Запропоновано просторовий метод оцінки потужності сигналу на вході приймача для сімейства стандартів 802.11х. Для цього було проведено аналіз основної енергетичної характеристики безпровідного каналу стандарту 802.11 та отримано експериментальну математичну модель, що враховує максимально-можливу кількість факторів впливу. На основі математичної моделі було визначено допустимі межі її зміни

Ключові слова: безпровідний канал стандарту 802.11, розподіл потужності сигналу, багатопроменеве поширення хвиль

Предложен пространственный метод оценки мощности сигнала на входе приемника для семейства стандартов 802.11х. Для этого был проведен анализ основной энергетической характеристики беспроводного канала стандарта 802.11 и получена экспериментальная математическая модель, которая учитывает максимально-возможное количество факторов влияния. На основе математической модели были определены допустимые пределы ее изменения

Ключевые слова: беспроводной канал стандарта 802.11, распределение мощности сигнала, многолучевое распространение волн

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DEVELOPMENT OF A SPATIAL METHOD FOR THE ESTIMATION OF SIGNAL STRENTH AT THE INPUT OF THE 802.11 STANDARD RECEIVER

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1. Introduction

There has been a significant surge in the implementation of wireless technologies and a wide spread of wireless networks recently. First of all, this is becoming possible due to the relative simplicity of creating high-speed access channels to modern infocommunication services of high quality. On the other hand, a concept of the internet of things has been gaining traction [1], which is characterized by connecting a large number of devices that can exchange data without human participation. As one of particular cases, it is possible to give an example of a smart home, which has its own internal multiservice network based on the IP protocol. There may exist unlimited number of nodes in such a network, household equipment, specialized devices, subscriber devices and sensors, which implies the presence of a fairly sophisticated topology taking into account obstacles and architectural barriers. Given a substantial quantity of devices in the network of a smart home, one of the optimal solutions for the construction of its physical level is the use of technologies from the 802.11x family of standards [2].

Networks from the 802.11x family of standards are characterized by permanent development in the direction of improving the main quality criterion – effective speed of information transmission. As is known, this criterion is directly proportionally dependent on the level of signal strength at the input of the receiver and it determines a parameter of signal quality. Given how widespread the wireless networks are, it is possible to assume that it leads to the occurrence of a number of negative factors that can significantly worsen transmitting characteristics of wireless channels of the information transmission. This, in turn, gives rise to delays and errors when accessing the services with a large volume of traffic. That is why it is a relevant task to search for the new methods and means to minimize the impact of these factors, which is aimed, first and foremost, at improving the characteristics of the basic quality criterion – effective speed of information transmission. One of the directions is the new methods for the diagnosis and optimization of network topology based on the spatial evaluation of energy characteristics of the signal, which would take into account the maximum possible number of factors of influence.

2. Literature review and problem statement

When conducting analysis of existing scientific papers, it is possible to draw a conclusion that the research into the field of wireless technologies of the standard 802.11 has been actively developing recently. However, from a viewpoint of research into one of the main energy signal parameters, it is possible to highlight the following.

Article [3] outlined main characteristics of the wireless systems and presented a general expression for the basic energy signal parameter – signal strength at the input of the receiver, taking into account wave distribution at complex architectural interferences. Paper [4] investigated influence of such destabilizing factors on the received signal strength indicator (RSSI) as: position of the receiver in space, time of measurement, interference noise, architectural obstacles. The results showed that this parameter has rather high fluctuations and is quite difficult to assess.

One of the areas of research that utilizes the evaluation of signal strength at the input of receiver is the widely used identification methods for the estimation of device positioning in the network coverage area [5–7]. The main informative parameter in these studies is also the RSSI parameter while the attenuation in free space and additional beacons to reduce the fluctuations of signal are applied in order to assess location of the devices.

Article [8] reported measurement of the signal under typical home conditions, using a mobile device. Based on this, it was found that the level of signal decreases with an increase in the distance between the access point and a mobile device, while parameters of downloading and unloading the information remain constant at distances of up to 8 m. In addition, the presence of noise showed a decrease in the overall signal level. Different studies were conducted on a larger scale for the city of Patras in Greece, taking into account complex urban development [9]. The authors investigated three models of attenuation in the range of 2.4 GHz: free space, by Hata and by Walfish-Ikegami. It was found that for complex urban development the use of the model of free space is impractical, while the other two are characterized by their advantages and shortcomings. In addition, it was established that the occurrence of attenuation due to architectural obstacles can have the Gaussian normal distribution for logarithmic values.

On the other hand, when considering the level of the input signal, it was established that it is one of the basic parameters characterizing the quality of wireless channel transmission [10]. Such parameter ensures effective speed of information transmission in certain limits. Because of allocating a small frequency resource, there may be interference and noise. Such obstacles arise from the large number of networks that use the same channels for information transmission (areas with high population density and building complexity) [11]. In this case, when the frequency channels collide, information packets for each network take time intervals between the packets of another network. All of these factors lead to the occurrence of interference and deterioration in the effective speed of information transmission.

Thus, summing up the aforementioned, it is possible to define the actions that can improve the efficiency of wireless networks of the 802.11x family of standards. These include: an increase in the level of input signal, installation of more efficient antennas, adding the repeaters to a network, the application of more effective models for the estimation of signal parameters, the use of the newer standard, etc. One of the important parameters is the signal strength at the input of a receiver, which is characterized by considerable fluctuations while the evaluation of this parameter presents a rather significant problem. That is why there is a scientific and technical problem to devise an effective method for assessing the main energy parameter of the wireless channel in line with the standard 802.11, which will make it possible to take into account a maximum number of destabilizing factors in the transmission medium.

3. The aim and objectives of the study

The goal of the present work is to develop a spatial evaluation method of signal strength at the input of the receiver of the standard 802.11. Such method is implemented based on a new mathematical model of allocation for any facility, which makes it possible to take into account a maximally possible number of destabilizing factors.

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

– to explore a general characteristic of the wireless channel of the standard 802.11 and to derive a mathematical model for the evaluation of signal strength at the input of the receiver, taking into account a maximally possible number of parameters in the transmission medium;

– to perform experimental studies for a typical premises and to receive a universal experimental mathematical model based on the spatial distribution of the signal strength;

– to formulate provisions for a spatial evaluation method of signal strength at the input of the receiver.

4. Estimation of the signal strength at the input of the receiver

A general mathematical model of the standard 802.11 wireless channel can be derived from a general model of the radio channel [12]. Such a radio channel can be considered to be the smallest structural unit of a wireless network that has a name – spatial channel of information transmission, which is created by two pairs of receivers and transmitters [13]. Assuming that the pairs are identical, a characteristic of the signal transmission for any standard 802.11 wireless channel in a general case can be written as follows:

$$P_{tr}(t) = L \cdot P_r(t) + P_i(t) + P_n(t), \quad (1)$$

where P_{tr} is the signal strength at the output of the transmitter; P_r is the level of signal strength at the input of the receiver; L is the characteristic of signal attenuation in the medium of transmission; P_i is the level of strength of interference obstacles; P_n is the level of strength of interference noise; t is the parameter of a change in the strength over time.

An 802.11 standard network is primarily regarded as an access point and mobile subscribers. In this case, the most important parameter is the strength of the transmitter of the access point. Since such a network is most often created for complex urban development, the transmitter strength can be to recorded as [3]:

$$P_{tr} = \frac{16kT\pi^2 D^{\mu} a\xi\Delta f L}{D_0^{\mu-2}\lambda^2 G_1 G_2 B\rho}, \quad (2)$$

where T is the noise temperature of the receiver; k is the Boltzmann constant; D is the distance from the transmitter antenna to the receiver antenna; D_0 is the basic distance; G_1, G_2 are the antenna gain coefficient of the transmitter and the receiver; L are the losses due to processes in the atmosphere; Δ_f is the frequency band of the receiver; λ is the wavelength; a is the coefficient of an increase in signal after processing, which depends on the signal/noise parameter; ξ is the coefficient of noise temperature increase due to interference; B is the base of the signal; ρ is the winning coefficient of the ratio signal to noise at range expansion; μ is the signal loss factor in the external environment.

Antenna amplification coefficients of the transmitter and the receiver can be determined by the following expressions:

$$G_1 = \left(\frac{D_0}{D}\right)^2, \; G_2 = S_a\left(\frac{2\pi}{\lambda}\right)^2,$$

where S_a is the effective area of the receiving antenna.

The loss of signal strength in the medium of transmission can be determined by the following formula

$$L = \frac{(4\pi D)^2}{\lambda^2 G_1 G_2 \eta_1 \eta_2}, \quad (3)$$

where η_1, η_2 are the efficiency coefficients of feeders of the transmitter and the receiver.

Attenuation is characterized by a change in the parameters of the environment during transmission under the influence of natural phenomena. This includes the effect of multibeam propagation of waves that occurs during motion of the subscriber in the facilities with complex development. As a result, the so-called maxima and minima of the electric field intensity may occur in the environment. This phenomenon happens because of the heterogeneity un the environment of wave propagation created by natural or artificial obstacles.

Assume that the standard 802.11 networks are used mainly for the facilities and territories with complicated urban development. Then the most common architectural unit is a room, which has a floor, a ceiling, walls, and the presence of a certain number of objects. Thus, in the presence of an emitting device, there would exist in such a room a complex multibeam interference pattern based on the laws of reflection from surfaces of different type and position in space. The overall resultant field can be determined by taking into account the amplitudes and phases of the reflected waves from the respective surfaces. Considering this, the correcting loss factor can be record as [14]:

$$F = \left| F_0 + F_f \rho_f e^{-j\alpha_f} + F_c \rho_c e^{-j\alpha_c} + nF_w \rho_w e^{-j\alpha_w} + \sum_{i=1}^{k} F_{o.or} \rho_{o.or} e^{-j\alpha_{o.or}} \right|^2,$$

where F_x are the interference coefficients that take into account directed radiation properties to the receiver via a corresponding surface (where x: f – floor, c – ceiling, w – walls, or – objects in the room); ρ are the comprehensive coefficients of wave reflection from the surface; α are the phase reflection coefficients, which take into account length of the direct and indirect wave; k is the number of reflection surfaces from the objects in the room.

Multibeam propagation of waves can create rapid attenuation of strength in space, which are based on receiving the waves with the same phase or those different in signs. That is why in certain points of space there may occur the maxima and minima of the signal level. In this case, attenuation coefficient, which will take into account the height of location of the transmitting and receiving antennas, can be recorded as [15]:

$$L = \frac{4\pi^2 D^4}{\lambda^2 G_1 G_2 \eta_1 \eta_2 h_1^2 h_2^2},$$

where h_1^2 and h_2^2 is the height of location of the receiving and transmitting antennas above the floor level.

Obstacles include the independent sources of radiation, which can be taken into account by the superposition rule. Such sources can be divided into two groups: interference obstacles and noise. Interference in the standard 802.11 wireless transmission channels is the signals from other transmitters of the same standard, which utilize the same frequency channel or partially overlap it. In this case, the so-called aligned and neighboring channels may form [11]. In the presence of a large number of wireless networks, the main source of obstacles is the interference. In practice, effect of the interference occurs at increasing load on the networks when transmitting large amounts of information, which employ one and the same frequency channel.

Given the fact that there can be a significant number of interference sources, the overall strength of these obstacles can be evaluated by the following expression:

$$P_i = \frac{G_2}{L_{RX}} \sum_{i=1}^{N} \frac{P_{i.s.i} G_{i.s.i}}{G_{\phi.i} L_{i.i} L_a}, \quad (4)$$

where L_i is the weakening in the interference channel; L_a is the attenuation in the antenna-feeder device of interference transmitter; G_φ is the weakening at minimal angular distance between antennas; $G_{i.s}$ is the antenna gain coefficient of the adjacent interference station; $P_{i.s}$ is the signal strength of the adjacent station; L_{RX} is the attenuation in the antenna-feeder device of receiver; N is the number of interference stations within the coverage area of a base station.

Noise sources can be estimated by parameter P_n, which includes both the internal noises of the receiving pathway and the external noises arriving from the transmission channel to the receiving antenna. Noise in the channel includes radiation sources from other devices that are not related to the standard 802.11. The noises also include emission in the external environment.

Given [13], the level of noise can be determined by the following expression:

$$P_n = kT\left[\left(\frac{k_n}{k_f} - 1\right) + \left(\frac{1}{P_0}\sum_{i=1}^{m} P_i - 1\right)\right], \quad (5)$$

where k_n is the noise coefficient of the receiving tract; k_f is the transmission coefficient of the feeder; P_i is the transmission medium noise strength; m is the number of noise obstacles in the transmission medium; P_0 is the level of thermal noise of the Earth.

Next, we shall consider the parameter of a change in the strength over time. As was established, the characteristic of signal strength at the input of the receiver has large enough fluctuations. It is also possible to confirm this based on simple observations of time characteristic using the monitoring of transmission medium for a typical facility with complicated development and the existence of interference obstacles. Fragments of the monitoring are shown in Fig. 1.

Fig. 1 shows that a characteristic can have quite a significant non-uniformity and the existing measurement errors made by the hardware and evaluation algorithms [10]. That is why there may be interference obstacles in the transmission medium whose number can be established only experimentally directly in the room. The impact of such obstacles would be purely accidental. In this case, it is necessary to introduce a normalized value and to apply averaging over a certain time interval. Then signal strength at the input of the receiver can be written as:

$$P_r^n = \frac{1}{n}\sum_{i=1}^{n} P_{r.i}, \quad (6)$$

where n is the number of measurements to obtain the required reliability of the evaluation.

As it is known [13], the signal strength of transmitters from the 802.11 family of standards is the magnitude defined in advance, which in most cases does not exceed 100 mW. Along with this value, internal noise of electric circuits of the transmitter are negligible and can be disregarded. Therefore, given the above expressions, a general expression for the mathematical evaluation of signal strength at the input of the receiving device of the 802.11 standard can be written as follows:

$$P_r^g = \frac{P_{tr}}{nL}\sum_{i=1}^{n} F_i - \sum_{i=1}^{n}\left(P_{i.i} + P_{n.i}\right). \quad (7)$$

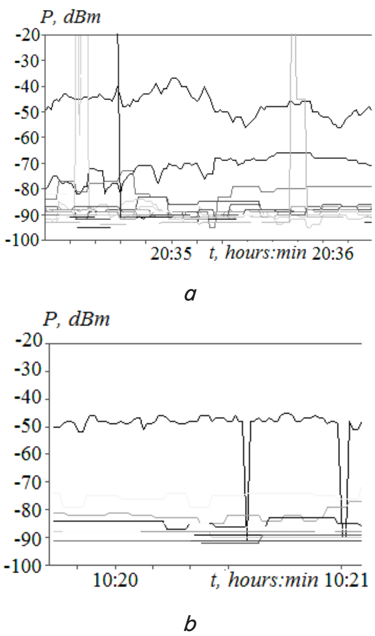

Fig. 1. Temporal distribution of signal strength at the input of the receiver: *a* — with a high level of interference obstacles; *b* — with a low level of interference obstacles

By performing an analysis of mathematical model (7), it is possible to state that the main factors that determine the fluctuations of signal are the interference obstacles, as well as the coefficient of the resultant field of wave reflection. Obstacles can be quite simple evaluated by the means of monitoring, while reflection coefficient is quite complex for computing. The accuracy of determining such coefficients will exert a fairly significant effect on the final result and it implies defining a confidence interval, which can be estimated experimentally.

5. Experimental mathematical model for the evaluation of signal strength at the input of the receiver

5. 1. Structure of the network and research procedure

From the standpoint of building wireless networks of the 802.11x family of standards, channels of information transmission can be represented as the receiving-transmitting equipment of an access point and a subscriber's device, or the so-called radio circle where the exchange of radio signals is executed through the medium of transmission [16]. This equipment acts as a converter of information from the network interfaces into radio signals, and vice versa.

In order to find an experimental characteristic of attenuation, a structure of the network for a typical facility was proposed. The network is built based on an access point (AP) that operates in a frequency range of 2.4 GHz with one emitting antenna, as well as a subscriber's device (SD), as shown in Fig. 2.

The facility has a standard rectangular structure with dimensions h=3 m, l=14 m and d=6 m. Location of AP in the room is angular, as one of the most common, and is defined by coordinates $d_1=d_2$=3 m and l_0=1 m. The basic criterion for evaluation is the received signal strength indicator (RSSI). In addition, there were various objects with different reflection surfaces to the height $h/4$ in the room. The monitoring in Fig. 1 shows that the optimal period for the estimation of a mean strength level is an interval of 5 minutes.

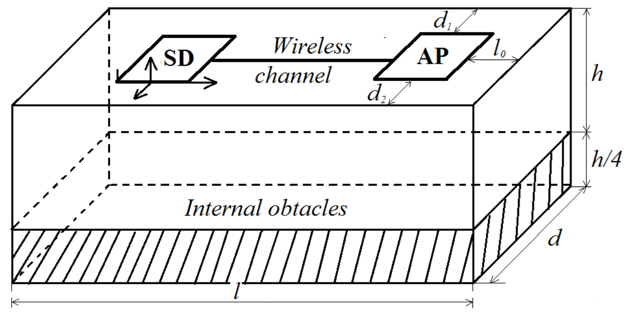

Fig. 2. Structure of the examined network

We selected three height parameters for the evaluation of distribution h in order to estimate the distribution of signal strength level in the room. First is h=0 m – where there is quite a large number of obstacles and the most probable area of possible location of devices in line with a concept of the internet of things [17]. The second parameter h=1.5 m shows one of the most common areas of AP location and the level of position of subscriber devices. The third parameter is h=3 m, which shows a standard height of a room, and another probable area where there can be located both devices in line with a concept of the internet of things and the access points or repeaters.

5. 2. Results of experimental research

Based on the proposed procedure, we investigated the basic energy parameter of signal for an 802.11 standard wireless network. Results of spatial distribution are shown in Fig. 3.

First of all, we shall consider a signal distribution for the condition h=1.5 m. Fig. 3, *a* shows that one observes here quite an uneven surface with clearly maxima and minima whose level increases when approaching the walls.

Equipment of the 802.11 family of standards uses an antenna that is a quarter-wave vibrator [18]. If we consider the unlicensed frequency range of 2.4 GHz, the wavelength here is 12.12...12.49 cm and, in a general case, the size of such antenna is 31 cm on average. In most cases, the antenna is positioned vertically and is omnidirectional. Then the maximal energy of radiation will concentrate at the center of such antenna in parallel to the room floor while the radiation along the axis will be missing. However, in this case there is the maximum amplification exactly near AP and the presence of maxima and minima exists due to the availability of a multibeam wave propagation.

As far as the distribution for the conditions h=0 m and h=3 m is concerned, one observes a fairly complex pattern with quite considerable fluctuations of the signal. The largest level of such fluctuations exists at the border between the ceiling and the floor with the walls. This leads to a significant attenuation of the signal at distances larger than 10 m from AP and, as a result, to the reduction in effectiveness of the wireless channel.

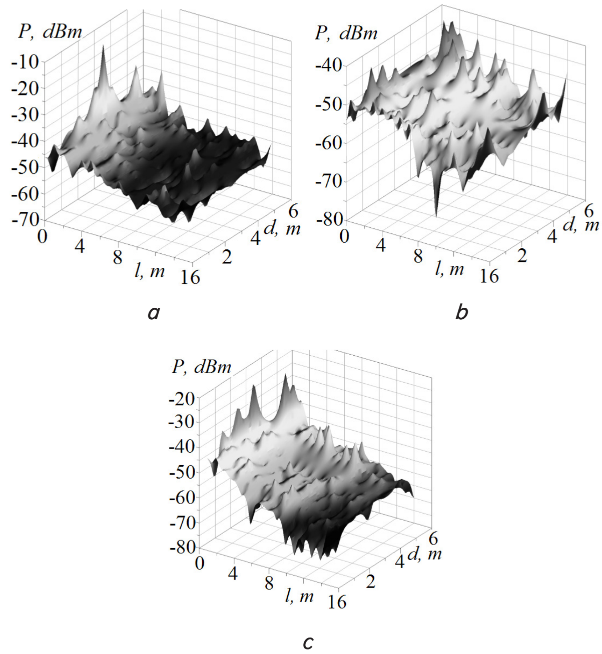

Fig. 3. Distribution of signal strength in the room at: *a* – *h*=1.5 m; *b* – *h*=0 m; *c* – *h*=3 m

5. 3. Finding an experimental mathematical model of the signal

In order to derive experimental model, we shall decompose the spatial distribution of strength into two coordinates *l* and *d*. Then, for condition *h*=1.5 m, the dependences will take the form shown in Fig. 4.

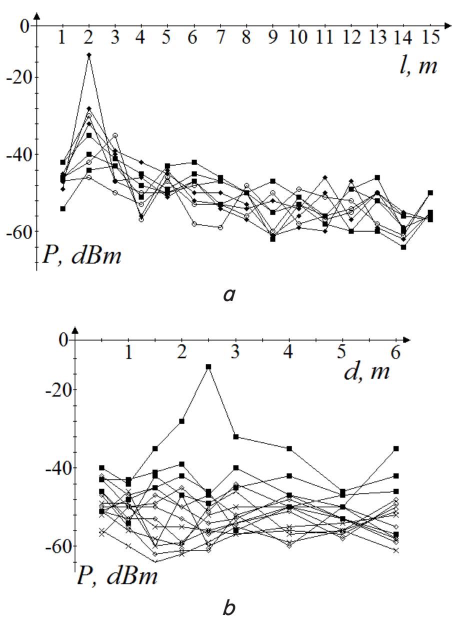

Fig. 4. Signal strength distribution by coordinate: *a* – l; *b* – d

Fig. 4 shows that quadratic attenuation is characteristic of the *l* and *d* coordinates. Then, based on a regression analysis, a model of the signal strength distribution at the input of the receiver in space can be written as:

$$\begin{cases} P_l = cl^2 + gl + k, \\ P_d = ad^2 + bd + z, \end{cases} \quad (7)$$

where *c, g, a, b* are the signal attenuation coefficients along the rspective coordinate; *k, z* are the initial levels.

Coefficients *c, g, a, b* can be determined experimentally, based on the derived distribution characteristics.

$$c = \frac{1}{m}\sum_{i=1}^{m} c_i \pm \Delta c, \; g = \frac{1}{m}\sum_{i=1}^{m} g_i \pm \Delta g,$$

$$a = \frac{1}{g}\sum_{i=1}^{g} a_i \pm \Delta a, \; b = \frac{1}{g}\sum_{i=1}^{g} b_i \pm \Delta b,$$

where *m* and *g* is the number of derived characteristics along the *l* and *d* coordinates, respectively; Δ*c*, Δ*g*, Δ*a*, Δ*b* are the coefficients that determine permissible limits of a change in the attenuation and assess the existence of maxima and minima of spatial distribution of signal strength that arises as a result of reflection from surfaces in the room.

The initial strength levels can be considered from the point of view of the sensitivity of receivers, which was examined in paper [19]. It was established that the receiving devices of the 802.11 family of standards from many manufacturers may have different values of sensitivity and amplification. Then the initial strength levels can be employed to assess the distribution based on the parameters of existing devices in the network.

Because this work examines an angular location, it can be assumed that at a distance of 1 m from AP along the *l* coordinate, signal strength at the input of the receiver has a maximum value. In order to assign a position of AP, we shall apply parameter d_0 from the center along the *d* coordinate. Then the coefficients of the initial levels can be written as:

$$k = P_r^n - c - g, \quad (9)$$

$$z = P_r^n - a\left(\frac{d}{2} + d_0\right)^2 - b\left(\frac{d}{2} + d_0\right),$$

$$d_0 \in (-d/2; d/2),$$

where P_r^n is the normalized value of signal strength at the input to the receiver, which is determined by formula (6).

As the graphs show the maxima and minima associated with the processes of reflection and multibeam wave propagation in a room, then in this case there is quite heterogeneous signal distribution. Based on a large number of experimental studies and article [20], it is possible to make a generalization that the signal distribution for any room demonstrates regions of amplification and weakening. In this case, there occur fluctuations to δ=±2.5 dBm, and at distances of up to four meters from the reflecting surface – δ=±5 dBm of deviation from the normalized value of strength. In addition, it is necessary to take into account a random deviation of strength parameter of the input signal over the evaluation time during measurement. Taking into account the temporal distribution in Fig. 1, such deviation can be determined as:

$$\delta_{r.i} = \left|\delta_{a.i} - \frac{1}{n}\sum_{i=1}^{n}\delta_{a.i}\right|,$$

where $\delta_{a.i}$ is the absolute error of the *i*-th measurement;

$$\delta_{a.i} = \left|P_r^n - P_i\right|.$$

The root-mean-square deviation of the random error is determined as:

$$\sigma^2 = \frac{1}{n-1}\sum_{i-1}^{n}\left(\delta_{r.i}\right)^2.$$

Taking into consideration the interval of 5 minutes with an estimation period of 1 s, the confidence interval with a probability of 0.995 for the random error will equal to:

$$\delta_{con} = t\frac{\sigma}{\sqrt{n}} = 0.16\sigma,$$

where t is the Student coefficient.

Thus, in order to assess signal strength at the input of the receiver, there will exist a confidence interval, which can be written as:

$$P_r^n - \delta - 0.16\sigma \le P_r \le P_r^n + \delta + 0.16\sigma. \quad (10)$$

Given the confidence interval and expressions (8) and (9), a model of the distribution of signal strength at the input of the receiver in space will take the following form:

$$\begin{cases} P_l = cl^2 + gl + (P_r^n - c - g) \pm \delta \pm 0.16\sigma, \\ P_d = ad^2 + bd + \left(P_r^n - a\left(\frac{d}{2} + d_0\right)^2 - b\left(\frac{d}{2} + d_0\right)\right) \pm \delta \pm 0.16\sigma. \end{cases} \quad (11)$$

Since in any point of the room (l, d) the condition $P_l = P_d$ must be satisfied, then the system of equations (11) can be rewritten as the total signal strength at the input of the receiver, which depends on the two coordinates:

$$P_r^e \approx \frac{P_l + P_d}{2} \approx \frac{1}{n}\sum_{i=1}^{n} P_{r.i} + \frac{1}{2}c\left(l^2 - 1\right) + $$
$$+\frac{1}{2}g(l-1) + \frac{1}{2}a\left(3d^2/4 - dd_0/2 - d_0^2\right) +$$
$$+\frac{1}{2}b(d/2 - d_0) \pm \delta \pm$$
$$\pm 0.16\sqrt{\frac{1}{n-1}\sum_{i-1}^{n}\left(\left|\frac{1}{n}\sum_{i=1}^{n} P_{r.i} - P_{r.i}\right| - \frac{1}{n}\sum_{i=1}^{n}\left|\frac{1}{n}\sum_{i=1}^{n} P_{r.i} - P_{r.i}\right|\right)^2}. \quad (12)$$

Based on the obtained experimental mathematical model, it is possible to quickly obtain the evaluation of basic energy parameter, using the monitoring algorithms that are in plenty at present. The confidence interval can be determined based on the experimental dependences of signal fluctuations on the pemissible limits in a change in the main criterion of network effectiveness.

6. Discussion of research results and the essence of the method for estimating signal strength at the input of the receiver

As equations (7) and (12) demonstrate, there is a possibility to assess signal strength at the input of the receiver using the settings responsible for different processes in the transmission medium. Based on the experimental model, it is possible to perform assessment of unknown parameters of the transmission medium and parameters of the receiver and the transmitter of the 802.11 standard using the following ratio:

$$P_r^e \approx 10\lg\frac{P_r^g}{P_0} \approx 10\lg\left(\frac{P_{tr}}{nLP_0}\sum_{i=1}^{n} F_i - \sum_{i=1}^{n}\left(P_{i.i} + P_{n.i}\right)/P_0\right),$$

where P_0 is the absolute zero level, which is 1 mW.

The application of the model of spatial evaluation is optimal from the point of view of the possibility to take into account a maximally possible number of factors for any wireless channel. This is the most simple and applicable at present. In order to conduct such an assessment, it is possible to formulate a method using the possibilities of the receiving part of subscriber's equipment. Such method can be divided into the following stages.

Stage one implies the evaluation of signal strength at the input of the receiver based on the monitoring whose fragment is shown in Fig. 1, using technical means and software of subscriber's equipment. It is sufficient to perform the evaluation over a period of five minutes, in order to obtain the mean value of P_n based on expression (6), and at a distance of one meter from the access point along the l coordinate.

Stage two involves defining the permissible limits of the evaluation taking into account the architecture of the room. Signal reflection from surfaces and objects of the room are determined by the spread of parameter δ depending on the dimensions; while the occurrence of maxima and minima – on the permissible values of parameters Δc, Δg, Δa, Δb.

Since determining the boundaries of a change in the attenuation coefficients is costly enough in terms of time, then we shall acquire the values from experimental data in Fig. 3, for h=1.5 m, h=3 m, and h=3 m.

Based on the obtained results, it was found that in order to ensure signal fluctuations up to 10 dBm, permissible boundaries for a change in the attenuation coefficients for the three parameters of h can be written as:

$$c = \begin{cases} 0.11 \pm 0.1 \text{ (dBm/m)}, & \text{at } h = 0, \\ 0.07 \pm 0.1 \text{ (dBm/m)}, & \text{at } h = 1.5, \\ 0.01 \pm 0.1 \text{ (dBm/m)}, & \text{at } h = 3; \end{cases}$$

$$g = \begin{cases} -3.5 \pm 2 \text{ (dBm/m)}, & \text{at } h = 0, \\ -2.5 \pm 2 \text{ (dBm/m)}, & \text{at } h = 1.5, \\ -1.5 \pm 1 \text{ (dBm/m)}, & \text{at } h = 3; \end{cases}$$

$$a = -0.5 \pm 1.5 \text{ (dBm/m)};$$

$$b = -2.5 \pm 7 \text{ (dBm/m)}.$$

Taking into account attenuations along the l coordinate, it is possible to introduce additional correction of the initial level z that can be written as:

$$z = \begin{cases} -1.5l - 48 \text{ (dBm/m)}, & \text{at } h = 0, \\ -0.7l - 44 \text{ (dBm/m)}, & \text{at } h = 1.5, \\ -0.9l - 48 \text{ (dBm/m)}, & \text{at } h = 3. \end{cases}$$

The last stage implies determining a map of signal strength values by formula (12) based on the coordinates of the room (l, d), in order to obtain the signal spatial distribution.

An error in the evaluation of the proposed method will depend on two components: correct choice of the signal fluctuation limits and error in the measurement of subscriber's equipment. It is possible to evaluate the limits of possible fluctuations using experimental mathematical model when considering a change in the attenuation coefficients from the boundaries Δc, Δg, Δa, Δb by the respective coordinate of the room. Charts of such dependences are shown in Fig. 5.

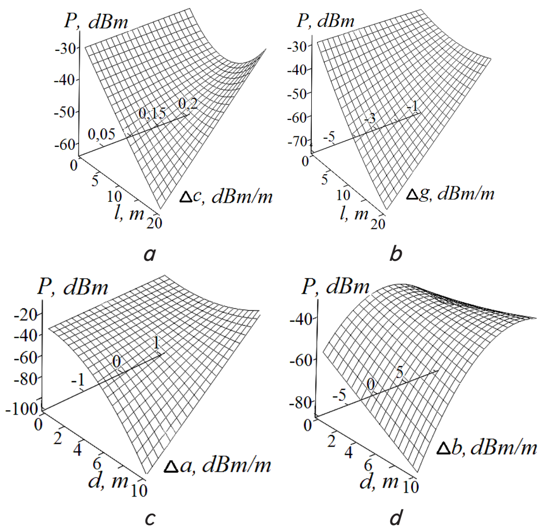

Fig. 5. Dependence of signal strength at the input of the receiver on the coefficients of permissible limits: *a* – Δc; *b* – Δg; *c* – Δa; *d* – Δb

Charts in Fig. 5 show that a maximum or a minimum can be obtained from the values of coefficients, namely, from the positive or negative values, and in this case an increase in the distance from SD raises the level of signal fluctuations. It makes it possible to predict the location of fluctuations in the room, if it is required. Characteristic of attenuation along the l coordinate exhibits almost a linear character of attenuation of signal distribution for the condition of h=3 m. Depending on the magnitude of coefficients c and g, one can argue about the presence of obstacles in the transmission medium and determine the level of attenuation contributed by them.

Since the signal fluctuations are a random process, we shall consider this together with a permissible confidence interval of the random error. Dependence charts of the signal strength distribution on the error of assessment are shown in Fig. 6.

When analyzing a change in the signal strength on permissible limits and assessment error, it is possible to conclude that the given method allows conducting the evaluation of informative parameter with a maximum deviation to 15 %. If one takes into account dependences of the effective speed of information transmission on signal strength at the input of the receiver, then this will suffice.

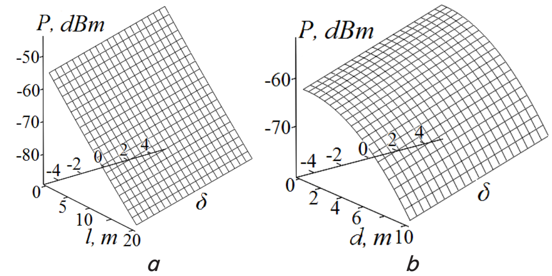

Fig. 6. Dependence of signal strength at the input of the receiver on fluctuations and random error: *a* – for the *l* coordinate; *b* – for the *d* coordinate

7. Conclusions

Results of the research conducted:

– we examined a general characteristic of an 802.11 standard wireless channel and found that the greatest influence on signal fluctuations indoors is exerted by such independent components: reflected signals from the room surfaces, interference obstacles and noise;

– we improved a mathematical model for the estimation of signal strength at the input of the receiver, which takes into account a maximally possible number of factors of influence, considering random fluctuations along the time coordinate. This model broadly describes all the processes that exist in a wireless channel; however, it is quite difficult to assess the distribution of the signal;

– we performed experimental investigation into spatial distribution of the signal indoors. Based on this, it was established that in the frequency range of 2.4 GHz for the 802.11 standard, there occurs a rather heterogeneous distribution of signals with the creation of fluctuations of up to 10 dBm, and under the most difficult conditions – up to 25 dBm. In addition, the heterogeneity of signal distribution increases proportionally to the number of reflective surfaces in the room, which is additionally amplified by the presence of interference obstacles and noise;

– we derived experimental mathematical model of signal distribution in a room that makes it possible to quickly receive the assessment using monitoring algorithms. Such model uses a confidence interval, employing which can determine the fluctuations of the signal;

– given the complexity of signal distribution in wireless networks of the 802.11 standard, we proposed a spatial method for the evaluation of signal strength at the input of the receiver, which applies a mathematical model obtained based on experimental research. The benefit of this method is the ease of implementation and the possibility to take into account a maximally possible number of destabilizing factors that can be relevant for a particular room.

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