Запропоновано математичну модель просторової оцінки потужності сигналу на вході приймача для сімейства стандартів 802.11x, для центрального розміщення точки доступу у приміщенні. Ця модель визначена на основі просторового розподілу сигналу, який отримано експериментально. Для даної моделі було визначено допустимі межі зміни, які враховують максимально-можливу кількість факторів впливу

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

Предложена математическая модель пространственной оценки мощности сигнала на входе приемника для семейства стандартов 802.11x, при центральном размещении точки доступа в помещении. Эта модель получена на основе пространственного распределения сигнала, полученного экспериментально. Для данной модели было определены допустимые пределы изменения, учитывающие максимально-возможное количество факторов влияния

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

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DEVELOPMENT OF A MATHEMATICAL MODEL FOR ESTIMATING SIGNAL STRENGTH AT THE INPUT OF THE 802.11 STANDARD RECEIVER

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1. Introduction

Intensive implementation of wireless technologies and a wide spread of wireless networks have been observed over recent time. This is explained first of all by a relative simplicity of creating high-speed access channels to modern high quality info-communication services. On the other hand, fairly wide accepted is the concept of the Internet of Things [1], which is characterized by connecting a large number of devices that can communicate without human participation. One of particular cases is the example of a smart home, which has its own internal multiservice network based on IP protocol. Such a network may host many nodes, household equipment, specialized devices, subscriber devices and sensors, which that implies the existence of a fairly sophisticated topology taking into consideration obstacles and architectural barriers. Given a quite substantial number of devices in the network of a smart home, one of the optimal solutions for constructing a physical level is the use of technology of the 802.11 family of standards [2].

Networks of the 802.11x family of standards are characterized by constant development in the direction of improving the main quality criterion – effective speed of information transmission. As is known, this criterion directly proportionally depends on the signal strength level at the input of the receiving device and defines the signal quality parameter [3]. Given a fairly widespread distribution of wireless networks, one can discover that it gives rise to a number of negative factors that can significantly impair transmitting characteristics of wireless channels of information transmission. This, in turn, leads to delays and errors when accessing services with a large volume of traffic. Therefore, it is a relevant task to search for new methods and means in order to minimize the impact of these factors, 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 of diagnosis and optimization of network topology based on spatial evaluation of energy characteristics of the signal, which would take into consideration maximally possible number of factors of influence.

2. Literature review and problem statement

By performing an analysis of existing scientific papers, one can argue about quite an intensive development of research into the field of wireless technologies of the 802.11 standard. But in terms of studies into one of the main signal energy parameters, we can point to article [4]. The authors proposed a spatial method for estimating signal strength at the input of the receiver for the 802.11 family of standards. In this case, they obtained a mathematical model for estimating a spatial distribution of the signal. Special feature of this model is accounting for maximum-possible number of factors of influence and permissible change limits of the energy parameter. The studies were carried out for the angular arrangement of an access point in the premises.

Paper [5] showed that in order to receive better energy parameters, the center of the room is the most efficient location for arranging the access point. This is true both when using a single antenna and to achieve maximum efficiency while employing the MIMO technology. The obtained characteristics demonstrate maxima and minima of the spatial distribution with a difference of up to 5 dbm.

In article [6], authors examined a wireless network for sensors of the concept of the Internet of Things. A special feature of this network is that it can include devices that have different channel and physical levels. It combines different technologies of information transmission. The basis for such networks is the access nodes that should provide effective coverage. The article proposes two technologies for the construction of effective sensor networks: Bluetooth and IEEE 802.11. Similar studies have been conducted in paper [7]. The authors, however, proposed a typical structure of the network where the 802.11 standard is used as an intermediate line to connect the nodes of sensors' combination. In this case, the main wireless access point may be located at the corner of the room, with repeaters both in the corners and in the center of the rooms.

Article [8] addresses the problems of obtaining an efficient network topology for the Internet of Things. The main of them is the alignment of mechanism of network control with the applications of upper levels, and receiving high efficiency of data transfer. Control over topology is understood to be a control over radiation strength and power supply management. Thus, using such methods of control can improve efficiency of the networks. It is also evidenced by the studies in paper [9]. The studies conducted have shown a significant change in the signal level of mobile devices over a considerable period of use. It is the application of the signal strength control that increases a period of autonomous operation without the loss of a noticeable reduction in the bandwidth throughput. In addition, research results in articles [10] and [11] indicate the presence of a threshold value of the strength level. In this case, the authors established the following features. A subscriber device is preset with a level of radiation of 10^{-6} W/m at a distance exceeding one meter. When transmitting information via a wireless channel the strength increased by an order. It was established for the access point that the signal level of about −55...−45 dbm (taking into consideration a variation in the strength of 10 dbm) at the input of the receiver has a minimal effect on the magnitude of effective rate of transmission while all the variations in most cases depend on the loading in adjacent and neighboring channels. This may lead to certain limitations in the stability of channels against external factors.

Moreover, in order to improve efficiency of the channel, signal processing algorithms can be used, which increase information capacity of the signal [12], as well as methods for reducing bit errors in the receiving devices [13].

Thus, summing up the above, one can define actions that can improve efficiency of wireless networks of the 802.11x family of standards. These include:

– increasing the level of input signal;
– installation of more efficient antennas;
– adding repeaters in the network;
– application of new models for estimating signal parameters;
development of new effective methods for designing wireless networks;
– utilizing a newer standard, etc.

But the most significant parameter that correlates with all the above measures is the strength of a signal at the input of the receiver. It has fairly significant fluctuations and its assessment is a rather significant problem.

That is why, in order to improve efficiency of signal strength distribution in a room, it is necessary to have a mathematical model for the central position of the access point.

3. The aim and objectives of the study

The aim of present work is to derive a mathematical model for estimating signal strength at the input of the 802.11 standard receiver for a central position of the access point in the premises. Such a model should take into consideration the maximum number of destabilizing factors.

To achieve the set aim, the following tasks must be solved:

– to obtain a spatial distribution of signal in the premises for a central position of the access point;
– based on the spatial signal distribution, to obtain dependences of the basic energy parameter on the coordinates of the premises;
– to explore a change in the basic energy parameter caused by the permissible limits of signal fluctuations.

4. Experimental mathematical model for estimating signal strength at the input of the receiver for a central position of the access point

4. 1. Structure of the network and research procedure

In terms of building wireless networks of the 802.11x family of standards, channels of information transmission consist of the receiving-transmitting equipment of an access point and the subscriber's device that has the name of a radio-range [14]. This equipment performs functions of the channel and physical level of the network and converts information from the network interfaces into radio signals.

In order to find spatial distribution of the signal, we proposed a network structure for a typical room. The network is built based on an access point (AP) in the frequency range 2.4 GHz with one radiating antenna and a subscriber's device (SD), as shown in Fig. 1.

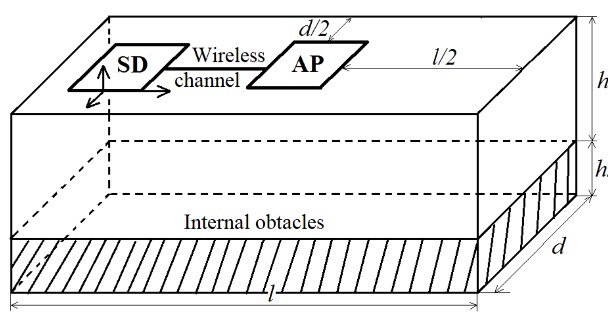

Fig. 1. Structure of the experimental network

The room has a standard rectangular shape with dimensions h=3 m, l=14 m, and d=6 m. The location of AP in the room is central, as the second of the most common, which can be set by the following coordinates $d_0=d/2$ and $l_0=l/2$. The main criterion for estimation is the signal strength at the input of the receiver (RSSI) [15]. In addition, the room housed, to the height $h/4$, various objects with different reflection surfaces. As was the case in paper [4], signal strength estimation was performed by averaging the results of measurement over an interval of five minutes with a period of acquiring values of one second.

To assess the distribution of signal strength in the room, we used three parameters of height h [4]. The first one, h=0 m, is where there is a presence of a rather large number of obstacles and which is the most probable area of possible location of devices in line with the concept of the Internet of Things. The second parameter, h=1.5 m, shows one of the most common areas of AP location and the level of placement of subscriber devices. The third parameter, h=3 m, is the standard height of the room, and a second probable zone of positioning access points or repeaters and devices in line with the concept of the Internet of Things.

4. 2. Results of experimental research

Based on the proposed procedure, we experimentally studied the basic signal energy parameter for the wireless network of the 802.11 standard for a central location of AP. Results of the spatial distribution are shown in Fig. 2.

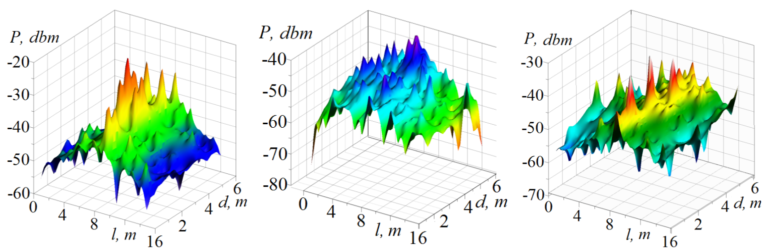

Fig. 2. Signal strength distribution for a central position of the access point in the room at: *a* – h=1.5 m; *b* – h=0 m; *c* – h=3 m

Spatial distribution of the signal for condition h=1.5 m shows that at a distance of up to two meters from AP one observes rather significant fluctuations with the pronounced maxima. These maxima consequently decrease to a generally-mean level. Since the transmitter is located in the center, then the fluctuations near walls are less pronounced, even in the presence of a large number of reflective surfaces.

For parameters h=0 m and h=3 m, there is a more uniform characteristic with less pronounced maxima. Here reflective surfaces are located directly at the radiating antenna, which is why distribution of the signal is close to the quadratic shape.

Thus, at central AP location, one observes concentration of radiation energy directly at the transmitting antenna at a distance of up to two meters. Farther than two meters away from the antenna, one observes a significant attenuation of the signal, about 20 dbm on average. In addition, at the d coordinate and near the ceiling (h=3 m) fluctuations have a larger deviation than at angular location, as is the case in paper [4].

4. 3. Experimental mathematical model of signal distribution

Similar to paper [4], in order to obtain an experimental model, we shall decompose spatial distribution of strength for two coordinates l and d. Then, for condition h=1.5 m, dependences will take the form shown in Fig. 3.

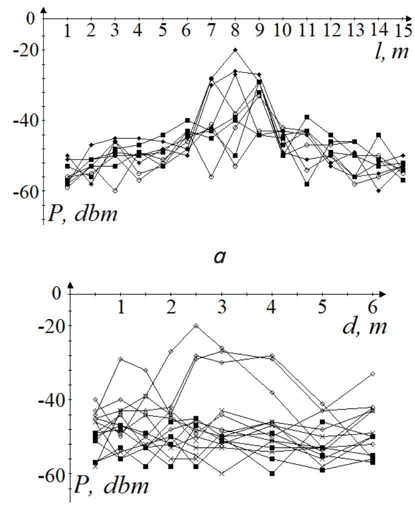

Fig. 3. Signal strength distribution for coordinate: *a* – *l*; *b* – *d*

Fig. 3 that the distribution of signal strength can be represented by a standard model of signal attenuation in a free space. But this holds only for characteristics at coordinate l for condition $d/2$. That is why, in order to estimate experimental data, we shall apply regression analysis for a polynomial model. According to analysis results, it proved to be optimal to use quadratic attenuation for coordinates l and d. Then the signal strength distribution model at the input of a receiver in space can be written as:

$$\begin{cases} P_l = cl^2 + gl + k, \\ P_d = ad^2 + bd + z, \end{cases} \quad (1)$$

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

Coefficients c, g, a, b are derived from the following expressions:

$$c = \frac{1}{m}\sum_{i=1}^{m} c_i, \quad g = \frac{1}{m}\sum_{i=1}^{m} g, \quad a = \frac{1}{g}\sum_{i=1}^{g} a_i, \quad b = \frac{1}{g}\sum_{i=1}^{g} b_i, \quad (2)$$

where m and g are the quantity of obtained characteristics for coordinate l and d, respectively; c_i, g_i are the coefficients of attenuation for coordinate l; a_i, b_i are the coefficients of attenuation of characteristic for coordinate d.

Assume that the maximum energy of the signal is concentrated in the center of the room. Then the initial estimation levels can be determined based on the normalized value of signal strength at the input of the receiver from the following expression [4]:

$$P_n = \frac{1}{n}\sum_{i=1}^{n} P_{r.i} \, ,$$

where $P_{r.i}$ is the measured value of strength; n is the number of measurements to obtain the required reliability of the estimate.

For a central position of the access point (d_0=$d/2$; l_0=$l/2$) formula (1) will take the following form:

$$\begin{cases} P_l = \frac{3}{4}cl^2 + \frac{1}{2}gl + P_n, \\ P_d = \frac{3}{4}ad^2 + \frac{1}{2}bd + P_n. \end{cases} \quad (3)$$

Research results in Fig. 3 show that the maximum energy of signal is concentrated at a distance of two meters from the radiating antenna of AP. Employing the initial levels in the specified limits may lead to an error of assessment of 20 dbm. Since in a given case the estimation is performed for a room that is much bigger than two meters, we shall disregard maximum concentration of strength. In this case, the initial levels for a central position of AP can be determined, for example, based on coordinate $(2+l/2;\ d/2)$:

$$k = P_n - c\left(2+\frac{l}{2}\right)^2 - g\left(2+\frac{l}{2}\right),$$

$$z = P_n - a\left(\frac{d}{2}\right)^2 - b\left(\frac{d}{2}\right). \quad (4)$$

Given expressions (4), the model of signal strength distribution can be written in the following form:

$$\begin{cases} P_l = cl^2 + gl + P_n - c\left(2+\frac{l}{2}\right)^2 - g\left(2+\frac{l}{2}\right), \\ P_d = ad^2 + bd + P_n - a\left(\frac{d}{2}\right)^2 - b\left(\frac{d}{2}\right). \end{cases} \quad (5)$$

For any point of the room $(l,\ d)$, condition $P_l=P_d$ must be satisfied. Then the system of equations (5) can be represented as the average value of signal strength for two coordinates. Thus, we obtain:

$$P_a = \frac{P_l + P_d}{2} \approx P_n + \frac{3}{8}\left(cl^2 + ad^2\right) - -c(l-2) + g\left(\frac{1}{4}l - 1\right) + \frac{1}{4}bd. \quad (6)$$

The mathematical model (6), obtained on the basis of experimental research into a wireless channel of the 802.11 standard, allows easy enough estimation of spatial distribution of the basic energy parameter applying the algorithms of monitoring. This gives quite a significant advantage, since it takes into consideration all of the factors of influence that exist in the coverage area of the access point.

Extension of the received model of distribution is the establishment of confidence interval, which will make it possible to assess limits of change in the energy parameter and fluctuations in any point of the room. For such an interval, a slight variation in the effective speed of information transmission along a wireless channel is justified. That is why permissible limits of change in the signal strength at the input of the receiver can be written in the following form:

$$P_a - \delta - 0{,}16\sigma < P < P_a + \delta + 0{,}16\sigma, \quad (7)$$

where δ is the coefficient of signal fluctuations whose value is determined experimentally based on a large number of our own experimental studies and can amount to $\delta=\pm 2.5$ dbm of the strength normalized value, and to $\delta=\pm 5$ dbm at distances of up to four meters from the reflective surface; σ is the random error of estimation of the normalized value of strength that can be derived from the following expression:

$$\sigma = 0{,}16\sqrt{\frac{1}{n-1}\sum_{i-1}^{n}\left(\left\|\frac{1}{n}\sum_{i=1}^{n}P_{r.i} - P_{r.i}\right| - \frac{1}{n}\sum_{i=1}^{n}\left|\frac{1}{n}\sum_{i=1}^{n}P_{r.i} - P_{r.i}\right\|\right)^2}.$$

The coefficient of signal fluctuations shows, first of all, maximum deviation of signal distribution from the normalized value. Such deviations, however, from a mathematical point of view, will both increase and decrease the total signal value, uniformly over the entire distribution. Therefore, to assess the level of fluctuations, it is necessary to use the limits of permissible changes in the coefficients of signal attenuation. To this end, we shall record the following condition:

$$P_a - \delta < P(\Delta c, \Delta g, \Delta a, \Delta b) \le P_a + \delta,$$

where $\Delta c, \Delta g, \Delta a, \Delta b$ are the coefficients that define the limits of permissible changes in the coefficients of signal attenuation. By using these coefficients, one can estimate the presence of maxima and minima in the spatial signal strength distribution that occurs due to multipath propagation of waves in the room. These coefficients can be determined from expressions (2) in the following way:

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

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

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

$$b = \frac{1}{g}\sum_{i=1}^{g} b_i \pm \Delta b.$$

In order to estimate confidential intervals of attenuation coefficients, we shall employ experimental dependences of signal fluctuations for coordinates l and d. Thus, the normalized values of attenuation coefficients and permissible limits of change can be written in the following way:

$$c = \begin{cases} -0{,}21 \pm 0{,}3 \text{ (dbm/m)}, & \text{at } h=0, \\ -0{,}25 \pm 0{,}5 \text{ (dbm/m)}, & \text{at } h=1{,}5, \\ -0{,}16 \pm 0{,}8 \text{ (dbm/m)}, & \text{at } h=3; \end{cases}$$

$$g = \begin{cases} 3{,}8 \pm 0{,}5 \text{ (dbm/m)}, & \text{at } h=0, \\ 4{,}5 \pm 1{,}5 \text{ (dbm/m)}, & \text{at } h=1{,}5, \\ 3 \pm 1 \text{ (dbm/m)}, & \text{at } h=3; \end{cases}$$

$$a = \begin{cases} -1 \pm 0{,}5 \text{ (dbm/m)}, & \text{at } h=0, \\ 0 \pm 0{,}9 \text{ (dbm/m)}, & \text{at } h=1{,}5, \\ -0{,}5 \pm 1{,}5 \text{ (dbm/m)}, & \text{at } h=3; \end{cases}$$

$$b = 1 \pm 6 \text{ (dbm/m)}.$$

The relations obtained show permissible limits of change in the attenuation coefficients for three parameters h at central position of AP. This satisfies the condition of signal fluctuations to 10 dbm depending on the geometrical dimensions of the room.

5. Discussion of research results and estimation of the confidence interval

By analyzing mathematical model (6) for a central position of the access point, one can say that the efficiency of estimation of signal strength at the input of the receiver of the 802.11 standard depends on the proper evaluation of signal fluctuations. The level of these fluctuations depends on the number of simultaneously existing destabilizing factors in the channel for the premises where there is a wireless network. Among these factors, the most significant one is the multipath signal propagation, which depends on the number of radiating surfaces. Taking these factors into consideration is possible through direct assessment using the algorithm of monitoring at a distance of two meters from the radiating antenna of AP. When applying these measures in real time, we shall obtain a spatial signal strength control method for any premises [4]. This makes it possible to predict the distribution of effective speed of information transmission, which is directly connected to the signal strength parameter for the 802.11x family of standards [16]. In addition, the accuracy of the model also depends on the estimation error of signal strength by subscriber equipment and on the monitoring algorithm.

First, we shall consider impact of the general indicator of signal fluctuations δ with a permissible confidence interval of random error σ. Dependence charts of the signal distribution on the level of fluctuations are shown in Fig. 4.

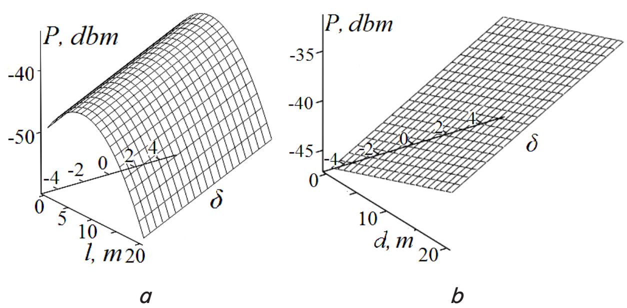

Fig. 4. Dependence of signal strength at the input of the receiver on fluctuations and random error: *a* – for coordinate *l*; *b* – for coordinate *d*

The charts in Fig. 4 show that the proposed model is applicable for estimating a signal spatial distribution in premises the size of up to 20×20 m.

Next, we shall consider a change in the signal strength at the input of the receiver caused by the signal attenuation coefficients, which will be represented through the limits of permissible deviations Δc, Δg, Δa, Δb. The charts of such dependences for the corresponding coordinate of the room are shown in Fig. 5.

The charts in Fig. 5 show that a maximum or a minimum can be derived from positive or negative values in the interval of permissible deviations. An increase in the distance from AP leads to increased intervals between maxima and minima. This makes it possible to predict location of fluctuations in the room if it is required.

The existing models of signal propagation in wireless channels [17, 18] fail to fully reflect actual characteristics of the propagation of signals and strongly depend on the conditions of their use. In the proposed model, the main advantage is taking into consideration any changes in the parameters of transmission medium in real time. This allows applying it for diagnosis and control of wireless channels of the 802.11x family of standards both at the stage of network design and during operation.

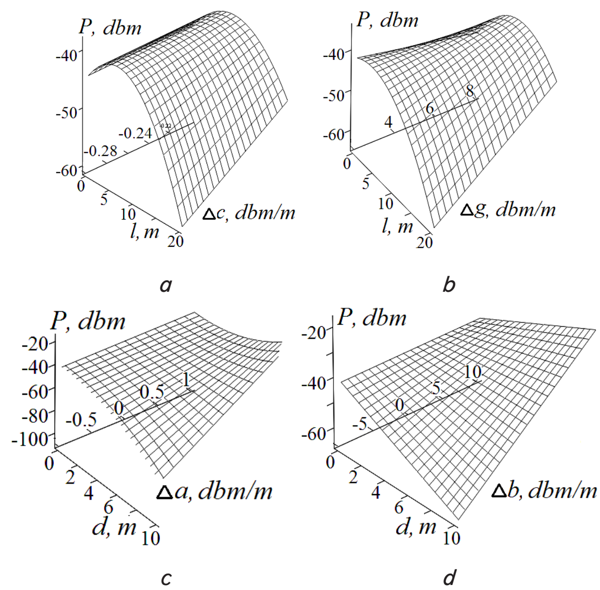

Fig. 5. Dependence of signal strength at the input of the receiver on the coefficients of permissible limits: *a* – Δc; *b* – Δg; *c* – Δa; *d* – Δb

7. Conclusions

1. We obtained spatial signal distribution in a room for a central position of the access point. At such a position of the access point one can observe the largest concentration of radiation energy directly at the transmitting antenna at a distance of up to two meters. Farther than two meters away from the antenna, one observes a significant signal attenuation, about 20 dbm on average.

2. Based on the spatial distribution, we obtained dependence of the basic energy parameter on the premises coordinates. This makes it possible to easily enough estimate spatial distribution of the basic energy parameter using the monitoring algorithms, taking into consideration all factors of influence that exist within the coverage area of the access point.

3. A change in the basic energy parameter caused by the permissible limits of signal fluctuations was investigated, which allows us to establish a confidence interval within which there is a slight variation in the effective speed of information transmission.

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