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Mathematical Models for Wireless Access Networks

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Abstract**: *The goal of wireless access networks is the expansion of access from any device to achieve a completely seamless coverage that will ensure the functioning of not only client access, but also of infrastructure schemes. The paper analyzes the main types of wireless access networks and identifies the need to solve the problem of increasing the density of coverage in premises for the goals of seamless switching in 5G networks.The authors have identified the possibility of using multiple-input and multiple-output networks as the highest quality standard for ensuring a spatial distribution of networks and opportunities for the formation of uninterrupted access to services. The authors note that the decision is more suitable for industrial networks in which access and control are carried out continuously and remotely. The orthogonal polarized model of the antenna is used as the basis.The authors suggest a model that reduces delays in transmitting a signal in wireless access networks in loaded bands, presents a visual form of technological solution, and identifies the peculiarities of using standard equipment for implementing the Internet of Things, based on traditional wireless access networks, new multiple-input and multiple-output forms in radio channel.***

The authors show the possibility of expanding current networks that use the traditional structure of cellular communications and thereby creating coverage areas. As it is shown in the article, the formation of seamless coverage zones in this way makes it possible to implement systems of speed access and information exchange not only between base stations or receivers, but also between subscriber devices directly. In this regard, the authors disclose the possibility of separating p2p subscriber networks.

Index Terms**: *Mathematical model, MIMO, network, standard, wireless access.***

I. INTRODUCTION

Modern standards IEEE 802.11 and IEEE 802.16, which are used in the implementation of WiFi and WiMAX-LTE protocols, envisage the possibility of using both industrial installations and small user antennas as an industrial access point of phased antenna arrays. We have reviewed the features of use of polarization-orthogonal antennas of radio access systems. J. Liu, and J Li reviewed the features of radio access systems such as the local system (LAN) of WiFi standards and the urban (MAN) of WiMAX standard [1]. It is obvious that all known characteristics of all types of access are already described in the literature [2, 3, 4, 5, 6]. Therefore, the relevance of the study is based on the development of a new form of permanent access — 5G or advanced technologies based on MIMO. This option makes it possible not only to create separate networks according to 5G standards, but also to form a system that meets these requirements based on the existing LTE and WiFi solutions — that is, it is about the possibility of upgrading the existing wireless access networks to 5G standards based on MIMO technology. This is technologically acceptable. Therefore, this study is also extremely important for a number of economic reasons.

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II. LITERATURE REVIEW

We have analyzed the polarization characteristics of typical antennas of radio communication systems, the results of experimental studies and mathematical modeling, as well as an improved methodology for analyzing the bandwidth capacity of radio access systems based on the polarization distortion of antennas in the service sector. B. Chen, A. P. Petropulu, and L. De Lathauwer reviewed the main characteristics of polarization-orthogonal antennas and features of the use of MIMO systems with polarization-orthogonal antennas [3]. C.-S. Park, Y.-S. Byun, J. W. Lee and Y.-H. Lee note that they can be built by using polarization-orthogonal antennas [7]. According to R. S. Blum, the use of MIMO systems in radio communication makes it possible to increase the speed of data transmission by many different methods, including the use of polarization-orthogonal antennas, when energy losses of a received signal can be reduced [8]. As shown in J. (C.) Zhang’s work, the use of polarization-orthogonal antennas of the MIMO system can improve the overall capacity and coverage radius [9], but C. Yoon and H. Lee show that the payoff for the positive effect is a complexity of processing algorithms and requirements for antenna designs [6]. The studies of A. Abdelraheem and M. A. Abdalla of the possibility of compensation of polarization distortions of radio waves in a system of radio access within the antenna pattern or access sector to reduce polarization losses, are insufficient [10], because in the work of X. Li, S. Jin and X. Gao the polarization of antennas in practice is normalized only along the axis of antenna [11].

III. MATERIALS AND METHODS

The theory of systems, which formed an understanding of how the system transmits a signal from the device to the receiver-antenna [9], was determined as the primary method of this research.

We made some calculations regarding the distribution of the signal with the joint action of two antennas [10]. We considered not only the possibility of the direct signal transmission, but also the amount of noises and the possibility of their reduction.

After calculating the signal transmission quality, we applied the polarization method. This method implies taking into account the spatial location of the antennas and their disposition relative to each other [11]. This calculation was based on a mathematical model of a vector type, which is shown not only in the calculation model, but also in the structure of the noise distribution [2]. The next step was applying the polarization method for the purpose of studying the probabilistic attenuation of the signal in the space and its interception. That is how we investigated the technologies of protection [12]. A general check of the correctness method calculation was carried out according to the method of relevant search [4].

IV. RESULTS AND DISCUSSION

All the formulas in the article were derived by authors. As far as the pictures and diagrams were composed on the basis of our investigations.

In general, we believe that the mutual antenna positions of the access point and subscriber can be arbitrary within the service sector (Fig. 1).

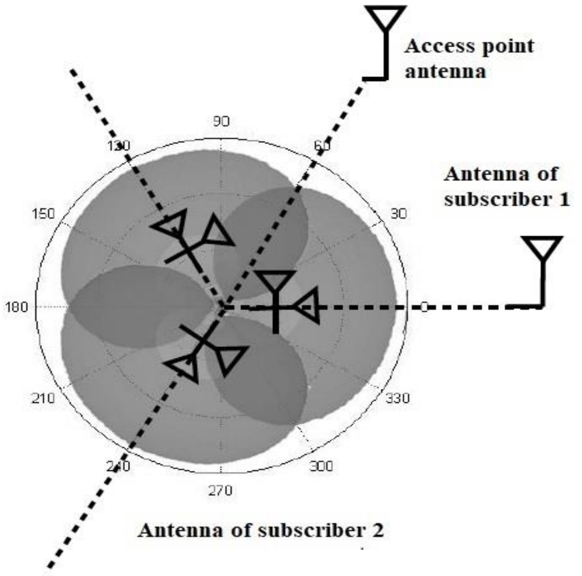

Figure 1: The mutual positions of access point of antennas and subscribers

For example, subscriber 1 is in the maximum pattern of antenna access in the horizontal plane, while subscriber 2 is on the border of the sector. Therefore, it should be assumed that polarization distortions in the second case will be big.

Polarization distortions of the antenna are the deviations of its polarization parameters from the set ones. The polarization parameters of the antenna, as well as the signals, are considered to be the parameters of the ellipse of polarization, such as the angle of ellipticity α and the angle of orientation β. The combination of polarization parameters of the antenna from spatial angles is polarization characteristics of the antenna. The destruction of polarization parameters of the signal and the antenna leads to polarization losses.

Polarization losses are characterized by polarization receiving coefficient:

$$\gamma_p = \frac{P_c}{P_{c\max}} \tag{1}$$

where P_c is the power of the received signal arriving at the receiver input; $P_{c\max}$ — the maximum power of the received signal with accurate matching of polarization characteristics of the incident wave and the receiving antenna.

The relationship between γ_p and polarization parameters of the antenna and the signal (radio waves) can be calculated using the following formula:

$$\gamma_p = \frac{1}{2}\left[1 \pm \frac{4k_c k_a}{(1+k_c^2)(1+k_a^2)} + \frac{(1-k_c^2)(1-k_a^2)}{(1+k_c^2)(1+k_a^2)}\cos 2\beta\right] \tag{2}$$

where k_c and k_a are the coefficients of ellipticity of the signal and antenna; β = βc − βa is the angle between the major semi-axis of polarization ellipse of the antenna and the signal.

The two-dimensional function of polarization reception depending on ellipticity angles of the signal α_c and antenna α_a is shown in Fig. 2 (a–b).

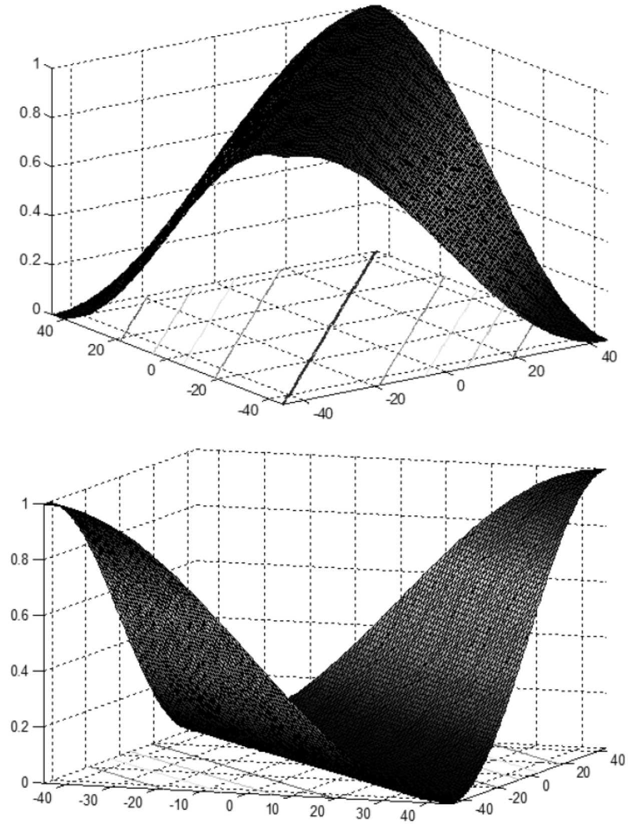

Figure 2. The function of polarization reception (axis α_a — to the left; axis α_c — to the right); (a) β=0˚, (b) β=90˚

It should be noted that with k_c=k_a or α_c=α_a and β=0˚ (Fig. 2a) we have a complete convergence of polarization parameters of the signal and antenna when γ γ_p=1, which indicates the absence of polarization losses. And if α_c=−α_a and β=90˚ (Fig. 2b) we have the maximal reasoning of polarization parameters, with γ_p=0. Under such conditions we have the maximum polarization losses.

Calculations show that polarization losses reach values up to γ_p=10 dB due to significant polarization differences when the differences between the angles of ellipticity and the orientation of polarization ellipses of the signal and antenna reach 85˚.

For the practice of radio channel antennas, it is important to study polarization losses when receiving on a linear polarization antenna, when $\alpha_a=0^\circ$ and $\beta_a=0^\circ$, while polarization losses are associated with distortion of the transmitting antenna and the peculiarities of radio waves propagation. The two-dimensional function of the polarization coefficient of the signal received by a linearly polarized antenna is shown in Fig. 3, the axis β_c is shown on the left, and the axis α_c is shown on the right.

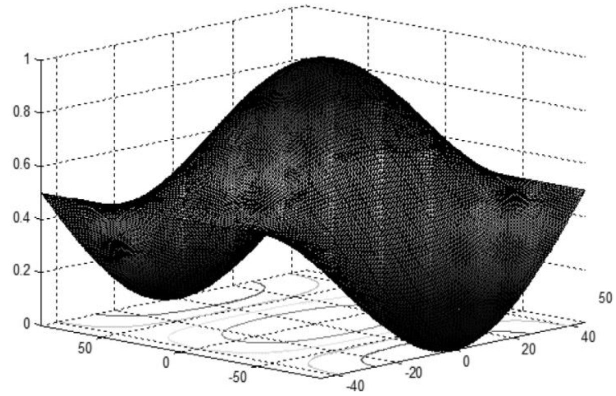

Figure 3: Polarization coefficient of reception

Under the condition that polarization parameters of the signal and the antenna $\alpha_c=\alpha_a=0^\circ$ and $\beta_c=\beta_a=0^\circ$ coincide, we have γ_p=1, and if $\alpha_c=\pm45^\circ$, the polarization coefficient of reception will be γ_p=0.5. If the polarization differences between the signal and the linear polarization antenna do not exceed $\alpha_a-\alpha_c=\pm25^\circ$ in ellipticity angles and $\beta_a-\beta_c=\pm50^\circ$ in orientation angles, the maximum polarization losses do not exceed γ_p=4 dB (Fig. 4).

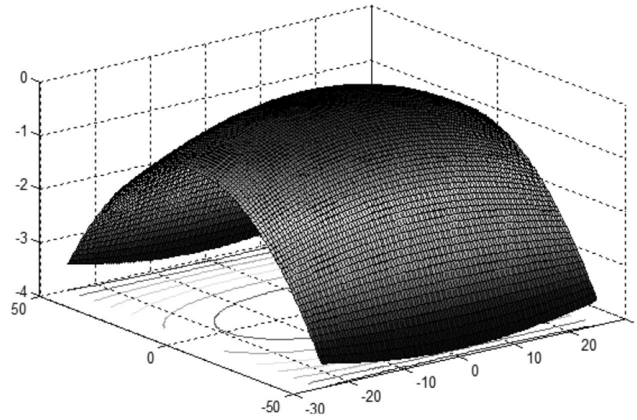

Figure 4: Relative polarization reception coefficient

The basis for the study of polarization characteristics of typical radio access channel antennas is the use of a mathematical model of antenna as a system of emitters and an experiment. The principle of building a model is based on the use of calculation formulas for the general and statistical theory of antennas. The field in the far zone of antenna along the angles θ and φ relative to the normal is presented in the form of a complex vector radiation pattern:

$$E_a(\theta,\varphi,t)=\sum_{i=1}^{I} b_i \sum_{m=1}^{M}\sum_{n=1}^{N} A_{m,n} e^{jF_{m,n}} e^{j(w_i t+\varphi_0)} e^{jk_i d_{m,n}\sin(\gamma(\theta,\varphi))} p_{m,n}(\theta,\varphi) \tag{3}$$

where θ and φ are the angles in the spherical system of coordinates; $A_{m,n}$ and $F_{m,n}$ — amplitude and phase distributors; w_i and k_i — current frequency and wave number; b_i — coefficients of frequency decomposition of the signal; $d_{m,n}$ — the distance between the central element and the current one in the plane of expansion; $\gamma(\theta,\varphi)$ — the angle between the current direction and the normal one; $p_{m,n}(\theta,\varphi)$ — the polarization vector element.

The integrated vector normalized radiation pattern (RP) of the antenna is represented as follows:

$$F_a(\theta,\varphi)=\begin{pmatrix} F_a^{mid}(\theta,\varphi) \\ F_a^{cros}(\theta,\varphi) \end{pmatrix} \tag{4}$$

where $F_a^{mid}(\theta,\varphi)$ and $F_a^{cros}(\theta,\varphi)$ and RP antenna on the main and cross polarization.

The results of modeling of polarization parameters of antenna with a deviation of the maximum of RP at angles $\varphi_{max}=37^\circ$ and $\theta_{max}=24^\circ$ (Fig. 5–6) indicate a distortion of polarization parameters of the radiated field.

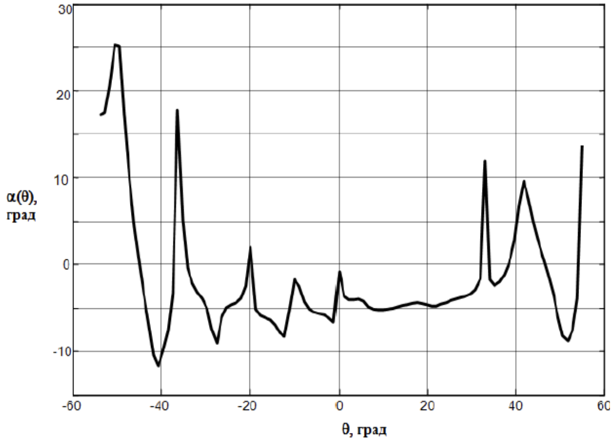

Figure 5: Ellipticity angle

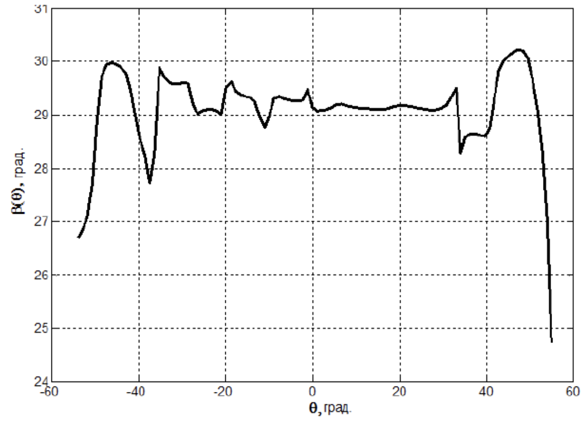

Figure 6: Orientation Angle

The ellipticity angle can vary from minus 12˚ to 26˚, and the orientation angle of polarization ellipse varies from 24.8˚ to 30.4˚. The maximum polarization loss when receiving on the ideal antenna with linear vertical polarization will be -1.87 dB.

Experimental studies of the polarization parameters of typical antennas were based on the use of laboratory equipment consisting of a generator, a transmitting antenna, a test antenna on a turntable and a meter. The following types of antennas were investigated: the open end of a rectangular waveguide; rectangular pyramidal horn; H-sectoral and E-sectoral horns; pyramidal horns with a phase-moving section and with a polarization grid in disclosing. In all cases the amplitude diagram of dependence of the ellipticity coefficient and the orientation angle of polarization ellipse on the antenna radiation angle was investigated. The polarization decoupling factor was also calculated.

The results of studies of antennas show that polarization losses in general can reach γ_p=4.6 dB due to polarization distortions of the radio access channel antennas.

The vector of the electric field strength near the transmitting antenna will be:

$$E_{imp}(t) = H_\alpha^T H_\beta^T (S(t) p_1^0)^T \qquad (5)$$

where $H_\alpha = \begin{pmatrix} \cos(\alpha) & -j\sin(\alpha) \\ -j\sin(\alpha) & \cos(\alpha) \end{pmatrix}$ — ellipticity matrix; $H_\beta = \begin{pmatrix} \cos(\beta) & -\sin(\beta) \\ \sin(\beta) & \cos(\beta) \end{pmatrix}$ — orientation matrix; $p_1^0 = (1\ 0)^T$ — the initial ort of the linear polarization basis.

Due to the propagation characteristics of radio waves the strength vector of the received signal on the receiving antenna will be shown in the form:

$$E_{pr}(t) = E_{imp}(t - t_0) K_{r0}(t) + \sum_{i=1}^{n} R_i(t - l_i) K_{ri}(t - l_i) E_{imp}(t - l_i) \qquad (6)$$

where n is the total number of reflections during the propagation of radio waves; $K_{r0}(t)$ and $K_{ri}(t-l_i)$ — are the attenuation factors of the direct and reflected radio waves; l_0 and l_i are the lag multipliers for direct and reflected radio waves; $R_i(t-l_i)$ — the reflection coefficient matrix.

The polarization parameters of the receiving antenna will be described using the polarization vector for the given angles of ellipticity and orientation of the polarization diagram of the receiving antenna respectively:

$$p_a = H_\alpha^{T*} H_\beta^T p_1^0 \qquad (7)$$

The output signal of the receiving antenna will be:

$$U_{pr}(t) = p_a^{T*} E_{pr}(t) K_a + U_m(t) = U_c(t) + U_m(t) \qquad (8)$$

where K_a is the coefficient taking into account the losses and the transforming role of the receiving antenna (effective length for vibrators); $U_m(t)$ — the thermal noise of the receiving channel.

If the potential value of the ratio of signal power to noise power, or just the signal-to-noise ratio matters:

$$h^2 = \frac{P_c}{P_m} \qquad (9)$$

then the real one depends on the coefficient of polarization reception:

$$h_{out}^2 = h^2 K_{pr} \qquad (10)$$

which is determined as:

$$K_{pr} = \cos^2 \delta \qquad (11)$$

where δ is the angle between the polarization vectors of the signal and the antenna, which is essentially a polarization mismatch between the signal and the antenna and is in accordance with the expression:

$$\delta = \arccos(E_{pr}^T p_a^*) \qquad (12)$$

Therefore, the actual ratio of signal power to noise power at the output of the considered transmission channel can be presented as:

$$h_{out}^2 = 10 \log\left(\frac{P_c}{P_m}\right) - K_{loss} \qquad (13)$$

The ratio of polarization reception channel and signal-to-noise ratio will be

$$K_{ch} = \frac{1 + m(2\cos^2\delta - 1)}{2} \qquad (14)$$

$$h_{out}^2 = h^2 K_{ch}$$

where m is the index or degree of polarization of electromagnetic wave.

We determine the bandwidth capacity of the receiving channel in a general form:

$$C = \Delta F \log_2\left(1 + h^2 \frac{1 + m(2\cos^2\delta - 1)}{2}\right) \qquad (15)$$

where ΔF is the channel bandwidth.

The probability of transmission errors of such channel will be:

$$P_{loss} = 1 - F\left(\sqrt{kh^2 \frac{1 + m(2\cos^2\delta - 1)}{2}}\right) \qquad (16)$$

where k is the coefficient associated with the type of modulation; F (x) is the Laplace function.

We will consider the dependence of the receiving channel capacity on the polarization mismatch at fixed values of the degree of polarization of the wave (Fig. 7) and the probability of error (Fig. 8).

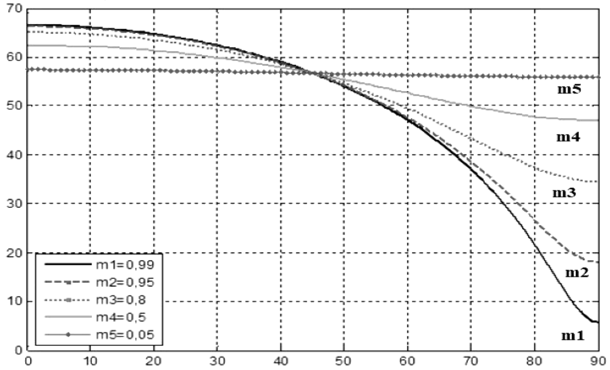

Figure 7: Capacity in megabits depending on the magnitude of the mismatch angle due to polarization

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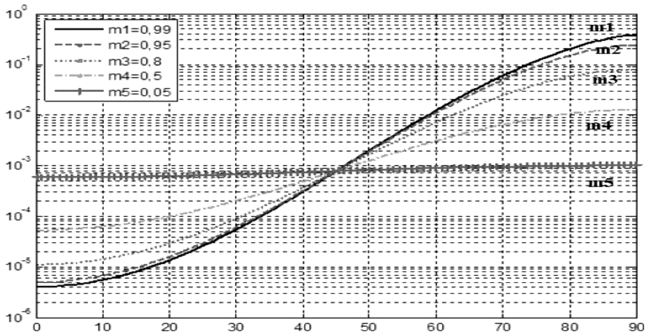

Figure 8: The probability of errors in megabits depending on the magnitude of the mismatch angle due to polarization

The value of the energy parameter h^2=20 dB and the channel bandwidth capacity ΔF = 10 MHz. The capacity depends strongly on the mismatch angle with a degree of polarization $m \geq 0.8$. For typical antennas, with a degree of polarization $m \geq 0.95$, the channel capacity can be reduced by almost 4 times, and with a degree of polarization m=0.5, only by 30%. The probability of transmission errors at different polarization indices (Fig. 8) indicates that an increase in the mismatch angle beyond a polarization of more than $\delta = 10^{\circ}$ leads to a significant increase in errors, and at $m \leq 0.8$ errors become unacceptable

V. CONCLUSION

On the basis of the conducted research it is possible to note the components of the methodology for the analysis of the capacity of radio access channel, including: the research of polarization characteristics of receiving and transmitting antennas in the sector of the radio access system; the study of polarization losses due to the mismatch of polarization parameters of signals and antennas; the study of bandwidth capacity, permissible channel transmission errors and the presence of polarization losses; the development of proposals to reduce the influence of polarization distortion of antennas and signals on the channel bandwidth capacity.

Consequently, the developed methodology for analyzing the bandwidth capacity of the radio access channel of wireless networks taking into account polarization distortions makes it possible to investigate the impact of polarization mismatch and the degree of polarization of radio waves on the bandwidth capacity of the receiving channel of the system and explore the possibilities of increasing the bandwidth capacity by compensating polarization distortions of antennas during emission and reception, which constitutes a significant practical importance for the organization of seamless access in 5G networks and the Internet of Things as well as for industrial access and the management of remote technological networks.

In this context, we should say about the application of the results of our research. As it was mentioned above, the application in the Internet of Things system is primarily in the possibility of developing the exchange of information between various devices. However, in this article we have formed an assessment of how to apply the results. We found that the applied model can be considered for the noise shielding. In other words, in a situation when it is necessary to release new frequencies for every new technological initiative, the application of the developed technology can promote both increasing of number of the same range users and coexistence of protected and open ranges in one technological chain.

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