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MODELING OF IEEE 802.11 COMPUTER NETWORKS OPERATION AT INCREASED INTERFERENCE INTENSITY

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ABSTRACT

Context. High level of industrial noise increases the loss of information frames during transmission, which in turn decreases the network throughput. We propose a mathematical model of IEEE 802.11 networks operation under conditions of increased interference intensity.

Objective. The purpose of this paper is to express in an explicit analytical form the effect of bit error rate (BER) on the probability of frame transmission and the network throughput.

Method. We have proposed the method for constructing a model that allows you to directly calculate the dependence of the frame transmission probability on the number of stations operating in saturation mode, which is convenient for engineering calculations. The values of the model coefficients were selected by comparing the calculation results with the results obtained using the known Bianchi model, which describes the network operation in the form of a Markov process. In the range of up to 23 stations working with one access point, which corresponds to a collision probability of up to 0.5, the indicated dependences for both models satisfy each other with an accuracy sufficient for the practical application. An expression for the network throughput has been defined.

Results. The results of the model development were used to take into account the effect of interference intensity on the information transfer process. This made it possible to explicitly express the effect of BER on the probability of frame transmission and the network throughput in the case of variations in the length of the frames and with a different number of competing stations. The degree of throughput reduction has been determined for BER = 10^{-5}, $5 \cdot 10^{-5}$, 10^{-4} and increasing value of minimum contention window.

Conclusions. In this work, a mathematical model has been developed for direct calculation of the probability of frame transmission and network throughput at different levels of BER.

KEYWORDS: IEEE 802.11 networks, mathematical model, frame, transmission probability, collision, throughput, interference intensity.

ABBREVIATIONS

BER is a bit error rate;

CSMA/CA is a Carrier Sense Multiple Access with Collision Avoidance;

DCF is a Distributed Coordination Function;

FER is a frame error rate;

OFDM is an Orthogonal Frequency-Division Multiplexing;

WLAN is a Wireless Local Area Network.

QAM is Quadrature Amplitude Nodulation.

NOMENCLATURE

ACK is a frame acknowledgment;

$DIFS$ is an interframe space;

$SIFS$ is an short interframe space;

$E[Fr]$ is an average frame payload size;

H is a frame header transmission time;

L is length of the frame data field in bits;

m is a number of window doublings allowed;

MAC_{hdr} is a frame channel layer header transmission time;

N is a number of features characterizing original sample;

n is a number of competing stations;

p is a probability that a transmitted frame encounters a collision;

P_b is a bit error rate;

P_f is a frame error rate;

PHY_{hdr} is a frame physical layer header transmission time;

R is a data transfer rate;

$R_{control}$ is a control information transfer rate;

S is a network throughput;

$SIFS$ is a short inter-frame space;

T_c is an average time the channel is sensed busy because of collision;

T_{sc} is an average time the channel is sensed busy because of successful transmission;

W is a contention window;

W_0 is a minimum value of contention window;

W_{avg} is an average backoff window;

α is a multiplicative constant coefficient;

β is a power constant coefficient;

δ is a propagation delay;

η is a number of empty slots;

σ is a duration of one slot;

T is a probability of frame transmission according to the proposed model;

τ is a frame transmission probability by the station in the Bianchi model;

T_s is a probability of successful frame transmission in a noisy channel.

INTRODUCTION

The IEEE 802.11 WLANs are increasingly being used for applications with stringent performance requirements

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due to their ease of deployment and low costs. An important component of these WLANs performance is the implementation of the contention resolution process known as DCF [1]. The DCF is a distributed process created to achieve fair medium sharing among single type stations without any centralized scheduling control of the medium. A distributed channel access process is based on CSMA/CA algorithm.

Even though the maximum physical layer rates are increasing with the introduction of new generation WLANs such as 802.11ac and 802.11ax, the effective throughput remains low, especially with a significant number of simultaneously operating stations and a high level of industrial interference. In its most basic form, the DCF consists of a carrier sensing function and a random backoff protocol. Carrier sensing allowed stations to wait when the medium is busy and to resume transmission attempts until the medium becomes free. If two or more stations have frames to send, the probability exists that their transmissions will immediately collide as soon as the medium becomes free. To avoid collisions, stations will backoff their attempts to transfer frames for a random number of slot times, based on a random variate selected from a contention window. If two or more competing stations select the same transmission slot times, their transmissions will collide again. They will detect the collision base on the lack of the positive acknowledgement of the frame reception from the access point. Stations that collide will increase their contention window size and repeat transmission, and reset the contention window upon eventual successful transmission.

High level of industrial interference increases BER in transmission channel. The result is an increased loss of information frames during transmission, which in turn decreases the network throughput. The problem lies in the limited ability of algorithmic support to cope with the complexity of the wireless channel due to fading, collisions, co-channel and external industrial interference. Network nodes cannot distinguish one type of loss from another because the symptoms are the same – lack of positive acknowledgment from the access point.

The object of study is the process of information transmission in wireless computer networks of the IEEE 802.11 standard.

The subject of study is the class of mathematical models that describe the operation of wireless networks with infrastructure topology.

The purpose of the work is to express in an explicit analytical form the effect of BER on the probability of frame transmission and the network throughput.

1 PROBLEM STATEMENT

The performance analysis of IEEE 802.11 DCF networks based on bidimensional Markov – chain model with ideal channel conditions showed [2–4] that the frame transmission probability by the station in a randomly chosen slot time is

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1)+pW_0[1-(2p)^m]}, \qquad (1)$$

where $W_0 = CW_{\min}$, $CW_{\max} = 2^m W_0$.

In a special case $m = 0$ the probability τ results to be independent of p, and (1) becomes the much simpler one independently found in [5] for the constant backoff window problem $\tau = 2 / (W_0 + 1)$.

However, in general, τ depends on the collision probability p, which is still unknown. The probability p that a transmitted frame gets into a collision is the probability that, in a time slot, at least one of the $n - 1$ remaining stations transmit. At steady state, each remaining station transmits a frame with probability τ. This yields [2]

$$p = 1-(1-\tau)^{n-1}. \qquad (2)$$

The purpose of this work is to develop a mathematical model expressing explicitly the dependence of the probability of successful frame transmission on the number of stations operating in saturation mode. Within the framework of this model, it is necessary to study the similar dependence for network throughput, and to determine the effect of the BER value on the probability of frame transmission and the throughput with varying frame lengths and a different number of competing stations.

2 REVIEW OF THE LITERATURE

Collisions are more likely to happen when there are many stations in the network with large numbers of frames to send. This situation is well modeled by applying a saturation load. In this mode every station always has a frame available for transmission after the completion of each successful transmission. In a well cited work published by Bianchi [2] and later updated by Tinnirello, Bianchi, and Xiao [3], the authors proved, with a Markov – chain analytical model and with network simulation that the DCF mechanism will converge to a stable and fair allocation of the medium under a saturation load, and provided throughput performance prediction as a function of station transmits probability in a randomly chosen slot time and number of competing stations.

The model takes into account all the exponential backoff protocol details, and allows define the saturation throughput performance of DCF for both standardized access mechanisms [6]. Bianchi showed that if the traffic is saturated, nodes can be modeled as being equally likely to send in any slot, and this assumption also roughly holds for unsaturated traffic which nearly Poisson [7, 8].

The system throughput S is defined as ratio of average payload information transmitted in a time interval to the length of this interval

$$S = \frac{E[\text{ payload information transmitted in an interval time}]}{E[\text{length of an interval time}]}. \qquad (3)$$

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In accordance with [2]

$$S=\frac{P_{tr}\cdot P_s\cdot E[Fr]}{(1-P_{tr})\eta\sigma+P_{tr}P_sT_{sc}+P_{tr}(1-P_s)T_c}\,, \qquad (4)$$

where $P_{tr}=1-(1-\tau)^n$, $P_s=n\tau(1-\tau)^{n-1}/P_{tr}$. In accordance with DCF

$$T_{sc}=H+\frac{E[Fr]}{R}+SIFS+\delta+ACK+DIFS+\delta\,, \qquad (5)$$

$$T_c=H+\frac{E[Fr]}{R}+DIFS+\delta\,. \qquad (6)$$

Contention window is initially set to W_0. If p is the collision probability, then the frame is successfully transmitted with probability $(1-p)$ and the average backoff window is $(W_0-1)/2$. If the first transmission fails, the frame is successfully transmitted on the second attempt with probability $p(1-p)$ and the average backoff window W_{avg} is $(2W_0-1)/2$, and so on. Based on the average backoff window, the probability that a station attempts to transmit in an arbitrary slot is given by $1/W_{avg}$ [9]. The probability that during the transmission of an arbitrary station there is no other active station is $(1-1/W_{avg})^{n-1}$. Thus the collision probability is given by

$$p=1-(1-\frac{1}{W_{avg}})^{n-1}\,. \qquad (7)$$

The probability that a station accessed a channel depends on whether the channel was idle or busy in the previous time slot. The authors in [10] proposed an analytical model taking into account this post – *DIFS* effect by extending the Markovian model developed in [2]. Their analysis did show some impact of the post – *DIFS* slot. However, the obtained numerical results for collision probability seem too low for such a saturated WLAN networks.

The authors of [11] have proposed the method wherein contending stations make their windows dynamically converge in a fully distributed way solely by tracking the number of idle slots between consecutive transmissions.

In [12] authors propose that initially if the intensity of collisions is low the contention window is increased in $\sqrt{2}$ factor then after four collisions the size of the contention window will be doubled in consecutive collisions.

3 MATERIALS AND METHODS

Methods for describing functioning of wireless networks with infrastructure topology using Markov chains modeling as the basic allowed the authors [2–4] to express the probability of frame transmission as a function on the collision probability in form (1). In turn, the probability of collision depends on the probability of the frame transmitting and the number of stations competing for access to the transmission channel (2). This system of equations (Bianchi model) explicitly is not solved. Data obtained by numerical solution of equations (1) and (2) with $W_0=16$ and $m=6$ are presented in Table 1 and Table 2.

This model does not demonstrate an explicit dependence of the probability of a successful frame transmission τ on the number of simultaneously operating stations n, which would be appropriate for engineering calculations.

For these reasons, by analogy with (7), we propose to determine the probability of frame transmission to the access point as follows

$$\tau=T=\frac{2}{[1+\alpha(n-1)]^{-1}\cdot 2^{\beta(n-1)}\cdot W_0+1}\,. \qquad (8)$$

With $n=1$ (one station in the network) $T=2/(W_0+1)$. This corresponds to expression (1) at zero collision probability. The values of the coefficients α and β were selected by comparing the results of calculating τ in accordance with the Bianchi model (presented in Tables 1 and 2), and the results of calculating T according to expression (8) at the same values of n. The corresponding dependences $\tau(n)$ and $T(n)$ for $\alpha=0.05$, $\beta=0.2$ and $\alpha=0.1$, $\beta=0.2$ are shown in Fig. 1.

As can be seen from the graphs in Fig. 1 in the region $1\le n\le 23$, which corresponds to the collision probability $0\le p\le 0.5$, the dependences $T(n)$, calculated in accordance with (8), generally correspond to the dependence $\tau(n)$, calculated in accordance with the Bianchi model. With a further increase in the number of competing stations $n>35$, which corresponds to $p>0.55$, the above dependences diverge: the values of the dependences $T(n)$ are practically zero, and $\tau(n)$ decreases very slowly and reaches 5% of the initial value only at $n=285$.

Table 1 – Results of calculations using the Bianchi model in the range $p=0-0.50$

p	0	0.10	0.17	0.25	0.30	0.35	0.40	0.45	0.50
τ	0.118	0.105	0.094	0.080	0.070	0.060	0.049	0.039	0.031
n	1	2	3	4	6	8	11	16	23

Table 2 – Results of calculations using the Bianchi model in the range $p=0{,}55-1{,}00$

p	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
τ	0.024	0.018	0.013	0.010	0.008	0.006	0.004	0.003	0.0025	0.002
n	35	52	79	121	185	285	443	705	1190	7000

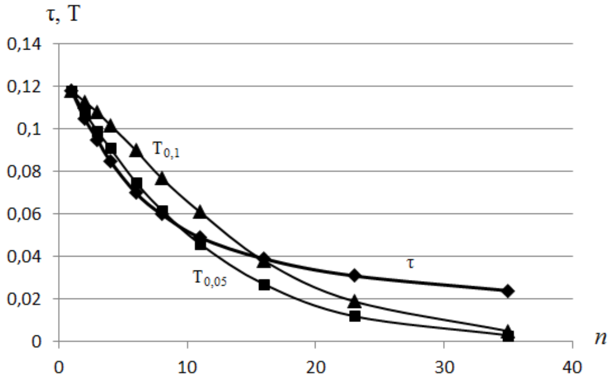

Figure 1 – Dependencies of frame transmission probability (τ, T) on the number of simultaneously operating stations n at $W_0 = 16$: $T_{0.05}$ corresponds to α = 0.05, β = 0.2, and $T_{0.1}$ corresponds to α = 0.1, β = 0.2 in (8)

Let us determine the system throughput S (4) taking into account (8). We represent T (8) in the form $T = 2/(Q + 1)$, where

$$Q = [1+\alpha(n-1)]^{-1} \cdot 2^{\beta(n-1)} \cdot W_0. \qquad (9)$$

Then we obtain

$$S = \frac{2n \cdot E[Fr]}{2n(T_s - T_c) + (Q-1)[(\frac{Q+1}{Q-1})^n T_c - (T_c - \eta\sigma)]}. \qquad (10)$$

Let's calculate the dependence $S(n)$, using the values of Q, which correspond to $T_{0.05}$ and $T_{0,1}$, as well as expressions (5), (6). Wherein:

$$\begin{gathered} T_{sc} - T_c = SIFS + ACK + \delta, \\ H = PHY_{hdr} + MAC_{hdr}, \\ PHY_{hdr} = 4\,\mu s \cdot 5\,OFDM\ symbols, \\ ACK = PHY_{hdr} + L(ACK)/R_{control}. \end{gathered} \qquad (11)$$

Here T_C is defined by expression (6). In the calculations, we used the following parameters values [13, 14]: $SIFS = 16$ µs, $DIFS = 34$ µs, $\delta = 0.33$ µs (the distance between the transmitter and the receiver was taken to be 100 m), $\sigma = 9$ µs, $PHY_{hdr} = 20$ µs, $L(ACK) = 112$ bits, $R_{control} = 6$ Mbit/s, $L(MAC_{hdr}) = 288$ bits, $R = 54$ Mbit/s, $W_0 = 16$.

The corresponding dependences of the throughput S on the number of simultaneously operating stations n at $W_0 = 16$ are shown in Fig. 2.

Note that $n = 79$ corresponds to the collision probability $p = 0.65$.

An increase in the data transfer rate R to 300 Mbit/s does not change the general nature of dependence $S(n)$. However, the maximum values of $S_{0.05}$ and $S_{0.1}$ increase to 47.3 and 51.6 Mbit/s, respectively.

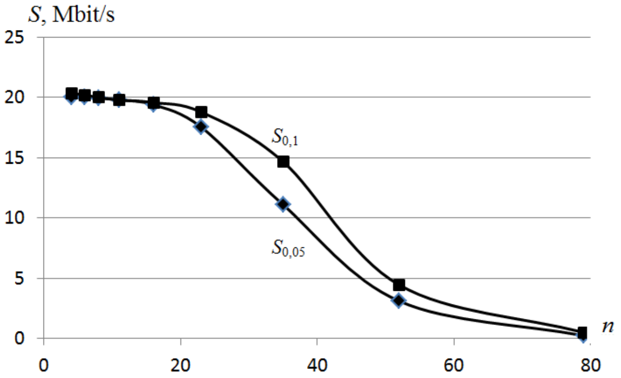

Figure 2 – Throughput S versus the number of competing stations n for $W_0 = 16$: $S_{0.05}$ corresponds to α = 0.05, β = 0.2, and $S_{0,1}$ corresponds to α = 0.1, β = 0.2 in (8)

Let us consider the influence of the initial value of the contention window $W_0 = CW_{\min}$ on the dependence $S(n)$. To do this, we will double the value of W_0 ($W_0 = 32$) and repeat the procedure of selecting the coefficients α and β in expression (8). The closest to $\tau(n)$ dependences $T(n)$ were obtained at α = 0.1, β = 0.15 ($T_{0,1}$) and α = 0.15, β = 0.2 ($T_{0.15}$). They are shown in Fig. 3.

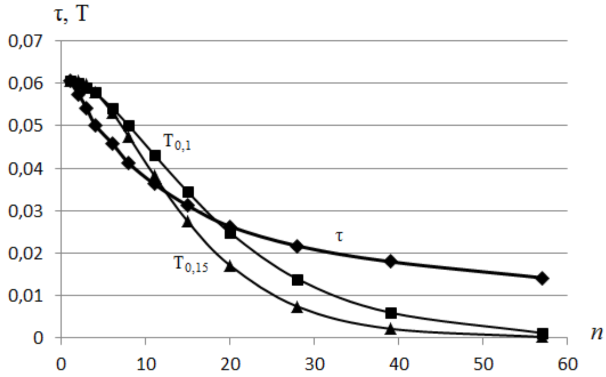

Figure 3 – Dependencies of frame transmission probability (τ, T) on the number of simultaneously operating stations n at $W_0 = 32$: $T_{0.1}$ corresponds to α = 0.1, β = 0.15, and $T_{0.15}$ corresponds to α = 0.15, β = 0.2 in (8)

In Fig. 3, $n = 57$ corresponds to the collision probability $p = 0.55$. With a further increase in the number of competing stations $n > 57$, dependence $\tau(n)$ decreases very slowly and reaches 5% of the initial value only at $n = 780$.

The corresponding dependences $S(n)$ for $W_0 = 32$ are generally similar to the dependences shown in Fig. 2. In this case, the maximum values of S are lower by about 20%, and practically zero values S are achieved at $n = 81$, which corresponds to $p = 0.60$.

4 RESULTS

This section summarized the results of investigation of the BER effect on the throughput with varying frame lengths and a different number of competing stations.

We use for transmission a discrete in time Gaussian channel without memory. In such a channel, bit errors are independent and equally distributed over the bits of the

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frame [15]. Probability that a frame will be transmitted undistorted is equal:

$$q=(1-P_{b1})(1-P_{b2})(1-P_{b3})...(1-P_{bL})=(1-P_b)^L, \qquad (12)$$

where $P_{b1}=P_{b2}=P_{b3}=\ldots=P_{bL}=P_b$.

In this case, the probability of frame distortion is equal to:

$$P_f=1-(1-P_b)^L. \qquad (13)$$

In conditions of increased interference intensity, the probability of successful frame transmission to the access point can be determined as follows:

$$T_S=T(1-P_b)^L, \qquad (14)$$

where T is determined by equation (8).

With the $L=12000$ bits and $\text{BER}=10^{-5}$, the multiplier $(1-P_b)^L=0.89$, with $\text{BER}=5\cdot10^{-5}$ this factor is 0.55, and with $\text{BER}=10^{-4}$, which corresponds to a high noise intensity – 0.30. Taking into account (14), the expression for the throughput S takes the following form:

$$S=\frac{2n(1-P_b)^L\cdot E[Fr]}{2n(1-P_b)^L(T_s-T_c)+[Q+1-2(1-P_b)^L]\left\{[\frac{Q+1}{Q+1-2(1-P_b)^L}]^n T_c-(T_c-\eta\sigma)\right\}}. \qquad (15)$$

The corresponding dependences for $S_{0.05}$ ($\alpha=0.05$, $\beta=0.2$) at $W_0=16$, and $(1-P_b)^L=0.89$, 0.55, 0.30 are shown in Fig. 4. Similar dependences for $S_{0.15}$ ($\alpha=0.15$, $\beta=0.2$) at $W_0=32$ and the same values of $(1-P_b)^L$ are shown in Fig. 5.

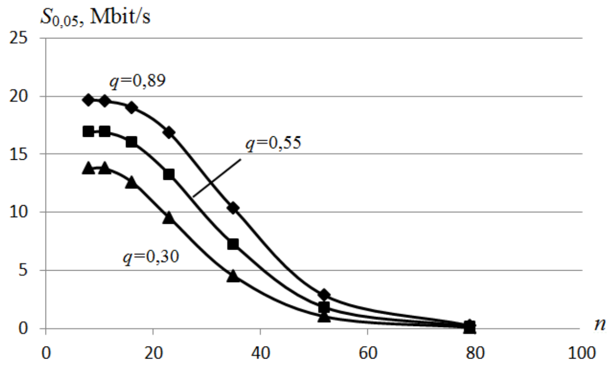

Figure 4 – Dependences of the throughput $S_{0.05}$ ($\alpha=0.05$, $\beta=0.2$) at $W_0=16$ on the number of competing stations n at different levels of $q=(1-P_b)^L$

As follows from the plots shown in Fig. 4 and 5, with an increase in the interference intensity (BER) and, as a consequence, a decrease in the value of q, the throughput S decreases. As before, this effect increases with the expansion of the initial contention window W_0.

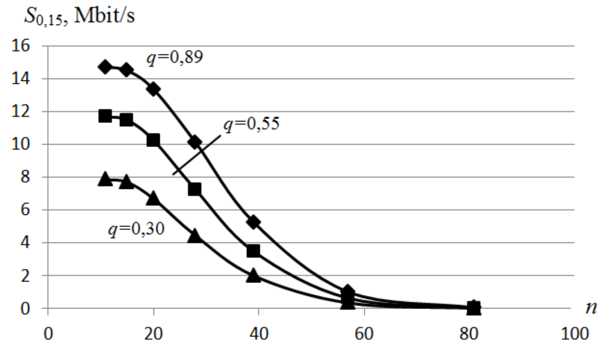

Figure 5 – Dependences of the throughput $S_{0.05}$ ($\alpha=0.05$, $\beta=0.2$) at $W_0=16$ on the number of competing stations n at different levels of $q=(1-P_b)^L$

5 DISCUSSION

Along with the main advantages of the Bianchi model, such as versatility of the solution, compliance with the DCF – process and algorithm CSMA/CA, this model has some disadvantages.

First, this model does not make it possible to directly calculate the probability of frame transmission depending on the number of stations simultaneously working with one access point. The same applies to throughput calculation. This complicates the use of the Bianchi model in engineering practice.

Secondly, as follows from the results shown in Table 2, with an increase in the probability of collisions beyond $p=0.5$, the convergence of the $\tau(n)$ dependence worsens and it decreases very slowly.

With such as intensive traffic, the dependence $\tau(n)$, corresponding to the original model (1)–(2), has only a qualitative character.

When studying the effect of noise, we used a channel for transmission in which the bit errors are independent and equally distributed over the bits of the frame. The probability of a successful transmission by a station depends on the BER and the number of competing stations. There is a practical interest in expressing explicitly the dependence of the network throughput on the BER for different frame lengths and different number of simultaneously operating stations. This allows the engineering staff to directly calculate the throughput based on the noise level and the quantitative characteristics of the network.

A reduction in the electromagnetic interference influence on the transmission of a frame is observed with a decrease in its size. But this increases the relative weight of overhead, that is, the service information required to ensure a successful transfer [16, 17]. All this affects the value of throughput and its dependence on the number of competing stations. The study of these processes will be carried out in the next work.

CONCLUSIONS

The scientific novelty. For the first time in an explicit analytical form, the influence of interference intensity

(BER) on the probability of frame successful transmission and the network throughput is determined in case of variations in the frame length and the traffic intensity. The resulting expression for the throughput makes it possible to evaluate the combine effect of the BER and the intensity of collisions, which depends on the number of stations operating in the network.

The practical significance. The practical significance of this work consists in the possibility of carrying out the engineering calculations in an explicit analytical form of the wireless network throughput at different layers of BER, different frame lengths and minimum contention window sizes for a given number of stations operating in the network.

One of the priorities of IEEE 802.11 technologies is their use for the automation of production processes in mechanical engineering, metallurgy and a number of other industries. A common factor that reduces the efficiency of wireless networks is the increased interference level in the shops of industrial enterprises, due to the operation of technological equipment. Therefore, the study of such networks operation at increased interference intensity (BER = 10^{-5}–10^{-4}) carried out in this paper is of significant practical importance.

Prospects for further research. Increasing the data transfer rate in the IEEE 802.11ac and IEEE 802.11ax networks to several Gbps necessitates the use of extended channels with a width of 160 MHz, which leads to an increase in the noise power in the channel. Improving the coding, that is, moving from 256 QAM to 1024 QAM increases the data rate too. However, being denser, subcarriers are more susceptible to mutual interference. Therefore, 1024 QAM technology provides speed improvements at a shorter distance from the access point and under normal conditions the signal to noise ratio decreases sufficiently fast as the coverage area is expanded. Thus, the use of modern high-speed technologies for wireless data transmission in industrial conditions requires the development of methods and means to increase the interference immunity of computer networks.

Improving the interference immunity in wireless networks can be achieved by reducing the size of transmitted frames. However, this increases the relative weight of service information, which reduces the throughput. The study of these processes on the basis of the mathematical model developed in this paper is promising.

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МОДЕЛЮВАННЯ РОБОТИ КОМП'ЮТЕРНИХ МЕРЕЖ IEEE 802.11 В УМОВАХ ВИСОКОЇ ІНТЕНСИВНОСТІ ЗАВАД

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АНОТАЦІЯ

Актуальність. Високий рівень промислового шуму збільшує втрати інформаційних фреймів в процесі передачі, що, у свою чергу, зменшує пропускну здатність мережі. Ми пропонуємо математичну модель роботи мереж IEEE 802.11 в умовах підвищеної інтенсивності завад.

Мета цієї статті полягає в тому, щоб в явній аналітичній формі відобразити вплив інтенсивності бітових помилок (BER) на імовірність передачі фрейму і пропускну здатність мережі.

Метод. Запропоновано метод побудови моделі, яка дозволяє безпосередньо обчислити залежність імовірності передачі фрейму від кількості станцій, працюючих в режимі насичення, що є зручним для інженерних розрахунків. Значення коефіцієнтів моделі були обрані шляхом порівняння результатів обчислень з результатами, одержаними при використанні відомої моделі Біанкі, яка описує функціонування мережі у вигляді Марковського процесу. В діапазоні до 23 станцій, які працюють з однією точкою доступу, що відповідає імовірності колізії до 0,5, означені залежності для обох моделей відповідають одне одному з точністю, що відповідає практичним вимогам. Одержано вираз для пропускної здатності мережі.

Результати. Результати розробки моделі були використані для урахування впливу інтенсивності завад на процес передачі інформації. Це дозволило в явному вигляді виразити вплив інтенсивності бітових помилок на імовірність передачі фрейму і пропускну здатність мережі у випадку варіацій довжини фрейму і кількості конкуруючих станцій. Ступінь зменшення пропускної здатності була визначена для BER = 10^{-5}, $5 \cdot 10^{-5}$, 10^{-4} і збільшення величини мінімального конкурентного вікна.

Висновки. У даній роботі була розроблена математична модель для безпосереднього обчислення імовірності передачі фрейму та пропускної здатності мережі при різних рівнях інтенсивності завад.

КЛЮЧОВІ СЛОВА: IEEE 802.11 мережі, математична модель, фрейм, імовірність передачі, колізія, пропускна здатність, інтенсивність завад.

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АННОТАЦИЯ

Актуальность. Высокий уровень промышленного шума увеличивает потери информационных фреймов, что, в свою очередь, уменьшает пропускную способность сети. Мы предлагаем математическую модель работы сетей IEEE 802.11 в условиях повышенной интенсивности помех.

Цель данной статьи состоит в том, чтобы в явной аналитической форме отобразить влияние интенсивности битовых ошибок (BER) на вероятность передачи фрейма и пропускную способность сети.

Метод. Предложен метод построения модели, которая позволяет непосредственно вычислить зависимость вероятности передачи фрейма от количества станций, работающих в режиме насыщения, что удобно для инженерных расчетов. Значения коэффициентов модели были выбраны путем сравнения результатов вычислений с результатами, полученными при использовании известной модели Бианки, которая описывает функционирование сети в виде Марковского процесса. В диапазоне до 23 станций, которые работают с одной точкой доступа, что соответствует вероятности коллизии до 0,5, указанные зависимости для обеих моделей соответствуют друг другу, с точностью, соответствующей практическим требованиям. Получено выражение для пропускной способности сети.

Результаты. Результаты разработки модели были использованы для учета влияния интенсивности помех на процесс передачи информации. Это позволило в явном виде выразить влияние интенсивности битовых ошибок на вероятность передачи фрейма и пропускную способность сети в случае вариаций длины фрейма и количества конкурирующих станций. Сте-

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пень уменьшения пропускной способности была определена для BER = 10^{-5}, $5\cdot10^{-5}$, 10^{-4} и повышения величины минимального конкурентного окна.

Выводы. В данной работе была разработана математическая модель для непосредственного вычисления вероятности передачи фрейма и пропускной способности сети при различных уровнях интенсивности помех.

КЛЮЧЕВЫЕ СЛОВА: IEEE 802.11 сети, математическая модель, фрейм, вероятность передачи, коллизия, пропускная способность, интенсивность помех.

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