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*A method of estimating the effective data rate in channels of the Standard 802.11 was proposed. It provides for the measurement of the main energy parameter using the software and hardware of the subscriber device. This method is based on the empirical models of statistical relationships between the main parameters of the channel which are obtained on the basis of experimental studies using monitoring algorithms. The solutions obtained during the implementation of this method make it possible to take into account the maximum possible number of destabilizing factors and significantly reduce the time of assessment of the effective data rate. It should be noted that this method can be used for technical diagnostics of wireless networks of Standards 802.11x at the stages of network design and operation.*

*It was established that when using the coefficient of energy efficiency, a significant error in the displacement of the points of intersection of the linear and logarithmic mathematical model occurs. This can lead to a discrepancy between the mathematical estimates of the effective data rate and real values. The statistical relationship gives a smaller error; however, it increases requirements for empirical studies to obtain the maximum possible reliability.*

*One of the features of the proposed method is the reliability of assessment of the effective data rate. This reliability depends on three main factors: accuracy of assessing the results based on which the mathematical model was obtained; estimation of fluctuation intervals and characteristics of the Standard 802.11 equipment of different manufacturers. The last factor can be considered as a disadvantage that involves the creation of a database of parameters of the model of statistical relationship for different devices with correction coefficients*

*Keywords: wireless channel, Standard 802.11, effective data rate, signal strength, assessment method, statistical relationship*

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# DEVELOPMENT OF A METHOD FOR ASSESSING THE EFFECTIVE INFORMATION TRANSFER RATE BASED ON AN EMPIRICAL MODEL OF STATISTICAL RELATIONSHIP BETWEEN BASIC PARAMETERS OF THE STANDARD 802.11 WIRELESS CHANNEL

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## 1. Introduction

At the present stage of technical development, wireless networks of the 802.11x standard family have become quite widespread [1]. Such networks are cost-effective, easy to build and maintain and have a fairly high bandwidth capacity. The range of their use is quite wide: from combining

devices of the Internet of Things concept to providing access to television and infocommunication services [2].

The widespread use of wireless networks of Standard 802.11 leads to a series of negative factors causing delays and errors during traffic sessions. However, the main task set at the design stage is the achievement of the maximum possible bandwidth capacity of the channel and its stability for the

subscriber devices. One of the solutions to this problem is the creation of new models and methods for evaluating the criterion of channel efficiency, which takes into account the nature and pattern of impact of the maximum possible number of destabilizing factors. Because Standard 802.11 devices are characterized by low levels of radiation, evaluation models with a high level of reliability can be obtained on the basis of empirical studies. This is relevant from the point of view of technical diagnostics of wireless channels which will make it possible to estimate effective data transfer rate using a statistical relationship between the main parameters of the channel. In addition, from the point of view of subscriber devices, there are no mechanisms for estimating parameters of channels in the space of the premises with the ability to predict traffic transmission. To some extent, this is implemented in professional specialized tools, however, they are rather costly and require a substantial period of observation. Therefore, it is important to develop a method of high reliability, speed, and economy and the possibility of its application for any subscriber device at the stages of network design and operation.

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## 2. Literature review and problem statement

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The study and analysis of the RSSI signal strength indicator for channels of Standard 802.11 were performed in [3]. The authors used information from the physical level which was obtained using a conventional subscriber device with MIMO technology. This has made it possible to obtain high accuracy in determining the position of objects in a room and reliability of the monitoring results. In addition, the presence of significant fluctuations and dependence of the energy parameter on a particular equipment manufacturer brought about by different frequencies of quantization and sampling were found. It was shown that the change of the device position changes the signal strength by 2 dBm and deviation in space by 1 m adds 6 dBm to fluctuations. This study does not take into account the typical factors of influence existing in the room. Taking into account the influence of noise and channel length was considered in [4] where measurements were performed using a conventional subscriber's mobile device and a monitoring application. As a result, it was found that as the channel length increased, the signal strength decreased while parameters of data upload and download remained constant. A similar situation was observed under the influence of noise. This is the study disadvantage as it did not take into account the limitations of internal buses of the access point and mobile device. Other factors were not taken into account as well.

Results of 356 measurements of signal strength in typical indoor conditions at a distance of 1 m from Standard 802.11 devices are presented in [5]. It was found that the measured values were significantly lower in most cases than the international limits set by IEEE C95.1-2005 and ICNIRP. This indicates a significant limitation for Standard 802.11 devices which determines signal strength at the receiver input. The results indicate the need to take into account such limitations when assessing the effective data transfer rate, especially in presence of the factors of impact in premises.

A problem of creating optimal coverage by the access point of the Standard 802.11 was raised in [6]. A compromise was settled there: provide a required signal strength at certain points in the room on the one hand and a low signal strength in other points to increase security on the other hand. In addition, the factors influencing signal propagation in space, such as equipment parameters, location in the room as well as architectural obstacles were studied there. As a result, it was shown that the ideal option for deploying a network is providing an optimal location based on measuring the signal strength parameter. However, one can only get information about the features of signal propagation in the room space.

Architectural obstacles and features of 2.4 GHz and 5 GHz frequency bands were taken into account in [7]. A significant number of results for the RSSI parameter were obtained for six multi-story buildings in two EU countries. The analysis showed that 5 GHz waves have significantly greater attenuation in the wireless channel. This is especially true in the vertical direction where materials of higher density are used. Thus, 5 GHz waves have a lower penetration through architectural obstacles. It can also be noted that higher device sensitivity gives a higher uniformity of the signal propagation characteristics. The disadvantage consists in the lack of studies on the factors influencing the informational parameters of the channel.

The effect of one of the main informational factors of influence was studied in [8]. The issue of proper operation of CSMA/CD technology in wireless networks of Standard 802.11 was raised. Because this technology is a probabilistic protocol of MAC level, then there are a series of problems when dividing the channel bandwidth between existing subscribers in the network in this case. As a result, it was found that an increase in the number of subscribers leads to a decrease in the signal/noise level and efficiency of the synchronization algorithm of the MAC level. In this case, an effective data transfer rate is more important than division according to the standard specifications. However, there is no analysis of the impact of other types of influencing factors and architectural obstacles. An approach was proposed in another paper [9] that effectively improves the network power efficiency and reduces interference impact with the use of broadband channels. The result was achieved using a multi-cluster network design which increases the channel bandwidth capacity but it will increase the total cost of the network.

It was noted in [10] that an increase in the channel bandwidth leads to an increase in the channel throughput as well as a decrease in the coverage area and an increase of sensitivity to interference. However, the effect of the factors influencing the effective data transfer rate was not taken into account in this case.

There are also studies related to monitoring parameters of wireless networks. Description of measurement and analysis of Standard 802.11 signals in a campus using a mobile device and software application was given in [11]. It was found that access points can have a coverage radius of up to 100 m. In the presence of architectural obstacles, the radius reduces significantly. It was established that in order to obtain a sufficient rate of information loading, it is necessary to provide a signal strength of 60 dBm which is achieved by increasing the number of access points and

changing their position. The disadvantages include a significant time input to obtain the monitoring results.

The use of radio monitoring to assess interference and noise in the 2.4 GHz band was presented in [12]. The authors proposed to use freely available software tools to assess signal propagation and channel performance within a house. Additionally, a spectrum analyzer was used. Based on the study, it was established that the use of hardware and software capabilities of mobile devices can be an alternative to spectrum analyzers when it is not necessary to obtain complete information about the spectrum. This gives grounds to claim the possibility of using available monitoring algorithms to estimate channel parameters. However, the studies were performed only for the 2.4 GHz band which does not make it possible to predict the channel capabilities.

As can be seen from the results of the above studies, there are a large number of factors influencing the basic parameters of Standard 802.11 wireless channels and different ways to detect them. The process of parameter evaluation is accompanied by a significant number of random factors affecting the accuracy and reliability of the final result and can also take a significant time to obtain the final result. Therefore, in general, there is a problem of lack of a common theoretical mechanism that combines the action of all influences with the parameters of efficiency of Standard 802.11 channels.

To solve this problem, it is necessary to perform a theoretical generalization of all processes occurring in wireless channels taking into account the maximum possible number of destabilizing factors and their impact on the effective data transfer rate. The target is the creation of models of estimating the effective data transfer rate using a statistical relationship between main parameters of the channel and, based on the models, propose provisions of the method of estimating the channel effective data transfer rate to predict the transmission of any traffic with high reliability, speed, and efficiency.

### 3. The aim and objectives of the study

This study's objective was to develop a method for estimating the effective data rate based on an empirical model of a statistical relationship between the main parameters of the Standard 802.11 channel. This will increase the reliability and speed of evaluating the channel efficiency at the network design and operation stages.

To achieve this goal, it was necessary to solve the following tasks:

- to develop a general mathematical model of the relationship of basic parameters of the Standard 802.11 wireless channel;
- to perform experimental studies of main channel parameters under conditions of minimal influence of multipath wave propagation and interferences;
- to develop an empirical model of estimating the effective data rate on the basis of the statistical relationship between the main parameters of the channel taking into account a maximum possible number of influencing factors;
- to formulate provisions of the method of estimating the effective data rate in Standard 802.11 channels with high reliability, speed, and cost-effectiveness.

### 4. The general mathematical model of the relationship between the main parameters of the channel

The process of transmitting information in a wireless channel in real conditions involves maintaining connection under the action of destabilizing factors such as interferences, delays, and noise in the transmission path, etc. To minimize the impact of such factors in packets and frames, there is a mechanism for entering additional service information, and a retransmission mechanism is used [13].

If the channel is considered from the point of view of an application level, the general information model can be determined using the efficiency factor which can be written as [14]:

$$K_k = \frac{V_{eff}}{V_{pl}}, \quad (1)$$

where  $V_{eff}$  is the effective data rate;  $V_{pl}$  is the channel bandwidth determined by the rate of conversion of frames into a bit sequence at a physical level.

Analysis of studies [15–18] shows a relationship between the main parameters of the wireless channel: the effective data transfer rate, bandwidth, and signal strength at the receiver input. These parameters are affected by various destabilizing factors. Then, expression (1) can be rewritten as the informational and energy efficiency of the channel. Thus, the following is obtained:

$$K_p = \frac{V_{eff}}{P_{RX}} f_1(S_c(x_1 \dots x_n), S_o(y_1 \dots y_m)), \quad (2)$$

$$K_v = \frac{V_{eff}}{V_{pl}} f_2(S_c(x_1 \dots x_n), S_o(y_1 \dots y_m)),$$

where  $P_{RX}$  is the signal strength at the receiver input;

$S_c(x_1 \dots x_n)$  is characteristic of the transmission medium which depends on the set of parameters  $x_n$  including signal attenuation, interferences, noise power, the distance between the receiver and transmitter, etc.;

$S_o(y_1 \dots y_m)$  is characteristic of the equipment used in the creation of the wireless channel depending on the set of parameters  $y_m$ : signal strength at the receiver input, signal/noise level, number of errors in received frames, number of lost packets, etc.;

$f_1$  and  $f_2$  are the functions of linking the destabilizing factors with the main channel parameters.

The effective data transfer rate is a common parameter in expressions (2).

This parameter can be assessed in two ways. One of them is the application of the models of assessing parameters of the transmission medium and equipment [17–19]. The other includes the use of a model based on the monitoring algorithm [20]. In both cases, the most reliable models will be obtained empirically.

From a mathematical point of view, functions  $f_1$  and  $f_2$  can be quite complex as they take into account a large number of parameters which are almost impossible to determine in some cases. Using the results of experimental studies, such functions can be replaced by regression models based on the channel length. In this case, the regression models should correspond as much as possible to the real characteristics of the channel. Taking into account the basic parameters of the Standard 802.11 wireless channel,

the model of parameter assessment for expression (2) can be written as follows:

$$\begin{cases} V_{eff}(l) \approx f_b(l) + V_0, \\ V_{pl}(l) \approx f_c(l) + V_{pl,0}, \\ P_{RX}(l) \approx f_a(l) + P_0, \end{cases} \quad (3)$$

where  $f_a(l)$ ,  $f_b(l)$ ,  $f_c(l)$  are regression models;  $V_0$ ,  $V_{pl,0}$ ,  $P_0$  are initial values of the regression models for corresponding channel parameters;  $l$  is the wireless channel length.

There is a common parameter  $l$  in the given model through which it is possible to express the assessment of one parameter through another. The channel bandwidth is determined by the MCS scheme and its values are specified in the Standard specifications. This parameter can be used as an indicator of channel stability and efficiency of the MCS circuit [21]. Then the parameter  $l$  can be expressed in terms of signal strength and effective data transfer rate. Thus, the following is obtained:

$$\begin{cases} l \approx \frac{V_{eff}(l) - V_0}{b}, \\ l \approx \frac{P_{RX}(l) - P_0}{a}, \end{cases} \quad (4)$$

where  $a$  and  $b$  are the attenuation parameters of the regression models  $f_a(l)$  and  $f_b(l)$ , respectively.

Substituting (4) in (3), equations of correspondence are obtained:

$$\begin{cases} V_{eff}(l) \approx \frac{b(P_{RX}(l) + P_0)}{a} + V_0, \\ P_{RX}(l) \approx \frac{a(V_{eff}(l) + V_0)}{b} + P_0. \end{cases} \quad (5)$$

Taking into account the regression models of channel parameters, coefficients of informational and energy efficiency of the channel (2) will be written as follows:

$$K_p = \frac{V_{eff}(l)}{P_{RX}(l)} = \frac{b(b(P_{RX}(l) + P_0) + aV_0)}{a(a(V_{eff}(l) + V_0) + bP_0)}, \quad (6)$$

$$K_v = \frac{V_{eff}(l)}{V_{pl}} = \frac{b(P_{RX}(l) + P_0) + aV_0}{aV_{pl}}.$$

Expressions (6) show that when knowing the value of one channel parameter, another can be determined. As is known, the estimation of the signal strength parameter at the receiver input is relatively simple and accessible based on the monitoring algorithms. Using the coefficients of informational and energy efficiency, it is possible to obtain mod-

els for assessment of effective data transfer rate and channel stability. However, this requires the most reliable model of the relationship between basic parameters of the channel which can be obtained on the basis of empirical studies.

## 5. Analysis of empirical studies

To develop a mathematical model, a series of studies were conducted on the basis of the Standard 802.11 wireless network in which there was one wireless channel as shown in Fig. 1 [15].

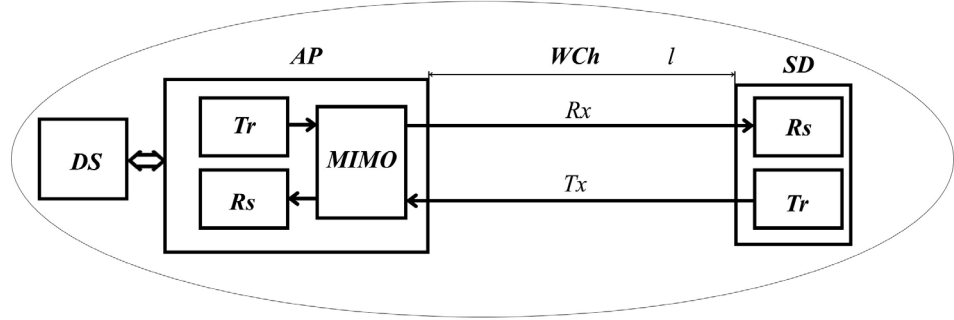


Fig. 1. The network structure for studying channel parameters

The wireless channel (WCh) was created indoors using an access point (AP) with support of MIMO 3x3 technology and a mobile subscriber device (SD) containing one antenna. This makes the average statistical most common option available in the market. SD and AP support all Standard 802.11s for the 2.4 GHz and 5 GHz bandwidths up to and including the 802.11ac standard.

The room allowed us to create a wireless line-of-sight channel with length  $l$  up to 80 m with a minimum number of reflective surfaces and minimize interference impact.

The main parameters for the study included effective data rate  $V_{eff}$ , bandwidth capacity  $V_{pl}$ , signal strength at the receiver input  $P_m$  which can be obtained using monitoring algorithms and applications of an (layer). The parameters were evaluated by averaging the measurement results for a monitoring time of 1 s and an observation period of 360 s [17].

To analyze the results of experimental studies, the following notation types were introduced for the graphs: 1 – 802.11a; 2 – 802.11g; 3 – 802.11n (20 MHz, 2.4 GHz); 4 – 802.11n (40 MHz, 2.4 GHz); 5 – 802.11n (20 MHz, 5 GHz); 6 – 802.11n (40 MHz, 5 GHz); 7 – 802.11ac (20 MHz); 8 – 802.11ac (40 MHz); 9 – 802.11ac (80 MHz).

The results of the study of the channel main parameters obtained based on the proposed method are shown in Fig. 2, 3.

As can be seen from the study results shown in Fig. 2, the level of signal attenuation and fluctuations is similar for all studied varieties of Standard 802.11. Signal fluctuations and the difference between the frequency bands 2.4 GHz and 5 GHz had the same value: 5...10 dBm. The low level of fluctuations of the  $V_{eff}$  and  $V_{pl}$  parameters show high stability of the channels of Standards 802.11a and 802.11g. They used the widest guard bands. Multi-beam propagation of waves and the presence of minor architectural obstacles had minimal impact on such channels.

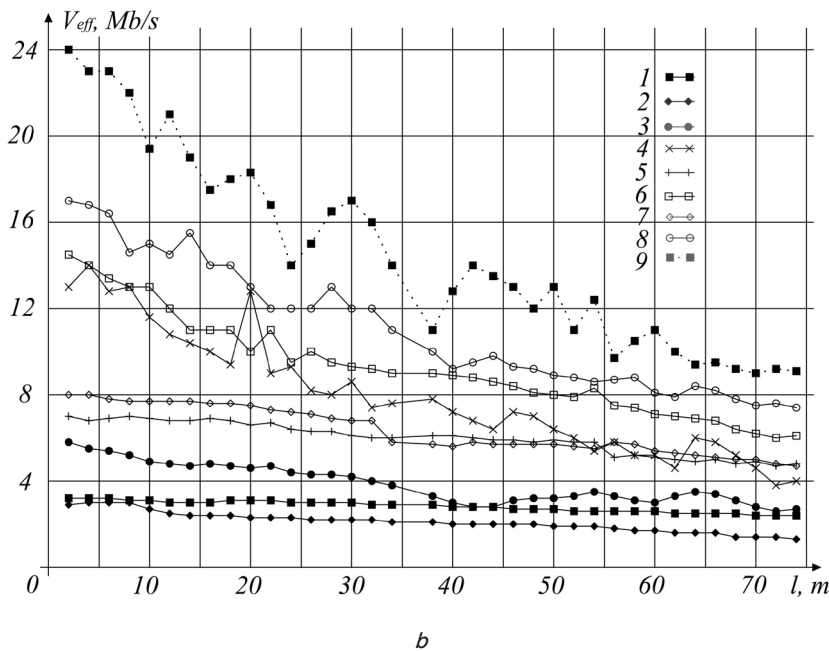
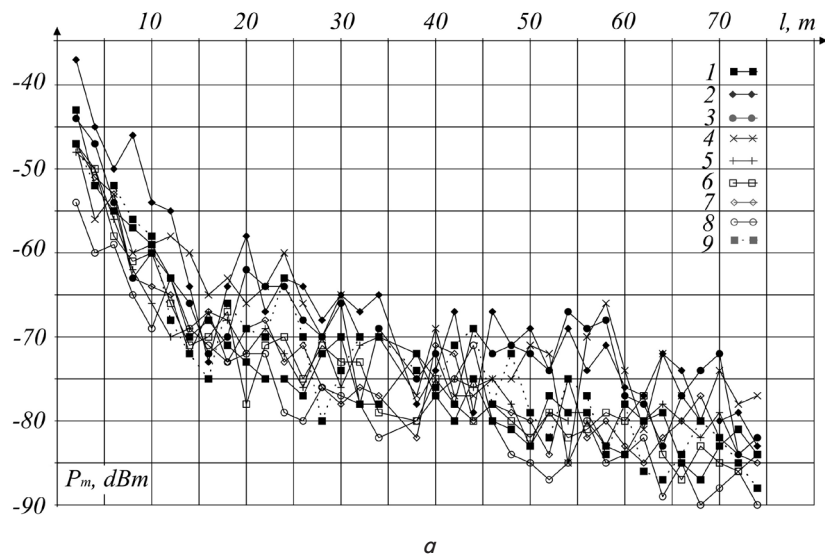


Fig. 2. The results of the study of the channel main parameters:  
 a – dependence of the signal strength at the receiver input on the channel length;  
 b – dependence of the effective data rate on the channel length

As for the Standard 802.11n, there was a difference in the effective data rate in 2.4 GHz and 5 GHz frequency bands. This confirms the fact that the loading of the 2.4 GHz band is quite high in the present-day realities and complete elimination of the effects of interference and noise is quite a challenge. Therefore, to find regression models, the most reliable results will be exactly in the 5 GHz band. On the other hand, 5 GHz channels have higher instability and signal attenuation coefficient. At a signal strength of 80 dBm, strapping of  $V_{pl}$  to 1 MB/s or 2 MB/s as well as very frequent connection breaks were observed for such channels.

The difference in speeds of the channels of different types of Standard 802.11 is predictable and determined by various optimizations and additional technologies of frame transmission [22]. For example, the Standard 802.11ac uses

the fewest guard bands and the highest QAM order. This increases the channel bandwidth capacity but significantly reduces the effective length of the channel with a high level of fluctuations. This can be traced by fluctuations of the parameter  $V_{pl}$  (Fig. 3). The Standard 802.11ac has shown the greatest instability. Connection breaks were observed at a length of 40 m and more where fluctuations were 15...200 MB/s. In addition, a channel with an 80 MHz band lost connection starting at 20 m at a minimal change in subscriber position.

Also, the studies show that the larger the bandwidth of the frequency channel, the greater efficiency of the channel can be obtained, however, at short distances. Channels with a bandwidth of 20 MHz are more efficient for stable data transmission over long distances.



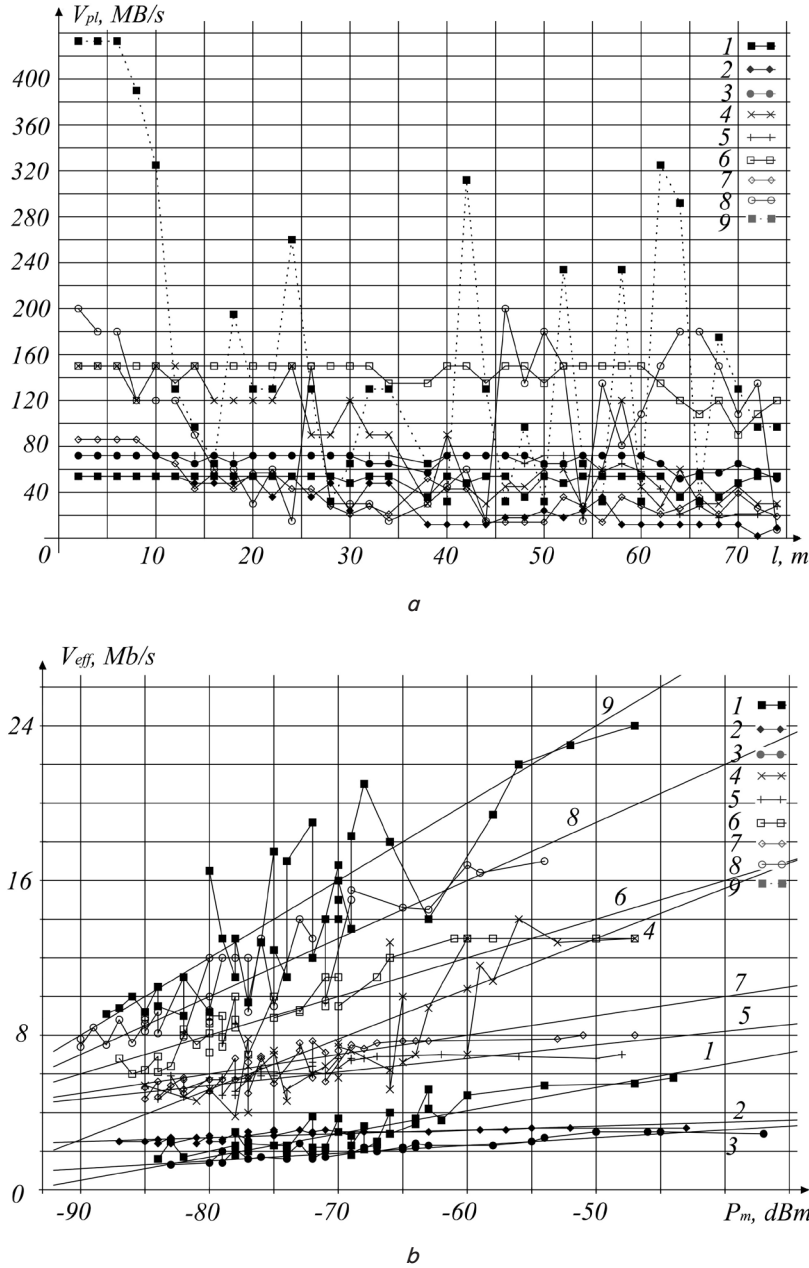


Fig. 3. The results of the study for: *a* – dependence of the channel bandwidth capacity on the channel length; *b* – the dependences of the effective data rate on the signal strength at the receiver input

**6. Development of a mathematical model of assessment of effective data rate based on the statistical interrelation**

As the results of experimental studies show, the main channel parameters had fluctuations along the entire length of the channel in any case. The magnitude of such fluctuations depended on the number and level of influence of destabilizing factors [15, 16]. In this case, taking into account the study results, the multi-beam propagation of waves occurring because of the presence of reflective surfaces in the room was the main destabilizing factor. As a result, when assessing the main parameters of the wireless channel, there were fluctuations at different time points of the observation period which can be seen in Fig. 2, *a*, *b*, as maxima and minima in the characteristics. They can be taken into account in assessment procedures as permissible fluctuations of main

parameters and determined from experimental data using the following expressions:

$$\Delta P \approx \frac{1}{2} \left( \frac{1}{n} \sum_{j=1}^n \max \{ P_{m,i} \}_j - \frac{1}{n} \sum_{j=1}^n \min \{ P_{m,i} \}_j \right),$$

$$\Delta V \approx \frac{1}{2n} \sum_{i=1}^n \left( \max \{ V_{eff,i} \}_j - \min \{ V_{eff,i} \}_j \right), \tag{7}$$

where *n* is the number of observation periods to obtain the experimental characteristics  $P_m(l)$  and  $V_{eff}(l)$ .

Taking into account expressions (8) and the results, shown in Fig. 2, *a*, *b*, correspondence of the fluctuation intervals to the signal strength at the receiver input  $\Delta P$  and the effective data transfer rate  $\Delta V$  is given in Table 1.

Table 1

Intervals of fluctuation of measuring parameters

Parameter	802.11a	802.11g	802.11n 20 MHz 2.4 GHz	802.11n 40 MHz 2.4 GHz	802.11n 20 MHz 5 GHz	802.11n 40 MHz 5 GHz	802.11ac 20 MHz	802.11ac 40 MHz	802.11ac 80 MHz
$\Delta P$ , dB·m	4±	5±	5±	6±	4±	6±	5±	7±	8±
$\Delta V$ , Mb/s	1.0±	2.0±	6.0±	2±	3.0±	1±	1±	2.1±	2±

The fluctuation of main parameters  $\Delta P$  and  $\Delta V$  determines limits of fluctuations of one parameter which leads to changes in other parameters within acceptable limits which will not affect delays in frame transmission. Then, using the methods of regression analysis and taking into account the fluctuation intervals, models for estimating basic parameters of the wireless channel were obtained which can be written as follows:

$$P_{RX}(l) \approx \begin{cases} a_1 l + P_0 \pm \Delta P, & \text{for } l < 16 \text{ m,} \\ a_2 \ln(l) + P_0 \pm \Delta P, & \text{for } l < 80 \text{ m;} \end{cases}$$

$$V_{eff}(l) \approx bl + V_0 \pm \Delta V, \tag{8}$$

where  $a_1$  is the regression coefficient  $f_a(l)$  for the linear law;  $a_2$  is the regression coefficient  $f_a(l)$  for the logarithmic law.

The characteristic of signal attenuation along the channel length can be divided into two sections. The first section is for short, up to 16 m, channels. This is the zone with a high signal attenuation coefficient in which the greatest channel stability is observed. After 16 m, attenuation is smaller, with the characteristic having a shape close to that of the logarithmic model for long channels. This corresponds to the classic models of signal attenuation. The model of assessment of the effective data rate is close to the linear model and standards differ in attenuation coefficients, initial values, and the fluctuation level  $\Delta V$ .

Taking into account peculiarities of assessing parameters of regression models in [15–17] and performing statistical processing of the study results, the following results were obtained:

$$P_{RX}(l) \approx \begin{cases} -2l + P_0 \pm \Delta P, & \text{for } l < 16 \text{ m;} \\ (-10 \pm 1.3) \ln(l) + P_0 \pm \Delta P, & \text{for } l < 80 \text{ m;} \end{cases}$$

$$V_{eff}(l) \approx \begin{cases} -0.2l + V_0 \pm \Delta V, & \text{for } \Delta f = 80 \text{ MHz;} \\ -0.1l + V_0 \pm \Delta V, & \text{for } \Delta f = 40 \text{ MHz;} \\ (-0.02 \pm 0.01)l + V_0 \pm \Delta V, & \text{for } \Delta f = 20 \text{ MHz,} \end{cases} \tag{9}$$

where  $\Delta f$  is the frequency channel band.

The initial level is within  $P_0 = 40 \pm 4$  dBm in the presence of fluctuations  $\Delta P = \pm 5 \dots 10$  dBm. Initial levels of parameter  $V_0$  are given in Table 2.

Initial levels for parameter  $V_0$

802.11a	802.11g	802.11n 20 MHz 2.4 GHz	802.11n 40 MHz 2.4 GHz	802.11n 20 MHz 5 GHz	802.11n 40 MHz 5 GHz	802.11ac 20 MHz	802.11ac 40 MHz	802.11ac 80 MHz
3.2 Mb/s	2.8 Mb/s	5.3 Mb/s	12.2 Mb/s	7.2 Mb/s	13.2 Mb/s	8.2 Mb/s	16.2 Mb/s	23 Mb/s

The models of assessment of the effective data rate and signal strength at the receiver input contain average regression parameters. In the line of sight, such parameters will be

valid for any Standard 802.11 equipment and various premises. However, there are no ideal conditions and therefore it is necessary to take into account static and accidental destabilizing factors. To do this, it is necessary to have a variable parameter that will take into account all these factors. This parameter is the measured value of the signal strength  $P_m$ . It can be assessed both in real-time and by means of the averaging period. Then, the initial level of the regression model  $P_0$  is expressed taking into account optimal conditions for assessing  $P_m$  at a distance of 2 m from the access point [17–19]. Using model (8) and taking into account the short and long channels in the room, the expression for calculating the initial value of the signal strength will be written as follows:

$$P_0 = \begin{cases} P_m - 2a_1, & \text{for } l < 16 \text{ m;} \\ P_m - a_2 \ln 2, & \text{for } l < 80 \text{ m.} \end{cases} \tag{10}$$

Next, determine the effective data rate through the signal strength at the receiver input. To do this, it is necessary to find a relationship between the characteristics of the channel  $V_{eff}(l)$  and  $P_{RX}(l)$ . This can be achieved in two ways. The first of them is through the coefficient of energy efficiency of the channel. Substituting expressions (8) and (10) in (6), the following is obtained:

$$K_p = \begin{cases} \frac{bl + V_0 \pm \Delta V}{a_1 l + P_m - 2a_1 \pm \Delta P}, & \text{for } l < 16 \text{ m;} \\ \frac{bl + V_0 \pm \Delta V}{a_2 \ln(l) + P_m - a_2 \ln 2 \pm \Delta P}, & \text{for } l < 80 \text{ m.} \end{cases} \tag{11}$$

The other way is finding a model of the statistical relationship between parameters  $P_m$  and  $V_{eff}$  using the regression method. The results are shown in Fig. 3,  $b$  individually for each studied standard where the linear regression lines pass through the averaged points ( $P_m^c$  and  $V_{eff}^c$ ). In this case, a general approximate expression can be obtained:

$$V_{eff}(P_{RX}) \approx KP_m + S_0, \tag{12}$$

where  $K$  and  $S_0$  are the coefficients of linear regression given in Table 3.

The linear regression gives a simple relationship model, however, it makes a minor error for some standards. Taking

Table 2

into account fluctuations of  $\Delta V$  and  $\Delta P$ , this error is within acceptable limits.

Based on mathematical modeling, determine the optimal relationship between main parameters of the channel using the condition

for long channels  $l < 80$  m for expressions (11) and (12) (modeling of expression (12) taking into account expression (8)). The results of mathematical modeling are shown in Fig. 4.

Table 3

Regression coefficients

Parameter	802.11a	802.11g	802.11n 20 MHz 2.4 GHz	802.11n 40 MHz 2.4 GHz	802.11n 20 MHz 5 GHz	802.11n 40 MHz 5 GHz	802.11ac 20 MHz	802.11ac 40 MHz	802.11ac 80 MHz
$K$	0.02	0.04	0.12	0.2	0.07	0.26	0.1	0.3	0.38
$S_0$	4.3	4.7	11	24	11	26	14	34	44

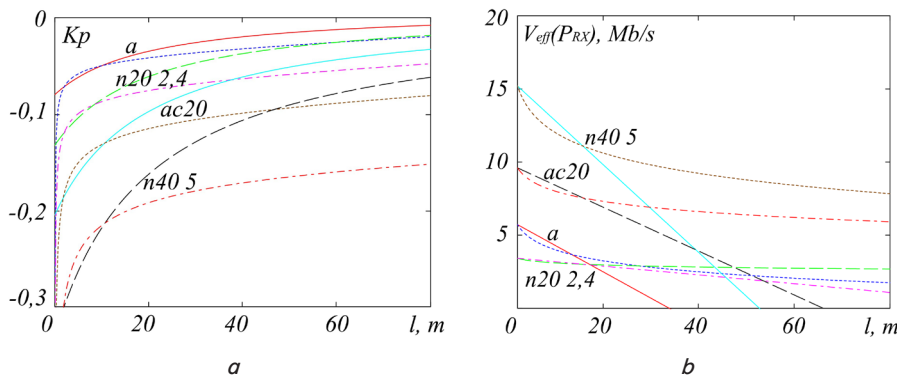


Fig. 4. The results of studying models of relationship between main channel parameters for:  $a - K_p$ ;  $b - V_{eff}(P_{RX})$

As can be seen from the graphs in Fig. 4, when using the coefficient of energy efficiency  $K_p$ , a significant error occurs at a displacement of points of intersection of linear and logarithmic models relative to  $V_{eff}(P_{RX})$ . As a result, this leads to a discrepancy between the mathematical estimate of the effective data transmission rate and real values. Then, it is advisable to use a regression model of statistical relationship which gives the most reliable result. Substituting (8) and (10) into (12), the following is obtained:

$$V_{eff}(l) \approx \begin{cases} K \begin{pmatrix} a_1 l + P_m - \\ -2a_1 \pm \Delta P \end{pmatrix} + S_0, & \text{for } l \leq 16 \text{ m;} \\ K \begin{pmatrix} a_2 \ln(l) + P_m - \\ -a_2 \ln 2 \pm \Delta P \end{pmatrix} + S_0, & \text{for } l > 16 \text{ m.} \end{cases} \quad (13)$$

The empirical model (13) makes it possible to estimate the effective data rate for any channel of the Standard 802.11 along its entire length using just the basic energy parameter. Because each Standard 802.11 device has built-in means of measuring the received signal strength, such estimation can be performed in real-time and for all standards simultaneously.

### 7. Working out provisions of the method of assessment of effective data rate

The obtained model (13) uses the measuring parameter  $P_m$  which can be obtained using software and hardware of Standard 802.11 devices. In addition, based on the  $V_{eff}$  parameter, information about the capabilities of the channel to transmit different types of traffic can be obtained. Therefore, a method for assessing the effective data rate using the monitoring algorithms has been proposed. The essence and sequence of the method are as follows.

At the first stage, signal strength at the input of the receiver is assessed on the basis of  $P_m$  monitoring algorithm using hardware and software of the subscriber equipment based on the structure shown in Fig. 1.

In the second stage, the effective data rate in the channel is calculated using the model (13). Moreover, the calculation is performed for all standards according to the coefficients given in Table 2 and Table 3.

At the third stage, coefficients of informational and energy efficiency  $K_i(l)$  and  $K_p(l)$ , respectively, (expression 11) for all types of wireless channels are determined. Taking into account expression (9), the coefficient of informational efficiency can be written as follows:

$$K_V(l) \approx \begin{cases} \frac{-0.2l + V_0 \pm \Delta V}{V_{pl}}, & \text{for } \Delta f = 80 \text{ MHz;} \\ \frac{-0.1l + V_0 \pm \Delta V}{V_{pl}}, & \text{for } \Delta f = 40 \text{ MHz;} \\ \frac{(-0.02 \pm 0.01)l + V_0 \pm \Delta V}{V_{pl}}, & \text{for } \Delta f = 20 \text{ MHz.} \end{cases}$$

At the fourth stage, derivation of assessment results is performed taking into account the fluctuation intervals. The result of an effective data rate has fluctuations that can be expressed by an appropriate interval which will correspond to the interval of power fluctuations:

$$V_{eff}(l) - \Delta V < V_{eff} \leq V_{eff}(l) + \Delta V.$$

Additionally, assessment of the current state of the wireless channel for transmission of the traffic of various types is performed. For high-quality infocommunication services, the bit rate  $V_b$  must correspond to the following condition:

$$V_b \leq (0.8..0.7)V_{eff} - \Delta V.$$

The obtained inequality makes it possible to assess the suitability of the wireless channel of Standard 802.11 for the transmission of any traffic when the bit rate  $V_b$  is known.

Using the proposed method, it is possible to get maximum efficiency of the channel when designing a network or setting up a wireless channel for maximum performance during operation without resort to the use of expensive equipment. The method is relatively simple and accessible and is based on the measurement of the main energy parameter using the software and hardware of the subscriber device (monitoring). This makes it possible to assess the effective data rate for a particular subscriber taking into account all current destabilizing factors for any room. A significant number of destabilizing factors, such as the presence of interferences which can lead to errors in assessment can be considered a limitation



of the application of this procedure. In addition, the impact of architectural obstacles can be assessed on the basis of the parameters  $\Delta P$  and  $\Delta V$ , as considered in [15, 16].

### 8. Discussion of the results obtained in the study of the proposed method

When applying classical methods and models for assessment of effective data rate, significant deviations of the obtained results occur with the appearance of various factors of influence. To reduce complexity, results of experimental studies for certain conditions [4, 5] or correction coefficients can be applied at individual stages of monitoring [8, 11]. However, the emergence of random factors of influence will reduce the accuracy of assessment because of the impossibility of their prediction. From a mathematical point of view, as expressions (2) show, assessment of parameters of Standard 802.11 wireless channels is a rather complex process if it is necessary to take into account all influencing factors. However, it is possible to get the distribution of channel parameters with one common parameter when using assessment along the entire channel length. Such distributions can be generally expressed using the regression models (3) which should correspond as much as possible to real characteristics of the channel.

The real characteristics of the channel are demonstrated by the study results shown in Fig. 2, 3 where similarity of characteristics for all studied varieties of the Standard 802.11 is seen. This means that the distribution of signal strength along the entire length of the channel can be predicted for any subscriber device by performing measurements at one point in the room. The difference between the standards will be only in the coefficients of regression decay, which depend on the number of the guard bands used and the initial levels. Therefore, the application of the model (12) gives a significant gain for the observation period during the monitoring process since the main energy parameter  $P_m$  is used. Information on the change of such a parameter over time can be obtained using monitoring algorithms. This is available for any subscriber device of Standard 802.11, which significantly reduces the costs of monitoring and time to obtain the final result. Also, presence in the model of intervals of fluctuation of main parameters is optimal in terms of the ability to take into account the maximum possible number of influencing factors for assessment of any wireless channel created with the participation of the subscriber device.

To confirm the adequacy of the obtained evaluation model, mathematical modeling was performed taking into account the limits of change of the measurement parameter  $P_m$ . The results are shown in Fig. 5.

As can be seen from the graphs in Fig. 5, the simulation results are consistent with empirical studies. The error between them is within the fluctuation intervals.

The proposed method combines operations of assessment of the parameter  $P_m$ , assessment of the channel efficiency along its entire length and the possible impact of destabilizing factors. The operations of assessment of the  $P_m$  parameter can be both for the straight distance between AP and AD and the models [17–19] can be used to obtain the spatial distribution of the effective data rate in the room.

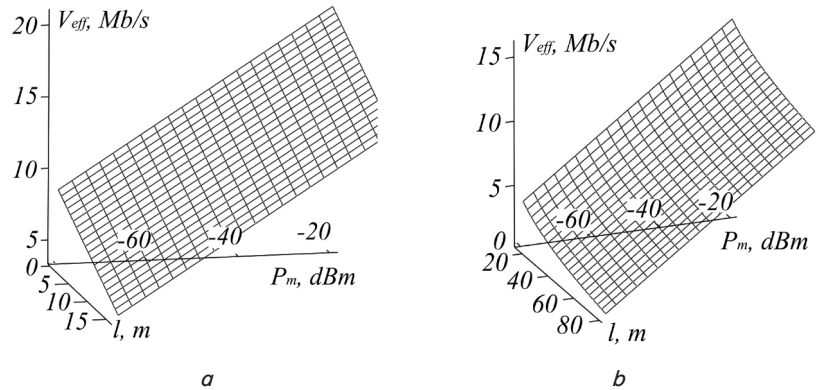


Fig. 5. Dependence of the effective data rate on the measuring power of the signal for:  $a - \leq 16$  m;  $b - > 16$  m

The reliability of the proposed method depends on three main factors:

- reliability of the results based on which the mathematical model was obtained (taking into account the confidence probability of 0.99, confidence interval of the measurement parameters will be  $\delta_{P_m} \pm 0.25$  dBm;  $\delta_{V_{eff}} \pm 0.03$  Mb/s);
- reliability of measuring the parameter  $P_m$  which will depend on characteristics of Standard 802.11 equipment from different manufacturers;
- reliability of assessment of the intervals  $\Delta P$  and  $\Delta V$  to take into account the factors of influence.

In general, the reliability of the  $P_m$  parameter measurement will be the biggest problem. However, this reliability can be improved by creating a database of parameters of the model of statistical interrelation  $V_{eff}(P_{RX})$  for different devices. In addition, it is the establishment of statistical interrelations, correcting coefficients of the channel between main parameters of the channel and a certain type of a destabilizing factor using the intervals of fluctuations that will make it possible to improve the accuracy of assessment, which is expected in future studies.

### 9. Conclusions

1. A general mathematical model of the wireless channel of the Standard 802.11 was developed on the basis of informational and energy efficiency. This model is based on the regression function which makes it possible to use models of assessment of the effective data rate using the relationship between basic parameters of the channel.

2. Experimental studies of main parameters of wireless channels of the family of the Standards 802.11x were performed. Based on this, it was found that the level of the signal attenuation and fluctuation is similar for all studied varieties of Standard 802.11. Therefore, the distribution of signal strength along the entire length of the channel can be provided for any subscriber device by performing measurements at one point in the room.

3. An empirical model of assessment of effective data rate using a statistical interrelation of main parameters of the channel was obtained. The model makes it possible to assess the effective data rate for any Standard 802.11 channel along its entire length using the energy parameter and its fluctuations.

4. A new method of assessment of the effective data rate in the Standard 802.11 channel has been developed taking into account the maximum possible number of destabilizing

factors. The method is based on the measurement of the main energy parameter using the software and hardware of the subscriber device. The main purpose is assessing the suitability of the channel of an individual subscriber in real time and at the

stages of designing wireless networks of Standards 802.11x in technical diagnostic operations. The method is characterized by high reliability and speed of obtaining the final result which can be implemented for any subscriber device.

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