

Розроблено двоточкові і багатоточкові комунікативні моделі бездротового середовища з однопроменевими і багатопроменевим поширенням радіохвиль. Запропоновані моделі дозволяють створювати різні типи комунікативних систем з урахуванням заданої геометрії розміщення затінюючих та розсіюючих конструкцій, а також використовувати на передавальній та приймальній сторонах антенні решітки довільної конфігурації. Виконано верифікацію розроблених моделей в умовах надзвичайних ситуацій

Ключові слова: бездротове середовище, комунікативна модель, надзвичайна ситуація, MANET, VANET, FANET

Разработаны двухточечные и многоточечные коммунікативные модели беспроводной среды с однолучевым и многолучевым распространением радиоволн. Предложенные модели позволяют создавать различные типы коммунікативных систем с учетом заданной геометрии размещения затеняющих и рассеивающих конструкций, а также использовать на передающей и приемной сторонах антенные решетки произвольной конфигурации. Выполнена верификация разработанных моделей в условиях чрезвычайных ситуаций

Ключевые слова: беспроводная среда, коммунікативная модель, чрезвычайная ситуация, MANET, VANET, FANET

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DEVELOPMENT OF COMMUNICATION MODELS OF WIRELESS ENVIRONMENT IN EMERGENCY SITUATIONS

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1. Introduction

A reliable communication system is necessary in order to organize rescue operations in emergency situations (ES). However, ES can completely destroy the infrastructure of existing communications in a given area. This puts communication and interaction between rescuers at risk. The communication system of ES should be able to rapidly create an infrastructure for supporting the interaction between groups of rescuers and survivors. In this regard, it is relevant to create reliable autonomous communication systems, capable of covering the disaster zone quickly in order to restore network interaction. In this case, it is preferable to develop autonomous systems, capable of creating spontaneous communication networks. A separate direction in the prevention of ES occurrence is the development of sporadic communication networks to remotely acquire information from intelligent sensors [1, 2] that control dangerous states of objects. Paper [3] focuses on research into sensors of ES occurrence under actual conditions of their application. Papers [4, 5] consider solving the task on enhancing sensor effectiveness under actual conditions in the operation of objects.

One of the most promising concepts in the development of systems and networks of operational communication for ES is wireless communication using a group of unmanned transportation ground-based and aerial vehicles. The imple-

mentation of this concept implies development of specialized systems of vehicle positioning in an emergency zone and mobile communication with a rapidly changing topology at a limited frequency resource. Under these conditions, in order to increase communication capacities of wireless networks, paper [6] proposes the use of a dynamic access to the frequency resource. The most promising technology is the deployment of Cognitive Radio (CR) networks over TV-White Spaces (TVWS) [7]. Given a particular complexity of implementation of wireless communication in ES, simulation [8] is one of the main methods used for analysis and development of new technologies. Studying communication characteristics of wireless environment (WE) is very important when choosing a reliable communication technology in ES. However, the complexity and diversity of actual WE in ES, as well as an objective need for reliable communication technologies, make the development of communication models of WE in ES particularly relevant

2. Literature review and problem statement

To organize wireless communication under special conditions, various types of ad-hoc networks are widely used. The best-known are MANET (Mobile Ad-Hoc Network) [9] and VANET (Vehicular Ad-Hoc Networks) [10]. MANET is

a special network of mobile nodes, and VANET is a network of automobile nodes. The new concept FANET (Flying Ad-Hoc Networks), a network of flying nodes, was presented in 2012 [11]. In paper [11], it is noted that one of the main problems of FANET is to enable a reliable connection between flying nodes. Article [12] proposed the adaptive protocol MAC (Media Access Control) that uses, for WE between nodes, an omni-directional antenna for control and a directional antenna for data transmission. The modified protocol OLSR and a directional antenna are discussed in [13]. The proposed approach decreases a delay and improves the overall throughput. Article [14] proposes the protocol GPMOR (Geographic Position Mobility Oriented Routing), based on geographical routes, that allows finding the best available node to decrease the impact of communication breakdown, caused by the mobility of nodes. The protocol is based on the Gauss-Markov mobility model for predicting a position when choosing the best transition node for routing.

In the networks based on unmanned nodes, the use of known clustering technologies is limited by high mobility and a frequent updating of clusters. To overcome these limitations, paper [15] proposed a new mobility prediction technology that uses the model, weighted by clusters, which utilizes node attributes, and allows the prediction of network topology taking into consideration the data structure Trie and the mobility model. Clustering algorithm in the networks of unmanned aerial vehicles (UAV) that employs short-range communication between nodes is discussed in [16]. It reduces the cost and complexity of the system for dynamic routing of UAV nodes. To enable efficient interaction between physical, channel, and network levels, it is proposed to use intelligent MAC, based on common data attributes, such as the type of an aerial, frequency of bit errors, packet type, coordinates of a mobile node. This generally provides a shorter delay in delivering the packets in comparison with the standard IEEE 802.11, and increases control efficiency. In order to plan time intervals at the level of MAC-addresses, it is proposed to use TDMA (Time Division Multiple Access) [11]. This enables creating a multi-user overlapping cluster for data aggregation and enhancing the ratio of delivered packets and end-to-end delay [17].

Article [18] proposes a new mechanism for sending packets in FANET, using the adaptive forwarding scheme, taking into account the probability of forwarding and redirection zone. This approach improves the resulting delay and a packet transmission coefficient. Paper [19] proposes the obstacle-free routing technology, which allows multimedia distribution supporting the quality of service in mobile and dynamic topologies. A new MAC protocol, LODMAC (Location Oriented Directional MAC) is proposed in paper [20]. Directional aeriels are used and the location of neighboring nodes is evaluated. It is noted that directional aeriels have a region with the absence of reception (transmission). This drawback is taken into consideration in LODMAC. The LODMAC protocol enhances throughput, improves delay and network utilization. In addition, the protocol proves to be better than conventional DMAC (Directional MAC) and may be considered promising for FANET MAC [20].

Thus, the presented analysis of literature data indicates that much work has been done up to now in the field of enhancing reliability of communication between mobile nodes; the original results have been obtained. However, most results are related to the modernization of technologies at the channel and network levels. The physical level of commu-

nication is practically not considered. Only the possibility of using directional aeriels is explored. However, the capabilities of WE itself for the transportation of radio waves from the source to the receiver, which determine potential throughput in the considered ad-hoc networks with and without consideration of directional properties of transmission and reception aeriels under complex conditions of ES, are not examined and are not tackled. But most destabilizing factors and interferences responsible for the complexity in solving the task on ensuring reliable communication under ES conditions, including consideration of mobility, occur at the physical level. That is why an important and unresolved part of the problem is the development of communication models of WE under ES conditions and their numerical verification.

3. The aim and objectives of the study

The aim of present study is the development of communication models of WE in ES, as well as their numerical verification under test conditions.

To accomplish the aim, the following tasks have been set:

- to develop a two-point beam communication model of WE in ES with and without consideration of directivity characteristics of the transmitting and receiving aeriels;
- to develop a multipoint beam communication model of WE in ES, taking into account directivity characteristics of the elements of aerial arrays, used at the transmitting and receiving sides;
- based on numerical study, to verify the two-point and multipoint beam communication models of WE for the test ES conditions.

4. Two-point beam communication model of the wireless environment in emergency situations

To develop a reliable technology of wireless communication under conditions of ES, the physical level must be well studied and described. In this case, the models of radio waves propagation and characteristics of aeriels are the key factors that influence the quality of wireless communications in ES. Precise mathematical description of any actual communication channel turns out to be a very difficult task. That is why the simplified mathematical models are used that make it possible to identify the most important regularities of an actual channel. The most common is the two-point wireless multi-beam communication between the transmitter and the receiver [21, 22].

However, under conditions of ES, multibeam propagation often manifests itself in the form of a limited number of local beams, predetermined by the complicated geometry of location and the shape of reflecting, shadowing, and scattering structures. In this case, well-known models [23, 24] of radio waves propagation in COST 231 specification (European Cooperation in the field of Scientific and Technical Research) are mostly confined to the attenuation and delay of radio waves in environment for various statistics of propagation pathways. Development of technologies of wireless communication and extension of their application scope resulted in the adoption of specifications for ES models, COST 259 and COST 273, based on beam representation of radio waves propagation [25–27]. In these papers, it is noted

that the ray theory is a promising procedure for the development of new communication models of WE and statistical modeling of wireless communication.

Increasing requirements to the rate and reliability of transmission in complex WE led to the emergence of MIMO technology (a set of transmitting and receiving aerials), which is a key component of such standards as LTE/3GPP, 802.11x and 802.16 x. This led to the modification of WE models. On the one hand, these are analytical (non-physical) models, characterizing the WE matrix of MIMO, including aerial effects, for example, the model of aerial array with angular delays 802.11n, as well as the correlation models by Kroneker and Wichselberger [28]. On the other hand, these are physical wave models, taking into account a delay, directions of waves radiation and reception in WE, as well as a complex character of their propagation taking into account polarization. The physical models are independent on the aerial, which is why they can be directly combined with the applied aerials for the assessment of communication characteristics of MIMO technologies. A separate group of promising physical models is the stochastic models based on the WE geometry (GSCM), taking into account a certain position of objects of scattering. Model COST 2100 MIMO [29] is GSCM, which is built based on early COST 259 and 273 models [30]. The channel model COST 259 [31] was the first GSCM that took into account a set of aerials only at the base stations. A set of aerials at the transmitting and receiving sides (full MIMO systems) was taken into consideration in the models of COST 273 specification. COST 2100 model is an extension of the model COST 273 for various types of MIMO systems, including multi-user ones. The basic varieties of WE in COST 2100 and COST 273 models are characterized by the specificity of radio waves propagation in macro-environments, micro-environments, pico-environments, and special ad-hoc environments [30].

In addition, it is noted that in macro-environments the base station is placed over the roofs of surrounding buildings. In micro-environments, the base station is at the level of or below the roofs of surrounding buildings in the open air. Pico-environments typically cover a small area, for example, at premises (offices, apartments, halls, corridors, etc.), or tunnels and mines. In special environments, all transceivers are placed approximately at the same height and are characterized by quasi-static mobility. According to [30], there are other varieties of WE under condition that the required parameters are known. However, under ES conditions, most WE differ from the specified ones and essentially depend on existing spatial, angular, and temporal characteristics of beams in possible radio waves propagation. The approximations of single scattering and the first approximation of multiple scattering usually hold for such conditions.

In addition, COST 2100 and COST 273 models are based on the clustering approach, taking into account radio waves propagation in WE in the form of a set of infinitely thin beams. In the case of wide enough clusters and MIMO technologies under ES conditions, this approach considerably complicates WE models. In this case, COST 2100 and COST 273 models do not affect communication characteristics of both WE and WE in combination with transmitting and receiving aerials and aerial arrays.

Let us assume that under ES conditions radio waves propagation in WE from arbitrary radiation point t to arbitrary reception point r takes place based on known beam

representations. However, in the considered case, instead of infinitely thin beams in WE, we will consider the beams of finite width, the characteristics of which in the general case are described by functions $F_t(\theta_t, \Delta\theta_t)$ and $F_r(\theta_r, \Delta\theta_r)$ for the transmitting and receiving beams, respectively, where θ_t and θ_r are angular coordinates of beams in the considered points of WE, and $\Delta\theta_t$ and $\Delta\theta_r$ determine the width of the respective beams. Consider the most difficult situation when, under conditions of ES, WE between radiation and reception points is characterized by a small number of possible beams. Such a situation typically occurs when WE includes a large number of considerable structures that shadow, reflect, and scatter radio waves. Let a direction of the beam at the radiation point be characterized by angular coordinate u_t , and the direction of beam at the reception point – by angular coordinate u_r . In the general case, effects of attenuation and scattering of radio waves along the route in the radiation direction u_t and reception direction u_r at time t will be described by arbitrary function $a(u_t, u_r, t)$. A specific form of $a(u_t, u_r, t)$ determines the resulting amplitude of radio waves scattering for a beam in WE, taking into account the features of scattering non-uniformity in the environment and attenuation along the entire route. Given the above parameters, the two-point one-beam communication model of WE for arbitrary angular coordinate θ_t at the radiation point and arbitrary angle coordinate θ_r at the reception point will be described as

$$H_{11}(\theta_t, \theta_r, t) = F_t(\theta_t - u_t, \Delta\theta_t) F_r(\theta_r - u_r, \Delta\theta_r) a(u_t, u_r, t). \tag{1}$$

If there is L of beams between points of radiation and reception in WE, the two-point multibeam communication model will be described as

$$H_{11}^L(\theta_t, \theta_r, t) = \sum_{k=0}^{L-1} F_{t,k}(\theta_t - u_{t,k}, \Delta\theta_{t,k}) F_{r,k}(\theta_r - u_{r,k}, \Delta\theta_{r,k}) a_k(u_{t,k}, u_{r,k}, t), \tag{2}$$

where $F_{t,k}(\theta_t - u_{t,k}, \Delta\theta_{t,k})$ is the function of the k -th radiation beam; $F_{r,k}(\theta_r - u_{r,k}, \Delta\theta_{r,k})$ is the function of the k -th reception beam; $u_{t,k}, \Delta\theta_{t,k}$ are the angular coordinate and the width of the k -th radiation beam; $u_{r,k}, \Delta\theta_{r,k}$ are the angular coordinate and the width of the k -th reception beam; $a_k(u_{t,k}, u_{r,k}, t)$ is the function of attenuation and scattering of radio waves for k -th beam of radiation and reception.

Models (1) and (2) allow us to describe and investigate communication characteristics of WE itself for various types of emergency situations in arbitrary directions, characterized by angles θ_t and θ_r of radiation and reception without taking into account the directivity characteristics of the used transmitting and receiving aerials, the phase centers of which are located in the considered points of radiation and reception of WE. Let the directivity characteristics of the transmitting and receiving aerials be described by respective functions $A_t(\beta_t, \Delta\gamma_t)$ and $A_r(\beta_r, \Delta\gamma_r)$, where β_t, β_r determine angular coordinates of direction of the main maximum of the transmitting and receiving aerials, and magnitudes $\Delta\gamma_t$ and $\Delta\gamma_r$ determine the width of their directivity characteristics for half power.

Taking into consideration the use of directional transmitting and receiving aerials in the considered points of WE, its communication characteristics, following models (1) and (2), will be described, respectively

$$\begin{aligned} AH_{11}(\theta_t, \theta_r, t) &= \\ &= A_t(\theta_t - \beta_t, \Delta\gamma_t) H_{11}(\theta_t, \theta_r, t) A_r(\theta_r - \beta_r, \Delta\gamma_r), \end{aligned} \quad (3)$$

$$\begin{aligned} AH_{11}^L(\theta_t, \theta_r, t) &= \\ &= A_t(\theta_t - \beta_t, \Delta\gamma_t) H_{11}^L(\theta_t, \theta_r, t) A_r(\theta_r - \beta_r, \Delta\gamma_r). \end{aligned} \quad (4)$$

Models (3) and (4) make it possible to describe and explore communication characteristics of WE in combination with the use of the directional transmitting and receiving aerials with specified parameters in various types of ES for arbitrary angular coordinates θ_t and θ_r of radiation and reception.

5. Multipoint beam communication model of wireless environment in emergency situations

In a number of cases, the use of MIMO technology (multiple aerials at transmitting and receiving sides) appears to be more preferable for enhancing communication characteristics of WE under ES conditions. To describe and explore communication possibilities of WE, the multipoint beam communication model is required in this case. Such a model must include two or more radiation points and two or more reception points. To simplify subsequent consideration, we will confine ourselves to the case of two arbitrary radiation points and two arbitrary reception points in WE. Let each point at the transmitting side be associated with each point at the receiving side by the limited set of beams with the specified parameters, determined by specific emergency conditions in WE. Then, in the considered case, taking into account model (2), the multipoint beam communication model will be defined by matrix

$$\begin{aligned} H_{2 \times 2}(\theta_t, \theta_r, t) &= \\ &= \begin{bmatrix} H_{11,11}^L(\theta_t, \theta_r, t) & H_{11,12}^L(\theta_t, \theta_r, t) \\ H_{11,21}^L(\theta_t, \theta_r, t) & H_{11,22}^L(\theta_t, \theta_r, t) \end{bmatrix}, \end{aligned} \quad (5)$$

where

$$\begin{aligned} H_{11,ij}^L(\theta_t, \theta_r, t) &= \\ &= \sum_{k=0}^{L_{ij}-1} F_{t,k}^{ij}(\theta_t - u_{t,k}^{ij}, \Delta\theta_{t,k}^{ij}) F_{r,k}^{ij}(\theta_r - u_{r,k}^{ij}, \Delta\theta_{r,k}^{ij}) a_k^{ij}(u_{r,k}^{ij}, u_{r,k}^{ij}, t), \\ &i, j=1, 2. \end{aligned}$$

Function $H_{11,ij}^L(\theta_t, \theta_r, t)$ in the model (5) determines the multibeam communication model of WE between the i -th radiation point and the j -th reception point, depending on functions $F_{t,k}^{ij}(\theta_t - u_{t,k}^{ij}, \Delta\theta_{t,k}^{ij})$ and $F_{r,k}^{ij}(\theta_r - u_{r,k}^{ij}, \Delta\theta_{r,k}^{ij})$ of the radiation and reception beams respectively, as well as function $a_k^{ij}(u_{r,k}^{ij}, u_{r,k}^{ij}, t)$ of attenuation and scattering of radio waves in the specified beams. In the case of arbitrary number of radiation and reception points in WE, the model will be determined by extended matrix (5) of the corresponding dimensions. The number of lines of the matrix will be determined by the number of radiation points, while the number of columns will be determined by the number of reception points.

In the case of model (5), current communication characteristics of WE for the correspondent matrix $H_{2 \times 2}(\theta_t, \theta_r, t)$ will be characterized by the Frobenius norm $N_F(\theta_t, \theta_r, t)$, determined by magnitude

$$N_F(\theta_t, \theta_r, t) = \sqrt{\sum_{i=0}^1 \sum_{j=0}^1 |H_{2 \times 2}(\theta_t, \theta_r, t)_{i,j}|^2}. \quad (6)$$

The merit of model (5) is its invariance relative to the coordinates of radiation and reception points in FE. This means that the specified points can be used for communication for different types of aerials. For example, for aerial arrays with isotropic directivity characteristics of aerial elements, placed at specified points on both sides of WE, current communication characteristics of $AR_{2 \times 2}(\theta_t, \theta_r, t)$ of the obtained system of wireless communication in general will be determined from

$$AR_{2 \times 2}(\theta_t, \theta_r, t) = |\alpha_r(\theta_r)^* H_{2 \times 2}(\theta_t, \theta_r, t) \alpha_t(\theta_t)|, \quad (7)$$

where

$$\alpha_r(\theta_r) = \left[1/\sqrt{2} \quad \exp\{-j2\pi d_r \sin(\theta_r) / \lambda\sqrt{2}\} \right]^T,$$

$$\alpha_t(\theta_t) = \left[1/\sqrt{2} \quad \exp\{-j2\pi d_t \sin(\theta_t) / \lambda\sqrt{2}\} \right]^T,$$

$\alpha_r(\theta_r)$, $\alpha_t(\theta_t)$ are the vectors of phase shifts in the aerial elements of the arrays on the receiving and transmitting sides, respectively, and magnitudes d_r , d_t and λ determine the distance between aerial elements for the transmitting and receiving arrays, as well as the operation length of radio waves. In the case of application of aerial arrays with the directional elements, communication characteristics of the obtained system considering current environment $KN_{2 \times 2}(\theta_t, \theta_r, t)$ will be determined from

$$KN_{2 \times 2}(\theta_t, \theta_r, t) = |v_r(\theta_r, u_r)^* H_{2 \times 2}(\theta_t, \theta_r, t) v_t(\theta_t, u_t)|, \quad (8)$$

where

$$\begin{aligned} v_r(\theta_r, u_r) &= \\ &= \left[1/\sqrt{2} \quad \exp\{-j2\pi d_r \sin(u_r) / \lambda\sqrt{2}\} \right]^T f_r(\theta_r - u_r, \Delta\theta_r) \end{aligned}$$

and

$$\begin{aligned} v_t(\theta_t, u_t) &= \\ &= \left[1/\sqrt{2} \quad \exp\{-j2\pi d_t \sin(u_t) / \lambda\sqrt{2}\} \right]^T f_t(\theta_t - u_t, \Delta\theta_t) \end{aligned}$$

$v_r(\theta_r, u_r)$, $v_t(\theta_t, u_t)$ are the vectors of amplitude-phase shifts in the aerial elements of the arrays on the transmitting and receiving sides taking account directivity characteristics of aerial elements, described by functions $f_t(\theta_t - u_t, \Delta\theta_t)$ and $f_r(\theta_r - u_r, \Delta\theta_r)$, respectively. Here u_t and u_r determine angular coordinates of radiation and reception beams for the assigned track in WE, and magnitudes $\Delta\theta_t$ and $\Delta\theta_r$ characterize the range of characteristics of directivity of the aerial elements for the transmitting and receiving arrays.

6. Numerical verification of the two-point and multipoint beam wireless communication models of wireless environment for test emergency situations

The results of numerical verification of the models, presented below, were obtained for the function of attenuation and scattering of radio waves in beams $a(u_t, u_r, t)$, described by a random Rayleigh process with a mean square deviation

of 0.98. Such a process is characteristic of deep fading in WE beams, often occurring under actual conditions of ES. The model values of initial angular coordinates of radiation and reception beams in WE for the one-beam and multibeam models were determined as $u_t = -30^\circ$ and $u_r = 60^\circ$, respectively, and the width of these rays was selected equal to $\Delta\theta_t = \Delta\theta_r = 25^\circ$ for all beams. Current communication characteristics of two-point WE in the case of one radiation beam and one reception beam, characterized by $H_1 = |H_{11}(\theta_t, \theta_r, t)|$ for arbitrary angular coordinates θ_t and θ_r of radiation and reception are shown in Fig. 1a, and in the case of eight beams $H_8 = |H_{11}^8(\theta_t, \theta_r, t)|$ – in Fig. 1b. The data, shown in Fig. 1b, were obtained at discrete shifts of angular coordinates of the k -th transmitting beam $u_{t,k} = u_t - \Delta_t(k-1)$ and the k -th receiving beam $u_{r,k} = u_r - \Delta_r(k-1)$. In this case, discrete pitch for radiation beams $\Delta_t = 12^\circ$, and for reception beams $\Delta_r = -5^\circ$.

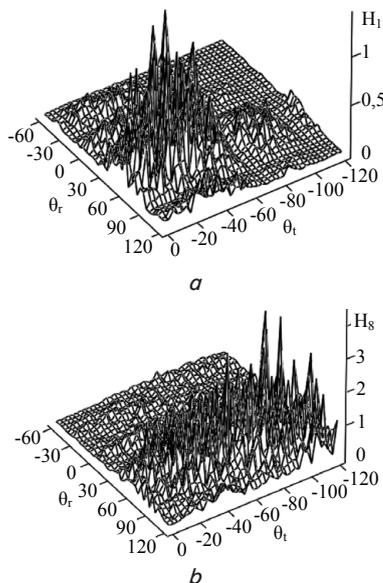


Fig. 1. Communication characteristics of tested two-point WE: *a* – in the case of one beam of radiation and reception; *b* – in the case of eight different beams of radiation and reception

Taking into account the use of directional transmitting and receiving aerials at considered WE points (in the case of Fig. 1), its communication characteristics are illustrated in the form of appropriate projections $AH_1 = |AH_{11}(\theta_t, \theta_r, t)|$ and $AH_8 = |AH_{11}^8(\theta_t, \theta_r, t)|$ onto the plane of angular coordinates θ_t and θ_r of radiation and reception in Fig. 2 for the considered parameters of the transmitting and receiving aerials $\beta_t = -30^\circ$, $\Delta\gamma_t = 14^\circ$ and $\beta_r = 60^\circ$, $\Delta\gamma_r = 14^\circ$, respectively. These data correspond to the situation in which angular coordinates of the maximum of transmitting and receiving aerials coincide with the initial angular coordinates of radiation and reception beams in the considered test WE. In this case, the width of characteristics of directivity of the transmitting and receiving aerials were selected identical and equal to about half the width of the beams in WE.

Fig. 2 shows in grey color the current communication characteristics of the considered WE, and in black color – similar characteristics, but taking into consideration the use of directional transmitting and receiving aerials.

A particular test model of the environment with two radiation points and two reception points, described in chapter 5, was examined for the numerical verification of multipoint

beam communication models of WE in ES. Initial data for the model test beam WE are given in Table 1.

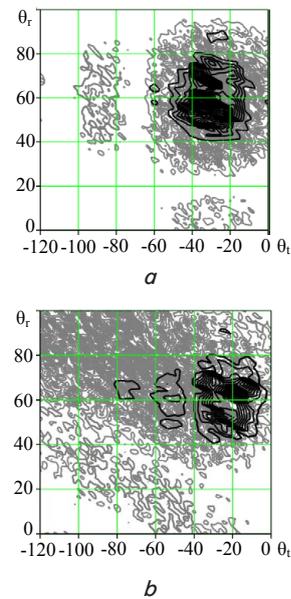


Fig. 2. Communication characteristics of two-point WE without (gray color) and with taking into account the use of directional aerials at the transmitting and receiving sides (black color): *a* – in the case of one radiation beam and one reception beam; *b* – in the case of eight different beams of radiation and reception

Table 1

Initial data for wireless environment

Directions of beams to points	Initial directions of radiation beams	Initial directions of perception beams	Width of radiation beam	Width of reception beam
1–1	-30°	60°	5°	1°
1–2	-10°	20°	10°	10°
2–1	0°	10°	10°	10°
2–2	-40°	-10°	5°	3°

In accordance with data from Table 1, Fig. 3 shows current communication characteristics $N_F(\theta_t, \theta_r, t)$ of multipoint WE for the case of one radiation beam and one reception beam and eight different radiation and reception beams in the environment.

The numerical experiment was conducted to study communication characteristics of different WE. A multipoint (two radiation points and two reception points) one-beam WE was considered (Fig. 3, *a*). Its current communication characteristics are shown in Fig. 4 in the form of the corresponding projections of the Frobenius norm $N_F(\theta_t, \theta_r, t)$ (shown in black) onto the plane of angular coordinates θ_t and θ_r of radiation and reception. For comparison, Fig. 4, *a* shows in color a similar projection for the same WE, but with direct determined beams in the environment between a pair of radiation points and the corresponding pair of reception points. The distance between the specified pairs of radiation and reception points corresponded to half a wavelength. Fig. 4, *b* shows in color a similar projection, but with indirect determined beams in the environment.

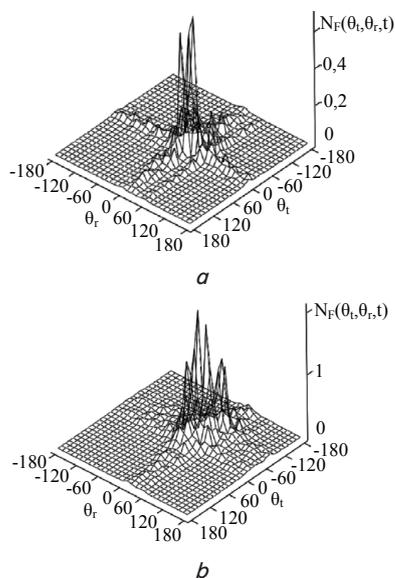


Fig. 3. Communication characteristics of multipoint wireless environment: *a* – in the case of one radiation beam and one reception beam; *b* – in the case of eight different beams of radiation and reception

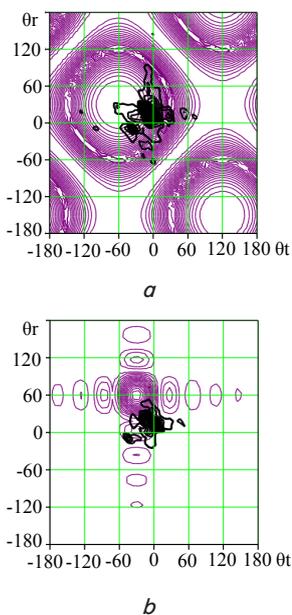


Fig. 4. Comparison of communication characteristics of different types of multipoint one-beam wireless environments: *a* – direct determined beams; *b* – indirect determined beams

As an example of the influence of directional properties of aerial arrays at the transmitting and receiving sides on communication characteristics of multipoint radiation WE, Fig. 5 shows results of numerical experiment on the current angular spectra of communication characteristics of WE.

The angular spectra of current communication characteristics for the considered multipoint WE at the initial values of angle -30° for the radiation beam, and 60° for the reception beam, are marked in blue color in Fig. 5. The angular spectra of current communication characteristics of WE considering the use of the transmitting and receiving aerial arrays with isotropic and directional characteristics of aerial elements are marked in red color.

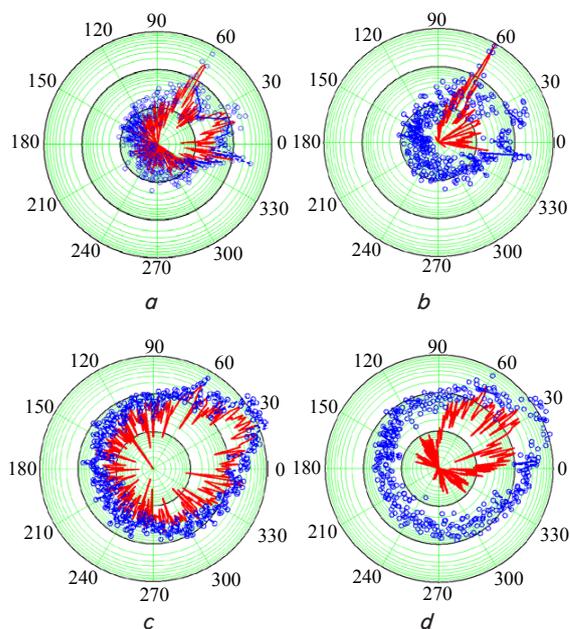


Fig. 5. Current angular spectra of communication characteristics of multipoint one-beam (*a, b*) and eight-beam (*c, d*) WE depending on the direction of reception at fixed value of initial angle -30° of radiation beam for the case of transmitting and receiving aerial arrays: *a, c* – isotropic aerial elements; *b, d* – directional aerial elements

7. Discussion of results of numerical study of beam communication models in wireless environment

Results of numerical studies, shown in Fig. 1–5, indicate the efficiency of the proposed two-point and multipoint beam communication model of WE, characteristic of actual conditions of the majority of ES. Communication characteristics of two-point WE in the case of one and eight radiation and reception beams in Fig. 1 indicate that with an increase in the width of radiation and reception beams, as well as in the number of beams in WE, its own communication characteristics expand – the area of permissible communication directions for radiation and reception increases. WEs with one narrow radiation beam and one narrow reception beam demonstrate their worst communication characteristics. In the case of the use of directional aerials at the transmitting and receiving sides of WE (Fig. 2), communication characteristics of the joint system decrease as the width of directivity of the applied aerial decrease. This explains low efficiency of known technologies for wireless communication under complicated conditions of actual emergency situations. In this case, it was established that an increase in the width of directivity characteristics of aerials cannot provide for an increase in communication capacities over those that are offered by WE itself.

Analysis of the numerical results in Fig. 3 shows that communication possibilities of the multipoint WE increase at an increase in the number of beams and depend on parameters of these beams. Based on the proposed approach, it is possible to develop particular models for various multipoint WE, specific for particular types of emergencies. Comparative numerical communication characteristic for various multipoint WE (Fig. 4) shows that the resulting communication possibilities are limited by WE. In the case

of determined direct beams, noise immunity decreases significantly. However, high noise immunity is provided when using deterministic indirect directional beams.

Current angular spectra of communication characteristics of the multipoint one-beam and eight-beam WE for different reception directions at the assigned direction of the radiation beam (Fig. 5) in the case of using aerial arrays with directional aerial elements at the receiving side indicate a high level of noise immunity of communication characteristics. In this case, the use of directional aerial elements in the transmitting and receiving aerial arrays provide in general a higher level of noise immunity of communication characteristics compared with the use of the aerial arrays with directional aerial elements only at the receiving side.

This study is limited to the consideration of communication models of WE and characteristics of the applied transmitting and receiving aerials, parameters of which do not change over time and in space, except for the function of radio waves attenuation and scattering in beams. In this case, the proposed models consider communication problems on the plane, and do not take into account polarization parameters of radio waves. That is why it is advisable to continue further research in the directions that are associated with non-stationary character of space-time parameters of communication models, consideration of communication tasks in space, as well as taking into account polarization parameters of radio waves of radiation, their beam propagation in WE, and reception.

8. Conclusions

1. Two-point communication model of WE with one-beam and multibeam propagation of radio waves in the presence of significant number of shadowing and scattering structures in the environment were developed. The proposed models differ from known models by using the beam approach with finite width of beams. This can simplify known clustering WE model and create different types of two-point

communication models based on the proposed models taking into account specific complex geometry of shadowing and scattering structures in the environment, for example, to develop the models of channel “keyhole (pinhole) effects”. It is shown that practical use of the developed two-point models with one-beam or multibeam radio waves propagation is limited only by two arbitrary points of the environment (a radiation point, and a reception point). This means that phase centers of the applied transmitting and receiving aerials must be located at the specified points.

2. Multipoint communication models of WE with one-beam and multibeam radio waves propagation from each radiation point to each reception point, taking into account shadowing and scattering structures, were developed to study different MIMO technologies under conditions of ES. The models are based on the proposed two-point beam models with finite width of radiation and reception beams in WE. This makes it possible to create, on their basis, specific models of the physical level under complex dynamic ES conditions for various technologies of a set of aerials of arbitrary configuration at the transmitting and receiving sides.

3. The results of numerical study of the developed two-point and multipoint communication models of WE in test situation prove verification of the presented models. In this case, it was found that the use of directional aerials at the transmitting and receiving sides of WE with significant structures, shadowing and scattering radio waves, makes it possible to significantly improve noise immunity. Thus, with the use of the developed communication models, based on beam representation of finite width, transition to 3D coordinates and taking into account temporal dependence of beam parameters in WE, there appears the possibility of the in-depth numerical study of the physical level with a view to developing a reliable and stable data transfer architecture under ES conditions that are non-traditional for communications. In this case, models of radio waves propagation and those of aerials remain key factors, influencing communication characteristics of wireless communications in ES.

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