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Influence of Cross-polarisation of Dual-Polarised Antenna Elements on the Ergodic Capacity of a Multichannel System

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Abstract - **Background.** Antenna arrays based on dual-polarisation elements are used as radiating devices for modern and prospective radio communication systems. The main factor reducing the effectiveness of this approach is the presence of spatial correlation and cross-polarisation between elements in the array. These effects can lead to a significant reduction in communication system capacity. **Aim.** Derive relationships based on the Kronecker model that allow the polarisation properties of antenna elements to be taken into account when calculating the ergodic capacity of a multi-channel communication system. Investigate the influence of the cross-polarisation parameter of the antenna element on the capacity. Assess the polarisation characteristics of synthesised real antenna elements of various types and their impact on the capacity value. **Methods.** When deriving the basic relationships, methods of statistical radiophysics and electromagnetic analysis of the propagation channel were used. When synthesising dual-polarisation antenna elements, electrodynamic analysis methods based on Maxwell's equations were used. **Results.** Based on the analysis using the derived relationships, it was established that the influence of the cross-polarisation properties of the array antenna elements on the capacity of a multi-channel communication system becomes significant when the value of the cross-polarisation parameters decreases below 10 dB. It is shown that synthesised real antenna elements of various types have high polarisation isolation, which will lead to a slight decrease in the system capacity. **Conclusion.** The derived relationships and the developed methodology make it possible to estimate the change in the capacity of the communication system when taking into account the cross-polarisation properties of the dual-polarisation elements of the antenna array. This will allow for the optimal selection of radiating elements for a given system. At the same time, the developed antenna elements of various types satisfy the imposed cross-polarisation restrictions.

Keywords - cross-polarisation; antenna arrays; cross-dipoles; patch antennas; ergodic capacity.

Introduction

Modern multi-channel radio devices in the ultra-high frequency (UHF) band increasingly use antenna arrays as transceivers. For wireless communication systems, dual-polarisation radiating elements (cross dipoles, patches, etc.) have recently been used to increase throughput without increasing the array aperture.

In this case, the distance between the antenna elements is often reduced, which leads to the manifestation of the mutual influence effect. In [1], relationships are derived showing how much the directional pattern (DP) of an isolated antenna element will differ from the DP of the same element in an antenna array (partial directional pattern).

In [2], it is shown that mutual influence can underestimate the throughput of the system.

However, in addition to the distortion of the radiation pattern due to the mutual arrangement of the elements, the main factor reducing the efficiency of the communication system is the presence of spatial correlation and cross-polarisation between the elements in the array [3]. The level of spatial correlation depends mainly on the propagation channel, while cross-polarisation is a characteristic of the antenna system and depends on its design.

Thus, the aim of the work was to develop a method for taking into account the polarisation properties of antenna elements when calculating the ergodic throughput of a multichannel system and to study the influence of the polarisation parameters of real elements on the throughput of various communication channels.

1. Ergodic Throughput of a Massive MIMO System

The ergodic throughput of a massive MIMO system is determined by the ratio [4]:

$$C = \frac{1}{K}\mathrm{E}\left[\log_2 \det\left(\mathbf{I} + \frac{P}{N\sigma^2}\mathbf{H}\mathbf{H}^{\mathrm{H}}\right)\right],$$

where E [...] is the averaging symbol; P is the total transmitted power; K is the number of users with one

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antenna; N is the number of antenna array elements; σ^2 is the noise variance; **H** is the channel matrix.

The Kronecker model is often used to calculate the channel matrix in analytical studies. Based on the Kronecker model, the channel matrix can be represented as follows:

$$\mathbf{H} = \mathbf{R}_{rx}^{1/2}\mathbf{H}_0\mathbf{R}_{tx}^{1/2},$$

where $\mathbf{R}_{rx}$ and $\mathbf{R}_{tx}$ are the matrices of mutual correlations of antenna elements on the receiving and transmitting sides, respectively, and the elements of the matrix H_0 are independent normally distributed random variables with zero mathematical expectation and unit variance. The Kronecker model is based on the assumption of independence of the correlation coefficients for two antenna elements on transmission or reception, respectively. The correlation between users equipped with a single antenna is negligible, so it is further assumed that $\mathbf{R}_{rx} = \mathbf{I}$, $\mathbf{R}_{tx} = \mathbf{R}$.

Using known assumptions about the properties of the channel and some system parameters, in particular the assumption that the array is affected by plane waves, the expressions for the elements of the input matrix can be written as a function of the geometric parameters of the array, the complex radiation patterns of the radiating elements, and the probability distribution of the signal arrival angles. Thus, for a flat array, we have:

$$R_{mn} = \int_{-\pi/2}^{\pi/2}\int_{-\pi}^{\pi} E_m(\theta,\varphi)E_n^*(\theta,\varphi)\times$$
$$\times\rho(\theta,\varphi)\cos(\theta)d\varphi d\theta.$$

Here, R_{mn} is an element of matrix **R**; $E_m(\theta, \varphi)$, $E^*_n(\theta, \varphi)$ are the complex directional patterns of the m-th and n-th emitters, taking into account their location relative to the phase centre; $\rho(\theta, \varphi)$ is the joint probability density of the signal arrival angles in azimuth and elevation. If we consider the array to be equidistant with the distance between elements d_y, d_z horizontally and vertically, respectively, the probability densities of the angles of arrival in azimuth and elevation are independent ($\rho(\theta, \varphi) = \rho_\theta(\theta)\,\rho_\varphi(\varphi)$), and the directional patterns of each independent radiator are equal $|E_m(\theta, \varphi)| = E_n(\theta, \varphi) = |E(\theta, \varphi)|$, then the expression for the correlation coefficient between elements with coordinates *(t, n)* and *(k, 1)* will be determined by the ratio

$$R(m,n,k,l) = \tag{1}$$
$$= \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{-\pi}^{\pi}\exp(j2\pi((m-k)d_y\cos(\theta)\sin(\varphi)+$$
$$+(n-l)d_z\sin(\theta)))p_\theta(\theta)p_\phi(\varphi)\times$$
$$\times\cos(\theta)\,|\,E(\theta,\varphi)|^2\,d\varphi d\theta.$$

2. Spatial Correlation of Dual-Polarisation Elements in the Presence of Cross-Polarisation

If the antenna elements of the array are dual-polarisation, then the correlation matrix will have a block structure:

$$\mathbf{R}' = \begin{bmatrix}\mathbf{R}'_{vv} & \mathbf{R}'_{vh}\\ \mathbf{R}'_{hv} & \mathbf{R}'_{hh}\end{bmatrix}, \tag{2}$$

where the lower indices denote the polarisation of the corresponding elements. In the absence of cross-polarisation between the elements, the matrix will have the form

$$\mathbf{R} = \begin{bmatrix}\mathbf{R}_{vv} & 0\\ 0 & \mathbf{R}_{hh}\end{bmatrix},$$

where the values of the matrix block elements $\mathbf{R}_{vv}$, $\mathbf{R}_{hh}$ are determined by expression (1). We will find the values of the matrix block elements from (2) through the polarisation properties of the radiating elements, taking into account the presence of cross-polarisation.

Cross-polarisation between two different ports of a dual-polarisation radiating element is usually described by the *XPI* parameter, which is defined by the ratio

$$XPI_v = \frac{E_{vv}(\theta,\varphi)}{E_{vh}(\theta,\varphi)},\quad XPI_h = \frac{E_{hh}(\theta,\varphi)}{E_{hv}(\theta,\varphi)},$$

where E_{vv}, E_{vh}, E_{hh}, E_{hv} are the co-polarisation and cross-polarisation radiation patterns of each port, respectively. From the definition, it can be seen that in general, the parameters XPI_v, XPI_h are functions of azimuth and elevation angle, but in further derivation, we will omit this dependence. Then, to calculate the cross-polarisation component of the element's directional pattern, the following relationships can be used:

$$E_{vh} = E_{vv}/XPI_v,\quad E_{hv} = E_{hh}/XPI_h.$$

First, we find the normalisation factors for each port that satisfy the condition of preserving the radiated power:

$$E_v^2 = E_{vh}^2\left(1+XPI_v^2\right)\rightarrow E_{vh} = \frac{E_v}{\sqrt{1+XPI_v^2}},$$

$$E_{vv} = \frac{|XPI_v|E_v}{\sqrt{1+XPI_v^2}}$$

$$E_h^2 = E_{hv}^2\left(1+XPI_h^2\right) \to E_{hv} = \frac{E_h}{\sqrt{1+XPI_h^2}},$$

$$E_{hh} = \frac{\left|XPI_h\right| E_h}{\sqrt{1+XPI_h^2}} \ .$$

Here, E_v, E_h is the directional pattern of a single-polarisation element.

The field strength of each component, taking into account the cross-polarisation effect:

$$E_v^{'} = E_{vv} + E_{hv} = \frac{E_v\left|XPI_v\right|}{\sqrt{1+XPI_v^2}} + \frac{E_h}{\sqrt{1+XPI_h^2}},$$

$$E_h^{'} = E_{hh} + E_{vh} = \frac{E_h\left|XPI_h\right|}{\sqrt{1+XPI_h^2}} + \frac{E_v}{\sqrt{1+XPI_v^2}},$$

$$E_v^{'} E_h^{'*} = \left(\frac{E_v\left|XPI_v\right|}{\sqrt{1+XPI_v^2}} + \frac{E_h}{\sqrt{1+XPI_h^2}}\right) \times \tag{3}$$

$$\times\left(\frac{E_h^*\left|XPI_h\right|}{\sqrt{1+XPI_h^2}} + \frac{E_v^*}{\sqrt{1+XPI_v^2}}\right) =$$

$$= \frac{E_v^2\left|XPI_v\right|}{1+XPI_v^2} + \frac{E_h^2\left|XPI_h\right|}{1+XPI_h^2},$$

$$E_v^{'} E_v^{'*} = \left(\frac{E_v\left|XPI_v\right|}{\sqrt{1+XPI_v^2}} + \frac{E_h}{\sqrt{1+XPI_h^2}}\right)^2 = \tag{4}$$

$$= \frac{E_v^2 XPI_v^2}{1+XPI_v^2} + \frac{E_h^2}{1+XPI_h^2},$$

$$E_h^{'} E_h^{'*} = \left(\frac{E_h\left|XPI_h\right|}{\sqrt{1+XPI_h^2}} + \frac{E_v}{\sqrt{1+XPI_v^2}}\right)^2 = \tag{5}$$

$$= \frac{E_h^2 XPI_h^2}{1+XPI_h^2} + \frac{E_v^2}{1+XPI_v^2}.$$

In the derivation, we used the condition

$$E_v E_h^* = E_h E_v^* = 0.$$

Then the coefficients of the correlation matrices of the subblocks (2) will have the form

$$R'_{vv}\left(m,n,k,l\right) = \tag{6}$$

$$= \int_{-\pi/2}^{\pi/2}\int_{-\pi}^{\pi} \exp(j2\pi\Big(\left(m-k\right)d_y\cos(\theta)\Big)\sin(\varphi)+$$

$$+\left(n-l\right)d_z\sin(\theta)))p_\theta\left(\theta\right)p_\phi\left(\varphi\right)\cos(\theta)\times$$

$$\times\left|E_v^{'}\left(\theta,\varphi\right)\right|^2 d\varphi d\theta =$$

$$= \frac{XPI_v^2}{1+XPI_v^2}R_{vv} + \frac{1}{1+XPI_h^2}R_{hh},$$

$$R'_{hh}\left(m,n,k,l\right) = \tag{7}$$

$$= \int_{-\pi/2}^{\pi/2}\int_{-\pi}^{\pi} \exp(j2\pi\Big(\left(m-k\right)d_y\cos(\theta)\Big)\sin(\varphi)+$$

$$+\left(n-l\right)d_z\sin(\theta)))p_\theta\left(\theta\right)p_\phi\left(\varphi\right)\cos(\theta)\times$$

$$\times\left|E_h^{'}\left(\theta,\varphi\right)\right|^2 d\varphi d\theta =$$

$$= \frac{XPI_h^2}{1+XPI_h^2}R_{hh} + \frac{1}{1+XPI_v^2}R_{vv},$$

$$R'_{vh}\left(m,n,k,l\right) = R'_{hv}\left(m,n,k,l\right) = \tag{8}$$

$$= \int_{-\pi/2}^{\pi/2}\int_{-\pi}^{\pi} \exp(j2\pi\Big(\left(m-k\right)d_y\cos(\theta)\Big)\sin(\varphi)+$$

$$+\left(n-l\right)d_z\sin(\theta)))p_\theta\left(\theta\right)p_\phi\left(\varphi\right)\cos(\theta)\times$$

$$\times E_v^{'}\left(\theta,\varphi\right)E_h^{'*}\left(\theta,\varphi\right)d\varphi d\theta =$$

$$= \frac{\left|XPI_v\right|}{1+XPI_v^2}R_{vv} + \frac{\left|XPI_h\right|}{1+XPI_h^2}R_{hh}.$$

If we assume that $XPI_v = XPI_h = XPI = \text{const}$, $\mathbf{R}_{vv} = \mathbf{R}_{hh}$, then for expression (2) we obtain

$$\mathbf{R}' = \begin{bmatrix} \mathbf{R}_{vv} & \dfrac{2XPI}{1+XPI^2}\mathbf{R}_{vv} \\ \dfrac{2XPI}{1+XPI^2}\mathbf{R}_{vv} & \mathbf{R}_{vv} \end{bmatrix}. \tag{9}$$

Thus, to calculate the spatial correlation matrix of a dual-polarisation antenna array taking into account cross-polarisation, it is necessary to have co-polarisation directional patterns and the values XPI_v, XPI_h. If these values are functions of angles, then relations (3)-(5) must be used in the calculations. If these values are constant, then we can use relations (6)-(8). Finally, when the co- and cross-polarisation properties of

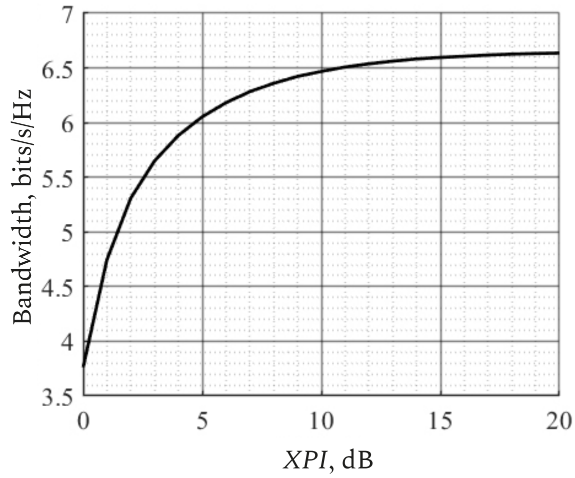

Fig. 1. Dependence of ergodic capacity on the level of cross-polarisation
Рис. 1. Зависимость эргодической пропускной способности от уровня кросс-поляризации

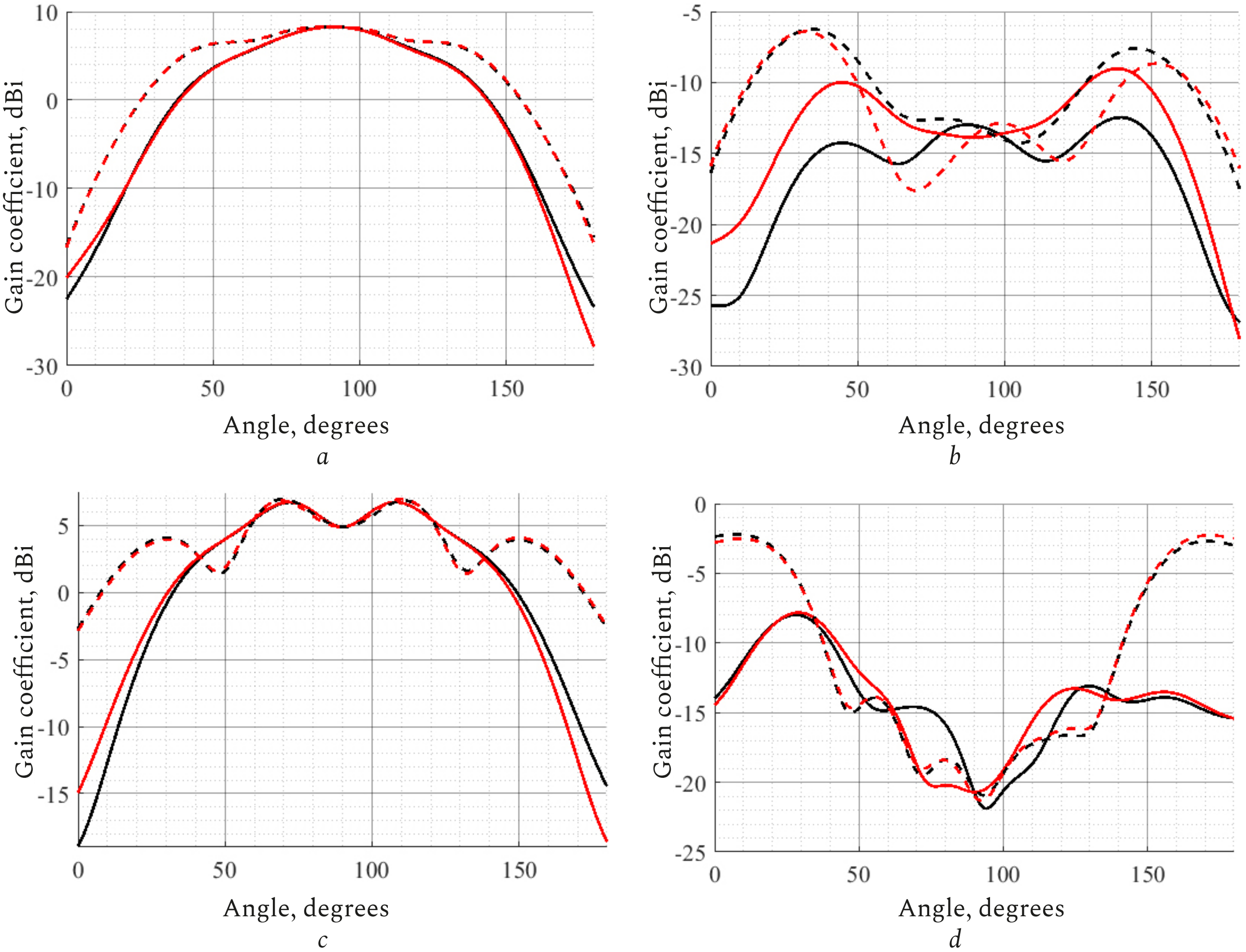

Fig. 2. Antenna patterns of cross-dipole (*a* – co-polarisation, *b* – cross-polarisation components) and stacked-patch elements (*c* – co-polarisation, *d* – cross-polarisation components) for the first (black line) and the second (red line) port. The dotted line indicates slices along the direction of port polarisation, the solid line – perpendicular)

Рис. 2. Диаграммы направленности кросс-дипольного (*а* – со-поляризационная, *б* – кросс-поляризационная компоненты) и stacked – патч-элементов (*в* – со-поляризационная, *г* – кросс-поляризационная компоненты) для первого (черная линия) и второго (красная линия) порта. Пунктирной линией обозначены срезы вдоль направления поляризации порта, сплошной – перпендикулярно)

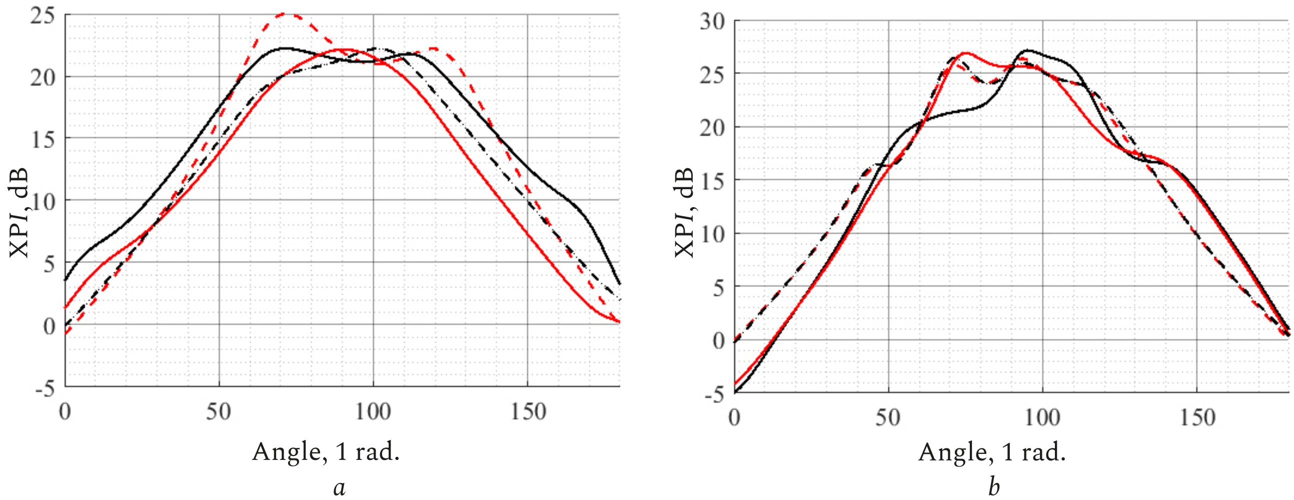

Fig. 3. XPI patterns of cross-dipole (*a*) and stacked-patch elements (*b*) for the first (black line (XPI_h) and the second (red line (XPI_v)) port. Dotted line indicates slices along the direction of port polarisation, solid line – perpendicular)

Рис. 3. Диаграммы XPI кросс-дипольного (*а*) и stacked – патч-элементов (*б*) для первого (черная линия (XPI_h) и второго (красная линия (XPI_v)) порта. Пунктирной линией обозначены срезы вдоль направления поляризации порта, сплошной – перпендикулярно)

Table. Ergodic capacity of an antenna array with real antenna elements
Таблица. Эргодическая пропускная способность антенной решетки с реальными антенными элементами

	Without cross-polarisation, Bits/c/Hz	With cross-polarisation taken into account, Bits/c/Hz	ΔC, %
Cross-dipole	6,884	6,869	1
Patch	6,641	6,616	1

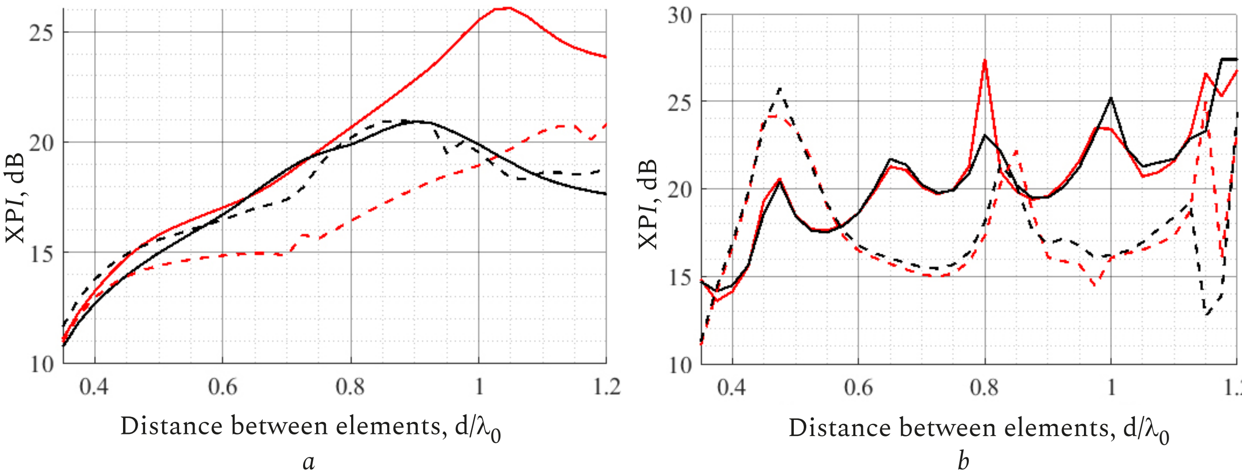

Fig. 4. Average XPI value of dual cross-dipole (*a*) and stacked-patch elements (*b*) for the first (black line (XPI_h) and the second (red line (XPI_v) port. The dotted line indicates slices along the polarisation direction of the port, the solid line – perpendicularly)
Рис. 4. Среднее значение *XPI* сдвоенного кросс-дипольного (*а*) и stacked – патч-элементов (*б*) для первого (черная линия (XPI_h) и второго (красная линия (XPI_v) порта. Пунктирной линией обозначены срезы вдоль направления поляризации порта, сплошной – перпендикулярно)

ports with different polarisation are equal, relation (9) is used for calculations.

From equation (9) it can be seen that if the cross-polarisation of a two-polarisation element is insignificant ($XPI \to \infty$), then the spatial correlation between elements of different polarisation tends towards zero. In the presence of cross-polarisation, the number of degrees of freedom of the system decreases due to an increase in spatial correlation, which will lead to a decrease in its resolution.

Using the derived relations and the Kronecker model with the Monte Carlo method, we calculate the dependence of the throughput for a flat antenna array with a size of 4 x 8 with distances between elements $d_y = 0{,}5\lambda$, $d_z = 2\lambda$ on the value of cross-polarisation *XPI*. An ideal dual-polarisation patch with a polarisation plane rotation of ±45° was used as the antenna element. The probability distribution of arrival angles by elevation was described by Laplace's law, and by azimuth by von Mises' law. Assumptions for expression (9) were used in the calculation. Fig. 1 shows the obtained dependence. It can be seen that a decrease in *XPI* below 10 dB leads to a decrease in the throughput of the system.

3. Modelling with Real Radiating Elements

To estimate the value of the cross-polarisation parameter *XPI* of real antenna elements and its effect on throughput, models of a dual-polarisation two-port stacked patch element [2] and a cross-dipole element with ±45° polarisation were synthesised in CST Studio Suite.

The directional patterns obtained by electrodynamic modelling by solving Maxwell's equations (method of moments): co-polarisation and cross-polarisation for each port are shown in Fig. 2.

It can be seen that the co-polarisation diagrams of each element coincide with each other in the direction of the main radiation. Therefore, it can be assumed that $E_{vv} = E_{hh} = E(\theta,\varphi)$.

Based on the obtained port directivity diagrams for each polarisation, the angular dependencies XPI_v, XPI_h were calculated for the cross-dipole and patch antennas (Fig. 3).

The figure shows that the dependencies for XPI_v and XPI_h coincide with graphical accuracy for both the patch element and the cross-dipole element. The slight difference in the shapes of XPI_v and XPI_h for the cross-dipole element can be explained by the asymmetry of its feed system.

Thus, we can consider $XPI_v = XPI_h = XPI(\theta,\varphi)$. Finally, XPI depends in a complex way on θ, φ. Based on this, the relations for calculating the elements of the spatial correlation matrix will be

$$\mathbf{R}'_{vv} = \mathbf{R}'_{hh} = \mathbf{R}_{vv},$$

$$R'_{vh}\left(m,n,k,l\right) = R'_{hv}\left(m,n,k,l\right) =$$

$$= \int_{-\pi/2}^{\pi/2}\int_{-\pi}^{\pi} \exp(j2\pi\left(\left(m-k\right)d_y\cos(\theta)\sin(\varphi)+\right.$$

$$\left.+\left(n-l\right)d_z\sin(\theta)\right))p_\theta\left(\theta\right)p_\phi\left(\varphi\right)\cos(\theta)\times$$

$$\times E^2\left(\theta,\varphi\right)\frac{2\times\left|XPI\left(\theta,\varphi\right)\right|}{1+XPI^2\left(\theta,\varphi\right)}d\varphi d\theta.$$

Using these relationships and the available required dependencies for real antenna elements – cross-dipole and patch – the change in the throughput of the antenna array discussed above was calculated, taking into account the presence of cross-polarisation. The results for both types of elements are presented in the table.

The results obtained show that the synthesised radiating elements have good polarisation isolation, which will only lead to a slight reduction in the throughput of the massive MIMO system.

As shown in [2], the optimal parameters of the antenna element's radiation pattern in the array, which ensure maximum throughput, cannot be achieved with a single antenna element. To reduce the width of the radiation pattern in the elevation angle, antenna elements are often paired (or stacked). Paper [2] presents the dependencies of ergodic throughput on the distance between paired elements.

To evaluate the contribution of the cross-polarisation effect to these dependencies, similar paired patch and cross-dipole elements were synthesised and their cross-polarisation coefficient was calculated.

The figures show the averaged (in the range ±40 from the main radiation direction) values *of* XPI_v and XPI_h as a function of the distance between the elements.

The figures show, first, that when patch elements are doubled, the dependencies remain the same up to a distance between the elements of about $0{,}75\lambda_0$, and then slight deviations appear, associated with the appearance of side lobes. At the same time, for cross-dipole elements at a distance greater than $0{,}75\lambda_0$, the dependencies are similar in nature but differ significantly in magnitude.

Despite the asymmetry of XPI_v and XPI_h, their values for both dual cross dipoles and patch antennas exceed 12 dB, which, as shown earlier, does not cause any loss in channel throughput.

Conclusion

The derived relations and the developed methodology allow us to estimate the change in the throughput of a communication system, taking into account the cross-polarisation properties of the dual-polarisation elements of the antenna array.

This will allow the optimal selection of radiating elements for a given system. Based on the analysis using the derived ratios, it has been established that the influence of the cross-polarisation properties of the antenna array elements on the throughput of a multi-channel communication system becomes significant when the cross-polarisation parameter decreases below 10 dB. It has been shown that the synthesised real antenna elements of various types have high polarisation isolation, which will lead to a slight decrease in the throughput of the system. This allows them to be used as radiators for multi-channel communication systems based on antenna arrays.

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Влияние кросс-поляризации двухполяризационных антенных элементов на эргодическую пропускную способность многоканальной системы

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Аннотация – **Обоснование.** В качестве излучающих устройств для современных и перспективных систем радиосвязи используются антенные решетки на основе двухполяризационных элементов. Основным фактором, снижающим эффективность такого подхода, является наличие пространственной корреляции и кросс-поляризации между элементами в составе решетки. Данные эффекты могут приводить к значительному снижению пропускной способности системы связи. **Цель.** Вывести соотношения на основе модели Кронекера, позволяющие учитывать поляризационные свойства антенных элементов при расчете эргодической пропускной способности многоканальной системы связи. Исследовать влияние величины кросс-поляризационного параметра антенного элемента на пропускную способность. Оценить поляризационные характеристики синтезированных реальных антенных элементов различного типа и их влияние на величину пропускной способности. **Методы.** При выводе основных соотношений использованы методы статистической радиофизики и электромагнитного анализа канала распространения. При синтезе двухполяризационных антенных элементов использованы методы электродинамического анализа на основе уравнений Максвелла. **Результаты.** На основе анализа с помощью выведенных соотношений установлено, что влияние кросс-поляризационных свойств антенных элементов решетки на пропускную способность многоканальной системы связи становится значительным при снижении величины кросс-поляризационного параметра ниже 10 дБ. Показано, что синтезированные реальные антенные элементы различного типа обладают высокой развязкой по поляризации, что приведет к незначительному снижению пропускной способности системы. **Заключение.** Выведенные соотношения и разработанная методика позволяют оценить изменение пропускной способности системы связи при учете кросс-поляризационных свойств двухполяризационных элементов антенной решетки. Это позволит оптимальным образом подобрать излучающие элементы для заданной системы. При этом разработанные антенные элементы различного типа удовлетворяют наложенным ограничениям по кросс-поляризации.

Ключевые слова – кросс-поляризация; антенные решетки; кросс-диполи; патч-антенны; эргодическая пропускная способность.

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