennas; J – the number of receiving antennas. The random nature of the amplitude-phase relations in $h_{ij}(t)$ was interpreted through typical scenarios of the absence or presence of a pronounced direct component corresponding to a Rayleigh or Rician channel.

For a consistent description of signals in a multichannel structure, the representation of each of the v -signals as a projection onto an orthonormal basis of functions on the time interval T was used:

$$\begin{aligned} x_{Lm}(t) &= \sum_{n=1}^L x_{Lmn} \omega_{Ln}(t) \dots, \\ x_{vm}(t) &= \sum_{n=1}^L x_{vmn} \omega_{vn}(t), \end{aligned} \quad (3)$$

where m – the signal (symbol) index; L – the number of basic functions; v – the number of channels (antenna branches); $\omega_{Ln}(t)$ – the orthonormal basis functions; x_{Lmn} – the coefficients of the orthonormal decomposition (projection).

This representation corresponded to the standard procedure for transitioning from a continuous signal to complex symbols after matched filtering and discretisation. In this case, the elements of the vectors $A(t)$ and $X(t)$ in model (1) were interpreted as the coefficients of the orthonormal decomposition of the signal.

The decomposition coefficients were defined as formula:

$$\begin{aligned} x_{Lmn} &= \int_0^T x_{Lm}(t) \omega_{Ln}(t) dt, \dots, \\ x_{vmn} &= \int_0^T x_{vm}(t) \omega_{vn}(t) dt, \end{aligned} \quad (4)$$

where T – the duration of the transmission interval of an elementary unit of information.

The energy limit for the L -th channel was given by the relation:

$$\int_0^T x_{Lm}^2(t) dt = E_L, L = 1, \bar{v}, \quad (5)$$

where E_L – the signal energy in the L -th channel (antenna branch) for the interval T .

The stochastic noise component was modelled as fluctuation noise in the basis representation:

$$n_L(t) = \sum_{n=1}^N n_{Ln} \omega_{Ln}(t), \dots, n_v(t) = \sum_{n=1}^N n_{vn} \omega_{vn}(t), \quad (6)$$

where n_{Ln} – random noise coefficients; N – number of basis components taken into account; v – number of channels. The coefficients n_{Ln} were assumed to be Gaussian with zero mean and variance $G_{L0}/2$, and the probability densities were given as formulas:

$$w_L(n_{Ln}) = \xi_L \left(0, \frac{G_{L0}}{2}\right) = \frac{1}{\sqrt{\pi G_{L0}}} \exp\left(-\frac{(n_{Ln})^2}{G_{L0}}\right), \quad (7)$$

$$w_v(n_{vn}) = \xi_v \left(0, \frac{G_{v0}}{2}\right) = \frac{1}{\sqrt{\pi G_{v0}}} \exp\left(-\frac{(n_{vn})^2}{G_{v0}}\right), \quad (8)$$

where G_{L0} – the parameter characterising the spectral energy of noise in the L -th channel.

Intentional interference was uniformly modelled as additive white Gaussian noise (AWGN) in the basis representation:

$$j_L(t) = \sum_{n=1}^L j_{Ln} \omega_{Ln}(t), \dots, j_v(t) = \sum_{n=1}^L j_{vn} \omega_{vn}(t), \quad (9)$$

where j_{Ln} – independent random noise coefficients with zero mean; the variances were equal to $G_{Lz}/2$. The corresponding probability densities were represented via formulas:

$$w_L(j_{Ln}) = \eta_L \left(0, \frac{G_{Lz}}{2}\right) = \frac{1}{\sqrt{\pi G_{Lz}}} \exp\left(-\frac{j_{Ln}^2}{G_{Lz}}\right), \quad (10)$$

$$w_v(j_{vn}) = \eta_v \left(0, \frac{G_{vz}}{2}\right) = \frac{1}{\sqrt{\pi G_{vz}}} \exp\left(-\frac{j_{vn}^2}{G_{vz}}\right), \quad (11)$$

where G_{Lz} – a parameter that characterised the spectral energy of intentional interference in the L -th channel.

The integral energy characteristic of the interference was given as formula:

$$\int_0^T J_L^2(t) dt = G_{Lz}, \quad (12)$$

where $J_L(t)$ – the implementation of the interference signal in the L -th channel.

The reception quality in each L -th channel was determined by the signal-to-noise ratio (SNR):

$$SNR_L = \frac{E_L}{G_{L0}} = \frac{P_L}{P_{L0}}, \quad (13)$$

where E_L – energy of the useful signal; G_{L0} – spectral energy of noise; P_L – effective radiated power in the L -th channel; P_{L0} – noise power in the L -th channel.

The signal-to-noise ratio SIR at the demodulator output was given as formula:

$$SIR_L = \frac{P_L}{P_{Lz}} = \frac{P_L}{G_{Lz}}, \quad (14)$$

where P_{Lz} – the power of intentional interference in the L -th channel; G_{Lz} – the parameter of the spectral energy of the interference (in the accepted definition of the comparison scale).

Multipath propagation was described by a discrete-path model in the form formula:

$$u_x(t) = \sum_{l=1}^{\Xi} C_{(l,\partial,r)} \Psi_{(r,c,l)} u(t - \tau_l) + n(t), \quad 0 < t < +\infty, \quad (15)$$

where $u_x(t)$ – the signal at the receiver input after passing through the channel; Ξ – the number of propagation paths; l – the path index; τ_l – the delay of the l -th path; $u(t - \tau_l)$ – a time-shifted copy of the transmitted signal; $C_{(l,\partial,r)}$ – the complex coefficient (amplitude and phase) of the signal-code structure for the l -th path in the ∂ -th symbol of the r -th frame; $\Psi_{(r,c,l)}$ – the generalised component of the channel model that integrated destabilising factors (in particular, correlation, non-stationary and interference); $n(t)$ – additive noise; t – time. The research area covered the time axis $t \in (0, +\infty)$ and space of complex channel coefficients and signals in each antenna branch, as well as the procedures for transitioning from channel parameters to reception error estimates for phase-shift keying M (FM-M), quadrature amplitude modulation M (QAM-M), and hierarchical quadrature amplitude modulation M (IQAM-M) under fading and intentional interference conditions.

The methodological logic of the study was based on a combination of matrix modelling of the MIMO channel with independent modelling of antenna branches and subsequent aggregation into complex indicators of reception quality, as well as on statistical identification of distortion parameters by momentary characteristics of received symbols. Procedurally, the model was built as a sequence of channel symbol transformations in each channel, with the separation of deterministic geometric transformations of the constellation and random processes that determined signal degradation.

At the first stage, the reception process was formalised as a superposition of the useful signal and noise-interference components in the form:

$$\hat{z}(t) = z(t) + n(t), \quad (16)$$

where $\hat{z}(t)$ – the observed input signal of the receiver; $z(t)$ – the useful component after passing through the channel; $n(t)$ – additive noise; t – time.

The transition from a “pure” channel symbol to an observed one was described by adding interference in the symbol and the channel:

$$\hat{C}_{(\partial,l)} = C_{(\partial,l)} + n_{(\partial,l)}, \quad (17)$$

where $C_{(\partial,l)}$ – complex channel symbol for symbol in the l -th channel; $\hat{C}_{(\partial,l)}$ – observed channel symbol; $n_{(\partial,l)}$ – disturbance (a combination of noise, interference and/or clutter) in the corresponding symbol and channel; ∂ – symbol index; l – channel index (antenna branch).

The channel symbol was given as a matrix of real and imaginary parts:

$$c_{(\partial,l)} = \begin{bmatrix} \Re\{C_{(\partial,l)}\} \\ \Im\{C_{(\partial,l)}\} \end{bmatrix}, \quad \hat{c}_{(\partial,l)} = \begin{bmatrix} \Re\{\hat{C}_{(\partial,l)}\} \\ \Im\{\hat{C}_{(\partial,l)}\} \end{bmatrix}, \quad (18)$$

where $\Re\{\cdot\}$ and $\Im\{\cdot\}$ – the real and imaginary parts of a complex quantity. This allowed describing the set of distortions as a composition of controlled constellation transformations and random processes.

The phase shift was formalised by rotating the constellation by an angle φ :

$$\hat{c}_{(\partial,l)} = R(\varphi) c_{(\partial,l)}, \quad R(\varphi) = \begin{bmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{bmatrix}. \quad (19)$$

The amplitude mismatch between the real and imaginary branches was given by different gain coefficients:

$$\hat{c}_{(\partial,l)} = G c_{(\partial,l)}, \quad (20)$$

$$G = \begin{bmatrix} k_I & 0 \\ 0 & k_Q \end{bmatrix}, \quad (21)$$

where k_I and k_Q – amplification factors for I - and Q -components.

The quadrature error was described by the mutual rotation of the quadrature components:

$$\hat{c}_{(\partial,l)} = R(\theta_{IQ}) c_{(\partial,l)}, \quad (22)$$

where θ_{IQ} – quadrature error parameter (angle of mutual displacement of axes I/Q).

The influence of intersymbol interference and additive noise was specified through the decomposition of interference into components:

$$n_{(\partial,l)} = n_{(\partial,l)}^{(ISI)} + n_{(\partial,l)}^{(AWGN)}, \quad (23)$$

where – component caused by the overlap of neighbouring symbols (intersymbol interference); – additive component with uniform spectral distribution.

Phase jitter was considered as a dynamic random process of random rotation of the constellation, for which the angle θ_i obeyed the normal law:

$$\theta_i \sim N(0, \sigma_i^2), \quad (24)$$

where σ_i^2 – phase jitter dispersion; $N(\cdot)$ – normal distribution.

Generalisation of transformations formula (20)-(24) led to an integral representation of the observed symbol as a composition of deterministic matrix transformations and random perturbations:

$$\hat{c}_{(\partial, l)} = T_{(\partial, l)} c_{(\partial, l)} + n_{(\partial, l)}, T_{(\partial, l)} = R(\varphi) G R(\theta_{IQ}) R(\theta_i), \quad (25)$$

where $T_{(\partial, l)}$ – the effective constellation transformation matrix in the (∂, l) -position; $R(\theta_i)$ – the random rotation matrix induced by phase jitter.

Next, a statistical procedure for estimating model parameters based on the moments of received symbols was applied. Assuming small phase fluctuations (or small angular parameters), a linearised approximation of the mathematical expectations of the components of the observed symbol was performed:

$$\begin{aligned} \mathbb{E} \left[\Re \left\{ \hat{C}_{(\partial, l)} \right\} \right] &= \mathbb{E} \left[a_1 \Re \left\{ C_{(\partial, l)} \right\} - a_2 \Im \left\{ C_{(\partial, l)} \right\} \right], \\ \mathbb{E} \left[\Im \left\{ \hat{C}_{(\partial, l)} \right\} \right] &= \mathbb{E} \left[a_3 \Re \left\{ C_{(\partial, l)} \right\} - a_4 \Im \left\{ C_{(\partial, l)} \right\} \right], \end{aligned} \quad (26)$$

where a_1, a_2, a_3, a_4 – generalised coefficients that accumulated the influence of amplification, mutual transformation of quadratures and components of the interference circuit; $\mathbb{E}[\cdot]$ – mathematical expectation operator.

The phase jitter variance was estimated through the covariance of the real and imaginary parts of the observed symbol (27):

$$\text{Cov} \left(\Re \left\{ \hat{C}_{(\partial, l)} \right\}, \Im \left\{ \hat{C}_{(\partial, l)} \right\} \right) = -\kappa \sigma_i^2 \Phi \left(C_{(\partial, l)} \right), \quad (27)$$

where $\text{Cov}(\cdot, \cdot)$ – covariance; κ – generalised scale constant (depended on the transformation structure $T_{(\partial, l)}$; $\Phi(C_{(\partial, l)})$ – a function that depended on the coordinates of the “pure” symbol and the parameters of static transformations.

The intensity of the interference component was characterised by the index A , which was determined through a combination of dispersions and high-order central moments (28):

$$A = F \left(\text{Var} \left[\Re \left\{ \hat{C}_{(\partial, l)} \right\} \right], m_4 \left(\Re \left\{ \hat{C}_{(\partial, l)} \right\} \right) \right), \quad (28)$$

where $\text{Var}[\cdot]$ – dispersion; $m_4(\cdot)$ – central moment of the fourth order; $F(\cdot)$ – the interference intensity function defined in the model.

After that, the characteristics of intentional interference and noise were related to the variances of the components of the received symbol (formula (29)):

$$\begin{aligned} \text{Var} \left[\Re \left\{ \hat{C}_{(\partial, l)} \right\} \right] &= G_R(\sigma_i^2, A) + \text{Var} \left[\Re \{ n_i \} \right], \\ \text{Var} \left[\Im \left\{ \hat{C}_{(\partial, l)} \right\} \right] &= G_I(\sigma_i^2, A) + \text{Var} \left[\Im \{ n_i \} \right], \end{aligned} \quad (29)$$

where $n_{(l)}$ – the additive noise-interference component in l -th channel; $G_R(\cdot)$ and $G_I(\cdot)$ – the model distribution

functions of the dispersion contribution of phase fluctuations and interference in the corresponding quadratures. Thus, the method provided separation of the contributions of phase fluctuations, interference and additive noise/interference by statistically observed quantities in each antenna branch.

At the second stage, correlation-frequency characteristics within the Jakes model were used to model nonstationarity and Doppler structure, where the autocorrelation function and spectral distribution over Doppler frequencies were given as:

$$R(\tau) = J_0(2\pi f_D \tau), P(f) = \frac{1}{\pi f_D \sqrt{1-(f/f_D)^2}}, |f| < f_D, \quad (30)$$

where $R(\tau)$ – autocorrelation function; $P(f)$ – spectral power density at Doppler frequencies; τ – time shift; f – Doppler frequency; f_D – maximum Doppler shift; $J_0(\cdot)$ – zero-order Bessel function.

For complex urban scenarios, an elliptical approach with two scattering ellipses was used, in which the parameters of the outer and inner contours were determined by time delays and motion geometry. The formalisation of the delays was carried out by the relation:

$$\tau_m = \frac{D_m}{c}, \quad (31)$$

where τ_m – the largest signal delay (for the limiting propagation route); D_m – appropriate length of the route; c – the speed of propagation of an electromagnetic wave.

The conditions for the formation of the reflected component and the correct consideration of the geometry of the antenna placement were set by the criterion:

$$d \geq \frac{4h_t h_r}{\lambda}, \quad (32)$$

where d – the distance between the transmitter and the receiver; h_t and h_r – antenna heights; λ – wavelength.

The Doppler shift for motion along an arbitrary path was defined as formulas:

$$f_D = \frac{v}{\lambda} \cos \beta, \quad (33)$$

$$\Delta f(t) = \frac{v(t)}{\lambda} \cos \beta(t), \quad (34)$$

where v or $v(t)$ – the relative speed of movement; β or $\beta(t)$ – the angle between the velocity vector and the direction of wave arrival.

The generalised instantaneous transfer characteristic of the channel was formed in:

$$h(t) = \sum_{i=0}^N g_i \exp(j(2\pi \Delta f_i t + \theta_i + \phi_i)) u(t - t_i), \quad (35)$$

where $h(t)$ – complex transfer characteristic; N – number of propagation paths; g_i – weighting factor (energy ratio of the i -th path); Δf_i – Doppler shift for the i -th path; θ_i – phase shift; ϕ_i – arbitrary initial phase; $u(\cdot)$ – step function; t_i – delay of the i -th path; j – imaginary unit.

At the third stage, an analytical assessment of noise immunity was carried out through the bit error rate (BER) for phase shift keying M -arn (FM- M), quadrature amplitude shift keying M -arn (QAM- M) and hierarchical quadrature amplitude shift keying M -arn (IQAM- M) in channels with fading and intentional interference. For FM- M in frequency-selective channels with additive noise and coherent reception, the bit error probabilities were given by the relation:

$$P_{(b,i)} = F_i(SNR, M, i), \quad i = 1, \dots, B. \quad (36)$$

where $P_{(b,i)}$ – the probability of a bit i error; M – the constellation dimension; B – the number of bits in the block; $F_i(\cdot)$ – the function given by the analytical formulas of the model.

In this case, for the first two bits, separate partial cases of this dependence were used, while for bits with numbers, $i = 3, \dots, B$ a generalised notation was used, taking into account the bit position number.

The auxiliary functions and angular parameters included in $F_i(\cdot)$ were given as formulas:

$$T_z(\cdot) = T(\cdot), \quad (37)$$

$$\psi_m = P(M, m), \quad (38)$$

where $T(\cdot)$ and $P(\cdot)$ – analytical expressions were defined in the model that ensured correct consideration of constellation geometry and bit mapping.

The average error probability in a B -bit block was determined by averaging (formula (39)):

$$P_B = \frac{1}{B} \sum_{i=1}^B P_{b,i}, \quad (39)$$

For KAM- M and IKAM- M generalised relations were used, these relations took into account the parameters of the constellation, fading, and hierarchical structure: the basic form was given as:

$$P_{(b,1:2)} = G(SNR, M, \alpha, \lambda^2), \quad (40)$$

with auxiliary quantities:

$$g = G(M, \alpha, \cdot), \quad (41)$$

and the extension for all bits of the block:

$$P_{(b,i)} = G_i(SNR, M, \alpha, \lambda^2, i), \quad i = 3, \bar{B}, \quad (42)$$

after which the total error probability was aggregated as:

$$P_B = H\left(\{P_{b,i}\}_{i=1}^B\right), \quad (43)$$

and in exact form was written as formula:

$$P_B = H_{exact}(SNR, M, \alpha, \lambda^2). \quad (44)$$

In these relations α – the hierarchy parameter (for classical QAM $\alpha = 1$, for hierarchical – $\alpha > 1$); λ^2 – the

parameter characterising the ratio of regular and fluctuation components in Rician scenarios; $G(\cdot)$, $G_i(\cdot)$, $H(\cdot)$, $H_{exact}(\cdot)$ – analytical expressions of the model that take into account the minimum Euclidean distances and the priority of subflows.

The bit weight coefficients $\{\alpha_{2j-1}\}$, which parameterised the contribution of critical transitions in the constellation, were given as:

$$\alpha_{2j-1} = \alpha_{2j-1}(M), \quad (45)$$

where j – the coefficient index, and the specific values $\alpha_{2j-1}(M)$ – determined by the selected mapping of bits to the constellation and the adopted variant of analytical formalisation.

The final aggregation of the error for the multichannel structure was carried out by averaging over the L antenna channels in the form:

$$P_B^{(L)} = \frac{P_{B,1} + P_{B,2} + \dots + P_{B,L}}{L}, \quad (46)$$

where $P_B^{(L)}$ – the average bit error probability for the multichannel structure; $P_{(B,l)}$ – the average fraction of bits received with error in the l -th antenna branch, taking into account selective fading, Doppler non-stationarity, intersymbol interference, phase jitter, and intentional interference.

As a result, the applied methodological approach provided a formalised combination of a matrix description of the MIMO channel, stochastic modelling of noise and intentional interference, a non-stationary geometric description of the moving environment, and a statistical estimation of distortion parameters based on the momentary characteristics of received symbols, which created the basis for a consistent analytical estimation of the bit error rate in spatially correlated channels in line-of-sight (LoS) and non-line-of-sight (NLoS) modes with controllable computational complexity.

RESULTS

Structure of signal transmission in MIMO system and conditions for spatial symbol recovery

Analysis of the structure of signal transmission in a multi-antenna system was performed for the matrix model of the channel under conditions of multi-path signal propagation, when the interaction between the transmitting and receiving antennas is described by the channel operator given by the relations formulas (1), (2). In this formulation, the transmitted symbol vector was considered as an element of the signal space, which under the action of the channel operator is mapped into the vector of received signals. The structure of the channel matrix in this case determines the geometry of the interaction of the antenna branches and sets the nature of the spatial mixing of signals at the receiver.

It was established that if the conditions of quasi-stationarity of the channel during the transmission interval of a block pair of symbols and if the conditions of orthogonality of the space-time structure of the signal are met, the

channel operator acquires the property of reversibility. This means that the system formulas (1), (2) allows a fundamental linear transformation of the received signal, which allows recovering the transmitted symbol vector without loss of information. In the signal space, a mapping is formed for which the received vector is a scaled projection of the initial information vector. In other words, the action of the channel operator is reduced to a linear transformation that changes the scale and orientation of the signal in the antenna coordinate space, but does not violate the possibility of its recovery under the condition of linear independence of the columns of the channel matrix. Thus, signal decoding can be implemented through the corresponding linear transformation of the received signal, which actually performs the role of a space-time decoder.

The interpretation of this result is related to the geometric structure of signals in the multidimensional space of antenna channels. Orthogonal space-time coding forms a signal system in which individual information symbols are transmitted along mutually orthogonal directions of the

signal space. As a result, coherent summation of the useful signal components occurs on the receiving side, while the noise components remain statistically independent. This property leads to an increase in the effective signal-to-noise ratio and ensures the stability of the information recovery process even in the presence of random fluctuations in the channel parameters. Analysis of the obtained relations showed that the geometry of the channel matrix determines the structure of the signal space of the transmission system. If the columns of this matrix remain linearly independent, each information symbol corresponds to its own direction in the space of antenna channels, and the mutual influence of information flows remains limited. Under these conditions, the spatial modes of the signal retain the identifiability, and the decoding process is reduced to restoring the corresponding coordinates in the signal space. To generalise the obtained result, the parameters of the signal transmission model that determine the channel geometry can be presented in the form of a systematised set of characteristics given in Table 1.

Table 1. Logic diagram for obtaining spatial symbol recovery conditions in a MIMO system

| Analysis stage | Ratios used | Result obtained |
|--|-------------|--|
| Formalisation of the signal transmission model | (1) | A matrix relationship is established between the transmitted and received signals |
| Multipath channel structure | (2) | The geometry of the interaction of the transmitting and receiving antennas is determined |
| Space-time block coding | (3) | The condition for linear recovery of the vector of transmitted symbols is obtained |

Source: compiled by the authors

The key element of the signal transmission structure in a multi-antenna system is the coordination of the channel matrix model with the spatiotemporal organisation of signals. Relation (1) specifies the general operator form of signal transformation during passage through the channel and determines the linear nature of the interaction between the transmitted and received signals. At the same time, the structure of the channel matrix, described by relation (2), reflects the multipath nature of signal propagation and specifies the geometry of the signal space in which information is transmitted. Further analysis showed that the use of space-time block coding, described by relation (3), leads to the formation of a special block structure of the channel operator. This structure ensures linear independence of signal components and creates conditions for the correct recovery of the transmitted symbol vector on the receiving side. Thus, the system of formulas (1), (2) allows for the existence of a linear transformation, which allows decoding the signal by projecting the received vector onto the corresponding basis of the signal space.

The obtained result means that a set of spatially separated signal modes is formed in the antenna coordinate space. Each such mode corresponds to a separate information flow and is characterised by its own energy weight, which is determined by the coefficients of the channel matrix. In this case, the action of the channel leads to scaling

and rotation of the signal vector in the antenna coordinate space, but does not violate the structure of the spatial separation of the flows, provided that the linear independence of the columns of the channel matrix is preserved. Collectively, this means that space-time coding provides a geometric decomposition of the signal space into independent directions along which information is transmitted. As a result, coherent summation of the useful signal components occurs on the receiving side, while the noise components remain statistically independent. It is this property that determines the possibility of effective signal recovery even in the presence of random changes in the channel parameters. Thus, the established structure of the system formulas (1), (2) determines the fundamental geometry of signal transmission in a multi-antenna system. It forms the basis for further analysis of the impact of random factors of the propagation environment, noise and intentional interference on the stability of the radio communication system and on the accuracy of the recovery of transmitted information.

Signal energy structure and statistical model of noise and intentional interference in a multi-antenna system

The analysis of the energy structure of the signal was performed for a mathematical model of a multi-antenna transmission system, in which the signal realisations are

considered in the functional space of orthonormal basis functions. The conditions for such a representation are determined by the relations formulas (3)-(5), which specify the decomposition of the transmitted signals in the coordinates of the signal space and impose restrictions on the energy parameters of the transmission. The use of an orthonormal basis allows representing each signal of a multi-antenna system as a vector of coordinates in the L -dimensional channel space. The coefficients of the orthonormal decomposition of the signal determine the energy contribution of the corresponding basis functions to the formation of the transmitted signal realisation. Thus, the signal energy is distributed between the coordinates of the signal space, and the structure of this distribution determines the geometry of the signal constellation in the multidimensional channel space.

Further analysis showed that the fluctuation noise in each antenna channel can also be represented in the same functional basis. According to the formulas (6)-(8), the noise components are described by random decomposition coefficients, which have a Gaussian distribution with

zero mathematical expectation and given variances. This means that the noise effect manifests itself in the form of random fluctuations of the coordinates of the signal vector in the signal space. A similar structure was established for intentional interference. According to the formulas (9)-(12), interference signals can be represented by decomposition in the same orthonormal basis of functions. In this case, the difference between noise and interference is determined by the statistical characteristics of the decomposition coefficients, in particular the variances and spectral power densities.

The obtained result showed that the signal, fluctuation noise and intentional interference have a consistent coordinate structure in a single signal space of a multi-antenna system. In this interpretation, the information transmission process can be represented as a superposition of a deterministic signal component and random disturbances that cause random shifts of the signal vector relative to its ideal position in the signal space. A generalisation of the structure of the mathematical model of signal, noise, and interference in a multi-antenna system is given in Table 2.

Table 2. Structure of the energy model of signal, noise, and interference in a multi-antenna system

| System component | Mathematical representation | Basic parameters | Physical interpretation |
|--------------------------|--|--------------------|--|
| Useful signal | Orthonormal distribution of signals in the basis of functions formulas (3)-(5) | x_{Lmn}, E_L | Distribution of signal energy between coordinates of the L -dimensional signal space |
| Fluctuating noise | Statistical model of noise distribution formulas (6)-(8) | G_{L0} | Random fluctuations of the signal vector coordinates |
| Intentional interference | Noise signal model formulas (9)-(12) | G_{L3} | Energy disturbances caused by external interference |
| Reception quality | Signal-to-noise ratio and signal-to-interference formulas (13)-(14) | $(hL02), (PL/PL0)$ | Integral characteristic of transmission channel stability |

Source: compiled by the authors

The generalisation of the results presented in Table 2 shows that the useful signal $x_{Lm}(t)$, the fluctuation noise $n_L(t)$ and the intentional interference $j_L(t)$ have a consistent coordinate structure in the orthonormal signal space formed by the basis functions $\omega_{Ln}(t)$. In this space, each signal realisation is described by a set of orthonormal decomposition coefficients x_{Lmn} , which determine the signal projections onto the corresponding basis functions and characterise the energy contribution of each coordinate to the signal formation.

Similarly, the noise and interference components are given by the coefficients n_{Ln} and j_{Ln} , the statistical properties of which are given by the dispersions $G_{L0}/2$ and $G_{L3}/2$, respectively. Such a structure means that the action of the fluctuation noise and intentional interference manifested itself in the form of random perturbations of the signal vector coordinates in the multidimensional channel space. In this representation, the transmitted signal in the L -th channel was characterised by the energy parameter E_L , which was determined by the transmission energy limitation condition (6), while the noise and interference intensity were described by the spectral parameters G_{L0} and G_{L3} .

Thus, the information transmission process in a multi-antenna system was interpreted as the energy interaction of the signal vector coordinates $\{x_{Lmn}\}$ with random perturbations $\{n_{Ln}\}$ and $\{j_{Ln}\}$ arising in the signal propagation medium. In the geometric interpretation, this corresponded to a random displacement of signal points in the L -dimensional signal space relative to the ideal positions.

The efficiency of information transmission in each channel of the multi-antenna system was determined by the energy balance between the useful signal power P_L and the noise powers P_{L0} and interference P_{L3} . This balance was formalised by integral indicators of reception quality – the signal/noise ratios $SNR_L = \frac{E_L}{G_{L0}} = \frac{P_L}{P_{L0}}$ and signal/interference $SIR_L = P_L/P_{L3} = P_L/G_{L3}$, determined by the formulas (14)-(15). The value SNR_L and the corresponding interference parameters determined the level of noise immunity of each antenna channel and characterised the degree of remoteness of the signal vector from the area of false reception. Thus, the obtained result showed that the consistent representation of the signal, noise and intentional interference in the common orthonormal signal space allows describing the process of functioning of a

multi-antenna system through the energy characteristics of the signal vector coordinates. It is these characteristics that determine the potential noise immunity of the system and create a mathematical basis for further analytical study of the probability of a bit error in the transmission channels.

Analysis of signal distortions and statistical evaluation of constellation degradation parameters

Analysis of the signal distortion structure was performed for the reception model, in which the observed signal was formed as a superposition of the useful component and noise-interference disturbances according to the relation (16). At the level of an individual channel symbol, this transition from the “pure” to the observed state was specified by the relation (17), where the disturbances included noise, interference and intentional interference within the corresponding antenna branch. It was this representation that created the initial analytical basis for the further description of the degradation of the signal constellation as a result of geometric transformations and stochastic perturbations of the signal vector coordinates. The initial conditions for such a description were given by the relations (18)-(20), which established the connection between the ideal channel symbol $C_{(\partial,l)}$ and the observed symbol $C_{(\partial,l)}$. In this representation, each transmitted symbol was characterised by a complex quantity.

$$C_{(\partial,l)} = \Re\{C_{(\partial,l)}\} + i \Im\{C_{(\partial,l)}\}, \tag{47}$$

where ∂ – symbol index in the signal block, l – antenna channel number. Using the formulae (18)-(20), the received signal was presented in the form of a vector model:

$$\hat{c}_{(\partial,l)} = \begin{bmatrix} \Re\{\hat{C}_{(\partial,l)}\} \\ \Im\{\hat{C}_{(\partial,l)}\} \end{bmatrix}, \tag{48}$$

which was associated with the ideal symbol vector:

$$c_{(\partial,l)} = \begin{bmatrix} \Re\{C_{(\partial,l)}\} \\ \Im\{C_{(\partial,l)}\} \end{bmatrix}. \tag{49}$$

This form of description allowed interpreting the signal passage through the channel as a transformation of the coordinates of the signal vector in a two-dimensional signal space. Further analysis showed that the deformations of the signal constellation could be interpreted as a composition of geometric transformations of the coordinates of the signal vector. According to the relation (19), the phase shift of the channel led to a rotation of the signal constellation by an angle φ , which changed the orientation of the coordinates (49) in the signal space. According to the relation (20), the amplitude mismatch between the quadrature channels was described by different gain coefficients for the I - and Q -components, which caused the scaling of the coordinates of the signal vector along the corresponding axes. An additional geometric transformation arose due to the quadrature error of the receiving path, which was described by the relation (22) and led to a mutual rotation of the quadrature components by an angle θ_{IQ} . Taking into account interference components and additive noise led to a generalised description of signal vector perturbations through the decomposition of interference into components according to (23). For a visual representation of the described signal vector transformations, it is advisable to use a graphical visualisation of the influence on the signal constellation configuration in the I - Q plane (Fig. 1).

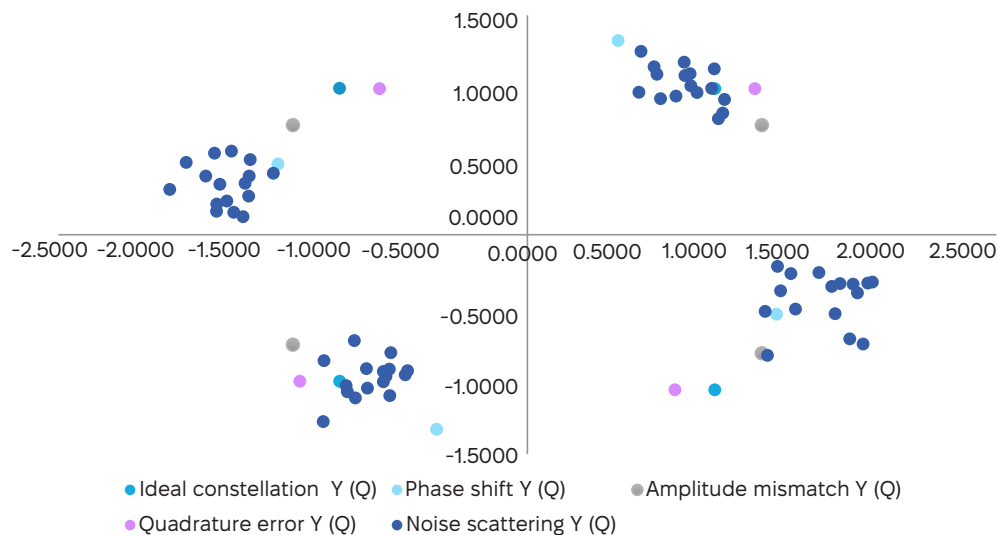


Figure 1. Geometric transformations of the signal constellation in the I - Q plane

Source: compiled by the authors

As shown in Figure 1, the phase shift, amplitude mismatch, and quadrature error change the spatial configuration

of the signal constellation, while noise and interference perturbations additionally cause a random scattering of

signal points relative to the ideal positions. This creates a basis for further statistical estimation of the degradation parameters from the characteristics of the received symbols. According to the relation (23), the interference-noise component in the symbol and channel was given by a vector.

$$n_{(\partial,l)} = \begin{bmatrix} \Re\{n_{(\partial,l)}\} \\ \Im\{n_{(\partial,l)}\} \end{bmatrix}, \quad (50)$$

which characterised the overlap of adjacent symbols (ISI) and additive oscillations (AWGN) and, in a parameterised description, could be characterised by the intensity A and the phase parameter ϕ (in the accepted definition of the model). An additional factor of signal constellation degradation was phase jitter, which was considered as a random process of rotation of signal points with a phase deviation $\theta_i \sim N(0, \sigma_i^2)$ according to (24), and its inclusion in the matrix contour of transformations was formalised by the relation (25). The generalisation of these transformations led to an integral representation of the observed symbol as a composition of geometric and stochastic changes in the coordinates of the signal vector, which was given by the relation (25), where the effective matrix $T_{(a,b)}$ accumulated static transformations (rotation, mismatched gain, quadrature error) and random rotation induced by phase jitter.

In this representation, the degradation of the signal constellation was determined by the gain parameters k_l and k_o , the angular parameters φ , θ_{IQ} , the dispersion of phase fluctuations σ_i^2 and the interference intensity A .

A further mathematical result was obtained by statistical analysis of the received symbols $\hat{C}_{(a,b)}$. Using the moment characteristics of the signal, in particular the mathematical expectation $E[\cdot]$, the dispersion $Var[\cdot]$ and the covariance $Cov[\cdot]$, the estimation of the degradation parameters of the signal constellation was performed. According to relations (26)-(27), the phase jitter was estimated through the covariance between the real and imaginary components of the received symbol:

$$Cov \left(\Re\{\hat{C}_{(\partial,l)}\}, \Im\{\hat{C}_{(\partial,l)}\} \right), \quad (51)$$

which allowed identifying σ_i^2 within the accepted parameterisation $\kappa\Phi(C_{(a,b)})$ in formula (27). The intensity of the interference component was determined through the statistical characteristics of the deviation of the signal vector coordinates from the average values, namely through the combination of the dispersion and the fourth-order central moment $m_4(\cdot)$ according to formula (28). Further analysis of the dispersions of the real and imaginary components of the received symbol provided an assessment of the contributions of noise and intentional interference according to (29), where the model functions $G_R(\cdot)$ and $G_I(\cdot)$ separated the dispersion contributions of phase fluctuations and interference in quadratures, and the residual term referred to the additive noise-interference component n_l . To generalise the obtained results, the structure of the signal constellation distortions and the corresponding parameters of the statistical assessment are given in Table 3.

Table 3. Structure of signal constellation distortions and parameters of the statistical evaluation

| Distortion type | Model parameter | Mathematical description | Statistical evaluation method |
|--------------------|-----------------|---|---|
| Phase shift | φ | Signal constellation rotation (19) | Estimation through coordinate covariance |
| Amplitude mismatch | kE | Coordinate scaling (20-21) | Variance analysis of coordinates |
| Quadrature error | θ_{comp} | Matrix rotation (22) | Evaluation by moment characteristics |
| Phase jitter | σ_i^2 | Random rotation of points (24-25) | Covariance of real and imaginary parts (27) |
| Interference | A | Breakdown of obstacles into components (23) | Fourth-order central moments (28) |
| Additive noise | $D[n_l]$ | Noise component variance (29) | Variance estimates (29) |

Source: compiled by the authors

As can be seen from Table 3, the signal constellation distortions in a multi-antenna system have a clearly structured nature and can be represented as a set of deterministic and stochastic transformations of the signal vector coordinates in the complex signal space. The deterministic distortion components are related to the channel and receiver path parameters and become manifested in the form of signal constellation rotation, coordinate scaling, and quadrature deformation, which are described by the parameters φ , kE and θ_{comp} , respectively. The stochastic signal degradation components are formed by random processes in the transmission channel and include phase jitter, interference, and additive noise, the statistical characteristics of which are

determined by the parameters σ_i^2 , A and $D[n_l]$. The generalisation of the obtained results shows that the signal constellation degradation can be formalised through a system of statistical estimates based on the momentary characteristics of the received symbols. The use of covariance and dispersion analysis of signal vector coordinates allows separating the contribution of different types of disturbances to the overall structure of signal distortions. This approach provides the ability to identify the parameters of phase fluctuations, interference components and noise components of the channel, which creates the basis for further analysis of the probability of bit errors and assessment of the noise immunity of a multi-antenna radio communication system.

Dynamic channel structure and the influence of non-stationarity of signal propagation

The dynamic structure of a multi-antenna communication channel is investigated taking into account the non-stationarity of propagation due to multipath and relative motion of the transmitter and receiver, and the time structure of the multipath signal is formalised by the discrete-path model (15). Under these conditions, the channel transmission coefficient h_{ij} is a random time-dependent quantity, and fluctuations in its amplitude and phase determine the statistical variability of the received signal. The initial conditions of the description are given by a class of fading models in which the amplitude statistics h_{ij} are consistent with the absence/presence of a dominant regular component: in the case of a predominance of scattered components, the Rayleigh mode is used, in the presence of a direct beam, the Rice mode, and for a generalised description of different degrees of “regularity-fluctuation” the Nakagami and Rice-Nakagami models are used.

The mathematical result of this step is the introduction of parameters that quantitatively record the contribution of the regular and random components to the average channel power: the ratio between $h_0^2(st)$ and $h_0^2(RI)$, as well as the parameter ζ , which specifies the ratio of the

average powers, allow formalising the boundary transitions between the Rayleigh ($\zeta \rightarrow 0$) and static ($\zeta \rightarrow \infty$) regimes and thereby specifying a single fading classification scale within the framework of a consistent statistical model (transition formulas are given in the methodology). The next step of the analysis is aimed at the temporal variability of the channel. Within the Jakes model, the correlation structure of the transmission coefficient is determined by the autocorrelation function and the corresponding Doppler spectrum, and the key parameter is the maximum Doppler shift f_D , proportional to the relative velocity of the receiver; the compact form of the autocorrelation record is given by relation (41). Interpretatively, this means that the “update rate” of the channel is given by the geometry of the multi-beam field and the kinematics of the subscriber motion: with increasing v , f_D increases, the decorrelation $h_{ij}(t)$ in time accelerates, and the effect of interference of waves arriving by different paths with different Doppler shifts is enhanced. The generalisation of the spatio-temporal structure of the channel is carried out in the geometric elliptical scattering model (Fig. 2), where the transmitter and receiver are considered as foci of a system of ellipses, and the scatterers are considered as points evenly distributed within the outer and inner ellipses.

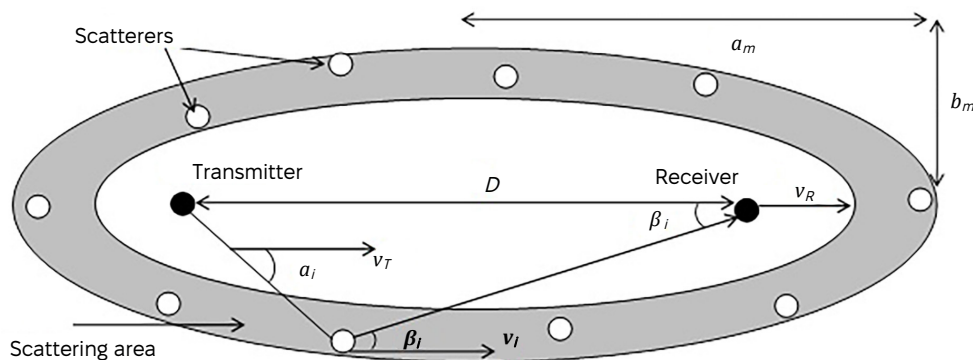


Figure 2. Taking into account the dynamic characteristics of the transmitter and receiver in the model in a multi-antenna system

Note: D – the length of the signal propagation path; β_i – the angle of reflection from the outer surface of the ellipse; α_i – the angle of reflection from the scatterer of the inner surface of the ellipse; v_T – the rate of change of the transmitter position; v_R – the rate of change of the receiver position; a_m – the semi-major axis of the outer ellipse; b_m – the semi-minor axis of the outer ellipse

Source: compiled by the authors

The model presented in Figure 2 is built on the basis of the elliptical approach to modelling a multibeam radio signal propagation channel. This approach is used to describe the operation of the channel in the uplink direction – from the mobile subscriber to the base station in microcell conditions, when the base station is located at a relatively low altitude and a line of sight (LoS) is possible between the transmitter and the receiver. Similar conditions are typical for urban wireless networks and tactical radio communication systems. Within the model, the transmitter, and receiver are considered as foci of a system of ellipses in which the signal scattering objects are located. It is assumed that

the scatterers are evenly distributed within two ellipses: external and internal. The parameters of the external ellipse a_m and b_m are determined based on the maximum signal propagation delay according to the relation (42), while the internal ellipse is given by the geometric characteristics of the mobile subscriber’s movement. The model assumes a minimum signal delay in the presence of direct visibility between the transmitter and receiver. An increase in the signal delay corresponds to the appearance of additional multipath components that arise as a result of reflection or diffraction of the signal on environmental objects. Thus, the elliptical geometric model allows linking the spatial

structure of the signal propagation environment with the time characteristics of the communication channel.

Analytical assessment of interference immunity and bit error probability in a multi-antenna system

As a result of the analysis, the sequence of formation of indicators of reliability of information transmission in a multi-antenna system was determined: the signal/noise and signal/interference ratios, given by formulas (13), (14), determined the effective energy parameter of the channel h_0^2 ; this parameter was included in the bit-dependent estimates of the error probability $P_{(b,i)}$, obtained in formulas (31)-(35) and (36)-(40); further generalisation of single-channel estimates led to the system error indicator $P_B^{(L)}$, determined by averaging over antenna channels according to (47). It is shown that the quality of the L -th antenna channel was formalised through the energy parameters E_L , G_{L0} and G_{L3} , introduced in the energy-statistical description of the signal, fluctuation noise and intentional interference in the common orthonormal signal space formulas (3)-(12). In particular, E_L characterised the energy of the useful component in the L -th branch, while G_{L0} and G_{L3} specified the intensity of the noise and interference components through the spectral (dispersion) parameters in the same coordinates. Based on these quantities, integral metrics of reception quality were obtained by the formulas (13-14), which recorded the effective scale of signal degradation in each channel and subsequently directly determined the parameterisation of analytical error estimates.

The modulation structure was given by the signal constellation parameters $M = 2^B$, where B denoted the

number of information bits per symbol, which allowed moving from the constellation geometry to the bit error probabilities. It was the dependence on B that was used in the bit-dependent estimates $P_{(b,i)}$ for the phase manipulation of the FM- M type in the relations formulas (36)-(39), where the expressions for the first bits of the symbol were given separately and the estimates for all bit positions were generalised. For the quadrature amplitude manipulation KAM- M and hierarchical quadrature amplitude manipulation, a similar transition from the constellation geometry to the bit error was implemented in the relations formulas (40)-(45), which allowed taking into account the configuration of the signal constellation and the differences between individual classes of erroneous transitions. For hierarchical quadrature amplitude manipulation, the parameter α was additionally taken into account, which changed the geometry of the constellation and affected the distribution of error probabilities between bit positions. As a result, it was found that varying this parameter provides differentiated reliability of bit streams by changing the decision-making boundaries in the signal space. After determining the single-channel estimates $P_{(B,i)}$, the analytical results were reduced to the integral characteristic of MIMO through averaging over antenna channels according to (46), which provided a transition from the quality of a separate branch to a generalised assessment of the reliability of data transmission in the system. To clearly display the sequence of transition from channel energy parameters and modulation structure to integral assessment of bit error, it is advisable to use the block diagram of the analytical BER model (Fig. 3).

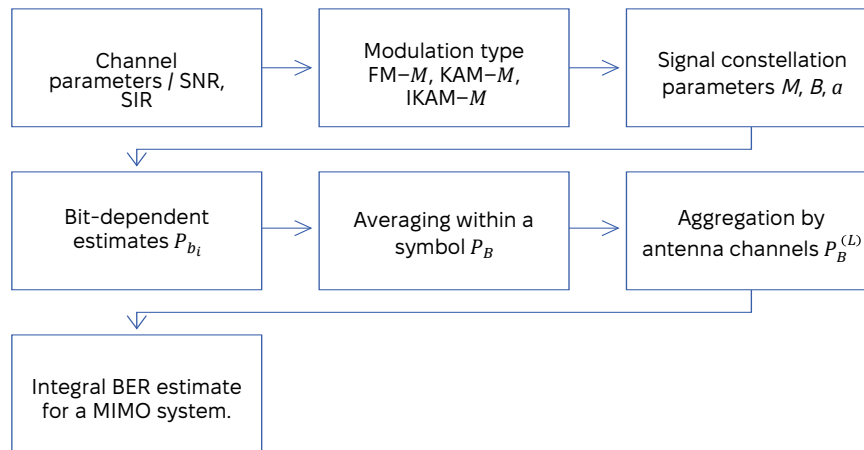


Figure 3. Analytical chain of BER formation in a multi-antenna communication system

Source: compiled by the authors

As shown in Figure 3, the formation of BER in a multi-antenna system is determined by the sequential interaction of the channel energy parameters, the characteristics of the interference environment, the structure of the signal constellation and the procedures for aggregating the error across the antenna branches. After determining the bit-dependent error estimates for individual positions in

the signal block, the total error probability was aggregated within the symbol according to the formulas (43), (44). This allowed moving from partial estimates $P_{(b,i)}$ to a generalised indicator P_B , which took into account the configuration of the signal constellation, the hierarchy parameter α and the ratio of the regular and fluctuating components in the channel. Additionally, the bit weight coefficients given by

the relation (45) parameterised the contribution of critical transitions between the constellation points and thereby specified the structure of the formation of the average bit error. The final step was the final aggregation of the error for the multichannel structure by averaging over the antenna branches according to (46). As a result, the single-channel estimates $P_{(B, i)}$ were reduced to the integral indicator $P_B^{(i)}$, which characterised the average bit error probability for the entire multi-antenna system, taking into account selective fading, Doppler non-stationarity, intersymbol interference, phase jitter and intentional interference.

It was established that the channel energy balance, determined by the relations (formulas (13), (14)), set the effective margin of separation of the signal constellation points relative to noise fluctuations. Within the analytical model, this margin was included in the expressions for the bit error probability through the parameter h_0^2 and the channel characteristics associated with it. As a result, a direct causal relationship was established between the channel energy parameters and the geometry of the signal space, which determined the analytical estimates $P_{(bi)}$ for individual bit positions. For phase manipulation in the coherent reception mode, an exact analytical expression of the error probability for the first two bits (31) was obtained, while for the remaining bits $i = 3, \bar{B}$ a generalised analytical notation (32) was used, in which the auxiliary functions formulas (formulas (33), (34)) reflected the geometry of the decision-making areas in the signal constellation. The average bit error within one symbol was determined by averaging over all bit positions according to (35), which allowed moving from local estimates of $P_{(bi)}$ to an integral characteristic of the transmission quality for a given value of M . For quadrature amplitude manipulation and hierarchical quadrature amplitude manipulation, a generalised expression for the error of the first two bits (36) was obtained.

Further analysis led to an accurate analytical record of the average error over all bit positions formulas (37)-(39). Weighting coefficients (40) determined the contribution of different classes of transitions between points of the signal constellation and thereby formalised the influence of the geometry of the decision boundaries on the structure of bit errors. It was found that, even with the same energy parameters of the channel M and h_0^2 , the error probability depended on the bit number i . This dependence is explained by the geometric structure of the signal constellation, since different bit positions correspond to different partitions of the set of signal points into the decision-making areas. As a result, the minimum distances to the decision boundaries turned out to be different, which caused an uneven distribution of errors between bits. It is shown that the parameter α , which is used in hierarchical quadrature amplitude manipulation, directly affects the minimum Euclidean distances between subsets of signal constellation points. For the value $\alpha = 1$, the constellation structure corresponds to symmetric quadrature amplitude manipulation, in which all bits have close discrimination conditions. With increasing α , part of the decision boundaries is removed, which

leads to a decrease in the probability of error for priority bits and, accordingly, to the redistribution of errors between bit streams. After determining the values of $P_{(B, i)}$ for each antenna channel, a system error indicator of the multi-antenna structure was obtained. The generalisation was performed by averaging over all antenna channels according to the relation (46), which allowed moving from a single-channel assessment to an integral characteristic of the reliability of the entire MIMO system.

The results obtained formed a consistent analytical scheme for assessing the noise immunity of multi-antenna radio communication systems. The energy metrics of reception quality determined the scale of signal degradation in the channel, the geometry of the signal constellation formed a bit-dependent error distribution for different modulation schemes, and the aggregation of the results over antenna channels allowed obtaining an integral error indicator of the system. Taken together, this provided a formalised transition from the parameters of the noise-interference environment and fading modes to a quantitative assessment of the bit error probability for both a separate channel and the entire multi-antenna radio communication system.

DISCUSSION

The obtained analytical results allow interpreting the mechanism of bit error formation in multi-antenna radio systems as a consequence of the interaction of channel energy parameters, signal constellation structure, and statistical characteristics of noise and interference disturbances. In this representation, the channel energy balance determines the scale of fluctuations in the coordinates of signal points, while the constellation geometry sets the configuration of decision-making regions in the signal space, through which these fluctuations are transformed into bit errors. This interpretation is consistent with the approach of Y. Ma *et al.* (2018), who proposed a geometrically conditioned non-stationary MIMO model for vehicular communications and showed that temporal changes in channel parameters have a physically interpreted relationship with the motion of the transmitter and receiver. The results of the study are also consistent with the conclusions of G.N. Kamga *et al.* (2017), which show that the characteristics of multi-antenna systems significantly depend on the comprehensive consideration of channel effects, rather than on the isolated analysis of individual factors. A similar result is also found in the work of M. Yang *et al.* (2017), where it is shown that the correlation characteristics of the channel can significantly change the spatial separation of signals and affect the reception error. This is consistent with the conclusions that the preservation of linear independence of spatial modes, the energy balance of antenna branches and the statistical structure of distortions directly determine the possibility of correct recovery of transmitted symbols. A similar logic of spatial analysis of communication channels was presented in the study of L. Ribeiro *et al.* (2022), where the concept of channel charting was used to display the geometric structure of the channel space in

massive MIMO systems. In the current study, this principle was manifested in the representation of the degradation of the signal constellation as a geometric transformation of the coordinates of the signal vector, which allowed linking the statistics of noise and interference with the geometry of decision-making.

In the review study of M. Ahmed *et al.* (2023), the authors showed that the use of STAR-RIS allows actively changing the structure of the multipath environment and thereby influencing the energy characteristics of the channel. Such an interpretation of the propagation environment as a geometric configuration of scatterers is consistent with the results of the analysis of the dynamic structure of the channel, where temporal fluctuations in the transmission coefficient were explained by changes in the multipath propagation trajectories and Doppler effects that arose during the movement of subscribers. Further development of this idea was demonstrated in the work of J. Xiao *et al.* (2024), where multitask learning was used to estimate the channel parameters in the near and far zones for networks with reconfigurable surfaces.

From a methodological point of view, the obtained results are also consistent with modern approaches to channel modelling in new generation systems. In the work of M.P. Kumar *et al.* (2025), it was shown that the accuracy of wireless channel modelling significantly depends on taking into account the real parameters of the propagation environment and measurement data obtained in field experiments. A similar logic is also observed in the current analysis, where the structure of channel non-stationarity is explained through the geometric scattering model and the correlation-Doppler properties of the signal. In the study of Y. Singh (2026), the possibilities of using the National Instruments – Universal Software Radio Peripheral (NI-USRP) platform for real-time monitoring and analysis of wireless signals were demonstrated, which confirmed the relevance of experimental verification of channel models. In this context, the results obtained on the statistical evaluation of the constellation degradation parameters can be used as a tool for interpreting the measured signal characteristics, since the instantaneous characteristics of the received symbols are directly related to the statistics of channel disturbances.

Machine learning methods used for channel parameter estimation and signal detection have also made a significant contribution to modern wireless systems analysis, for example, A. Singh & S. Saha (2022) showed that deep learning algorithms can effectively compensate for the effects of various types of channel distortions in Orthogonal Frequency Division Multiplexing (OFDM) systems. A similar trend was continued in the study of A.S. Alqahtani *et al.* (2024), where generative models with self-attention mechanisms were used to improve channel estimation in MIMO-OFDM systems. In the presented study, a similar result was obtained analytically by introducing constellation degradation parameters that described the effects of noise, interference, and phase fluctuations. Further development

of intelligent signal processing methods in massive multi-antenna systems was demonstrated in the work of A. Kumar & A. Nanthaamornphong (2025), where deep neural networks were applied to the problem of detecting signals in Multiple Input Multiple Output – Orthogonal Time Frequency Space (MIMO-OTFS). In turn, R. Shankar (2023) used a bidirectional Long Short-Term Memory (LSTM) architecture for channel estimation in 5G massive MIMO-OFDM systems. The results obtained are consistent with this trend, since the analysis of the dynamic structure of the channel showed that the non-stationarity of signal propagation is directly related to the correlation properties of the channel and Doppler broadening of the spectrum. In the work of M.M.E. Kotb *et al.* (2025), a comparative analysis of algorithms for estimating the carrier frequency shift in OFDM and MIMO-OFDM systems was carried out. The results obtained in the current study showed that even minor phase and frequency deviations can significantly affect the accuracy of signal recovery.

In the broader context of the evolution of wireless networks, the presented results correspond to the general trend of development of multi-antenna technologies. In the work of M. Pande *et al.* (2025), it was shown that MIMO systems have become a key element of the architecture of mobile networks of the third, fourth and fifth generations, since spatial diversity allows simultaneously increasing the throughput and reliability of data transmission. In the current study, this property was manifested in the formation of a systematic error estimate through the aggregation of bit errors over antenna channels, which allowed interpreting the MIMO system as a set of parallel error modes with different statistical characteristics. Further comparison of the results with modern studies showed that increasing the reliability of information transmission in multi-antenna systems is increasingly associated with a combination of analytical channel models and intelligent signal processing algorithms. In the work of M. Islam *et al.* (2025), the authors demonstrated the use of deep neural networks to optimise the parameters of the receive-transmit path in 5G MIMO systems. In the analysis conducted, a similar problem was solved analytically through the formalisation of the signal constellation degradation parameters and the statistical evaluation based on the moment characteristics of the received symbols. A similar approach was observed in the work of L.S.S.P.K. Chodisetti *et al.* (2023), where a soft detection algorithm based on coordinate descent was proposed for massive MU-MIMO-OFDM systems.

Another direction of modern research is related to the compensation of nonlinear distortions and optimisation of signal transmission parameters. In the work of G.K. Reddy & G.M. Sheeba (2024), the use of hybrid equalisers Minimum Mean Square Error – Maximum Likelihood Sequence Estimation (MMSE-MLSE) to reduce the peak signal values in MIMO-OFDM systems was considered. The results were consistent with the results of the analysis of signal constellation distortions, where phase perturbations, quadrature errors and interference components led to deformation

of the coordinates of signal points and, accordingly, to a change in the structure of decision-making areas. New principles of multiple access also play a significant role in the development of modern communication systems. The work of H. Iklodiya & M.S. Bhanwar (2025) considered the application of Non-Orthogonal Multiple Access (NOMA) technology in combination with OFDM and machine learning methods to improve the efficiency of spectrum use. In this context, the results of the analysis of bit errors acquire special importance, since the uneven distribution of errors between bit positions in the signal constellation can be used for differentiated protection of information flows of different priorities.

A separate area of research concerns the optimisation of data transmission in satellite and hybrid networks. In the work of K. Balamurugan & N. Janakiraman (2025), a cascade coding scheme was proposed for the optimisation of satellite channels of the Digital Video Broadcasting – Return Channel via Satellite, 2nd generation (DVB-RCS2) standard in MIMO-OFDM systems. The authors showed that the combination of coding methods and spatial diversity allows reducing the probability of data transmission errors in channels with a high level of noise. A similar logic is also observed in the obtained results, where the system error estimate was formed by aggregating bit errors over antenna channels, which allowed interpreting the MIMO system as a set of parallel channels with different statistical characteristics.

An important contribution was made by the study of L. Ge *et al.* (2022), where a classification-weighted neural network model was proposed to compensate for channel distortions in massive MIMO-OFDM systems. The results obtained showed that the use of deep models allows for effective signal structure reconstruction even under difficult channel conditions. In the study by H. Harkat *et al.* (2022), it was shown that MIMO-OFDM technology has become a key element of modern communication networks due to its ability to simultaneously increase bandwidth and reliability of signal transmission. This conclusion is consistent with the results of the study, in which the multi-antenna structure is also considered as a systemic basis for increasing interference immunity and transmission stability. A similar conclusion was supported in the work of N. Ye *et al.* (2021), which analysed modern approaches to the use of deep learning in NOMA systems. The study also focuses on an analytical description of signal degradation mechanisms, in particular, the influence of intentional interference, phase distortion, intersymbol interference, and Doppler non-stationarity on the probability of a bit error. The final link in the comparison was formed by the results of the study by M.A. Abdallah *et al.* (2023), devoted to increasing the accuracy of data transmission in MU-MIMO-OFDM systems through the use of efficient coding schemes. This conclusion is consistent with the obtained analytical results, where the bit error probability was considered as an integral characteristic formed under the influence of the energy parameters of the channel, the structure of the

signal constellation and the statistical characteristics of noise and interference.

Taken together, the comparison showed that the results of the study are consistent with the main directions of development of modern wireless technologies, where the spatial properties of the channel, the statistical structure of the signal and adaptive processing algorithms play a central role. At the same time, the obtained analytical dependencies allowed forming a consistent scheme for assessing the reliability of information transmission in multi-antenna systems, in which the energy characteristics of the channel, the geometry of the signal constellation and the statistical parameters of interference are integrated into a single model for analysing data transmission errors.

CONCLUSIONS

The study analysed the features of the functioning of multi-antenna radio systems built on software-defined means in conditions of fluctuating noise, intentional interference and channel non-stationarity. The analysis showed that for a correct description of the information transmission process in MIMO systems, a coordinated representation of the useful signal, noise, and interference in a common signal space is necessary. This approach allowed considering the degradation of the received signal not as a set of isolated effects, but as a single process in which the spatio-temporal structure of the transmission, the energy characteristics of the channel and the statistics of disturbances form a general picture of the error. As a result of the study, it was established that with quasi-stationarity of the channel at the block transmission interval and with orthogonal spatio-temporal organisation of signals, the possibility of correct recovery of the transmitted spatial symbols is ensured. This means that the multi-antenna structure can maintain resistance to random channel changes, provided that the channel operator agrees with the spatio-temporal transmission scheme. It is shown that the decoding efficiency in these conditions is determined not only by the very fact of the presence of several antenna branches, but also by the preservation of linear independence of spatial modes, which ensures the separation of information flows on the receiving side. It was also established that the distortions of the signal constellation are complex in nature and are formed under the influence of both deterministic geometric transformations and random perturbations. This made it possible to present the signal degradation as a result of the combined action of phase, amplitude, interference, and noise factors and proceed to the statistically interpreted evaluation by the characteristics of the received symbols.

The results obtained confirmed that the reception error is determined by the combined action of the channel energy balance, the structure of the signal constellation and the intensity of the interference environment, and not by a separate factor in itself. A separate block of results concerned the influence of channel non-stationarity on the stability of information transmission. It is shown that the temporal changes in the transmission coefficients are associated with

the correlation properties of the channel and Doppler variability, which complicates the process of signal recovery with increasing mobility of the transmitter and receiver. This made it possible to link the channel dynamics with the conditions for the formation of fading and take this effect into account in the general analytical scheme for assessing the reliability of transmission. As a result, the bit error was interpreted as an integral indicator that reflects the coordinated action of the channel parameters, the type of modulation and the multichannel structure of the system.

The practical significance of the results obtained is that the proposed approach can be used to analyse and optimise multi-antenna radio systems on software-defined devices in conditions of noise, interference and a non-stationary channel. Its application creates a basis for substantiating

the parameters of modulation, coding, and signal processing in order to increase the reliability and immunity to interference of radio communications. Prospects for further research are related to applied verification of the model using experimental data and its adaptation to more complex scenarios of spatial correlation and multipath propagation.

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CONFLICT OF INTEREST

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Григорій Радзівілов

Кандидат технічних наук, доцент
Військовий інститут телекомунікацій та інформаційних технологій імені Героїв Крут
01011, вул. Князів Острозьких, 45/1, м. Київ, Україна
<https://orcid.org/0000-0002-6047-1897>

Дмитро Павлюк

Ад'юнкт
Військовий інститут телекомунікацій та інформаційних технологій імені Героїв Крут
01011, вул. Князів Острозьких, 45/1, м. Київ, Україна
<https://orcid.org/0000-0001-8461-3899>

**Математична модель функціонування рухомої системи радіозв'язку
побудованої на програмно керованих засобах**

Анотація. Метою дослідження було розроблення узагальненої математичної моделі функціонування багатоантенних систем радіозв'язку в умовах дії випадкових та навмисних завад і аналітичне описання впливу завадово-шумових та нестаціонарних чинників на захищеність і надійність передавання інформації. У роботі застосовано матричну модель каналу, просторово-часове блокове кодування, ортонормальне подання сигналів у спільному сигнальному просторі та статистичне моделювання шуму і завад у координатах базису. Результати дослідження показали, що за квазістаціонарності каналу на інтервалі блокової передачі та ортогональності просторово-часової структури формується оборотний канальний оператор. За таких умов забезпечується лінійне відновлення переданого вектора символів і когерентне підсумовування корисної складової при статистичній незалежності шумових компонент на виході декодера. Корисний сигнал, флуктуаційний шум і навмисні завади мають узгоджену координатну структуру в одному ортонормальному сигнальному просторі. Унаслідок цього якість кожного антенного каналу визначається енергетичним балансом між корисною енергією та спектральними параметрами шуму і завад, що задає віддаленість сигнальних точок від областей помилкового рішення. Деградація констеляції описується композицією геометричних перетворень (обертання, масштабування, квадратурна деформація) і стохастичних збурень (фазове тремтіння, інтерференція, адитивний шум), а параметри цих спотворень ідентифікуються за математичним сподіванням, дисперсією та коваріацією координат прийнятих символів. Часова нестаціонарність каналу визначається доплерівським зсувом і кореляційною структурою коефіцієнта передачі, а еліптична геометрична модель розсіювання пов'язує затримки багатопробієвих компонентів із просторовою конфігурацією розсіювачів. Практична значущість результатів полягає у можливості використання запропонованої моделі для аналізу й оптимізації багатоантенних радіосистем на програмно керованих засобах в умовах шумів, завад і нестаціонарного каналу. Її застосування сприяє обґрунтуванню параметрів модуляції та кодування, а також підвищенню надійності й завадозахищеності радіозв'язку

Ключові слова: просторово-часове кодування; адитивний шум; навмисне втручання; МІМО; програмно визначене радіо; ефект Доплера