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# PERFORMANCE ANALYSIS OF WIRELESS COMPUTER NETWORKS IN CONDITIONS OF HIGH INTERFERENCE INTENSITY

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## ABSTRACT

**Context.** The decrease in the probability of successful frame transmission in the infrastructure domain of IEEE 802.11 DCF wireless network is caused both by the influence of the collision intensity and by the impact of external interference in the radio path. Using the Markov chain approach as a baseline, we explicitly expressed the dependence of the network throughput on the number of operating stations, bit error rate (BER), and the frame fragmentation factor.

**Objective.** The purpose of this article is to study the influence of interference intensity on the throughput of a wireless network domain in a wide range of the number of operating stations when transmitting frames of various lengths in the absence and with the use of the fragmentation mechanism.

**Method.** The performed mathematical modelling showed, that in the range of increased and high noise intensity (BER = $10^{-5}$ – $10^{-4}$), a decrease in the length of the frame data field from the standard length of 12000 bits to 3000 bits is accompanied by a decrease in the throughput for all values of the number of competing stations. At the same time, it must be noted that as the amount of the frame data decreases, the throughput becomes less susceptible to an increase in the noise intensity. Qualitatively different results are obtained in the region of very high interference intensity (BER = $2\cdot10^{-4}$). A significant increase in the probability of frame transmission in this region observed with a decrease in the standard length of the frame data field by 2–3 times, made it possible to increase the throughput compared to the original one. This effect is especially pronounced when the length is halved.

**Results.** The study of the standard frame transmitting process, but with a fragmented data field, showed that if for BER = $5\cdot10^{-5}$ and less with an increase in fragmentation factor, the throughput values decrease, in the entire range of the number of stations due to the predominant increase in overhead costs, then in the region of high (BER = $10^{-4}$) and very high noise intensity (BER = $2\cdot10^{-4}$) we have the opposite effect. To the greatest extent, the throughput increases when the frame data is transmitted in two equal fragments. We have made a comparison of the network throughput determined by simply reducing the length of the frame data field and using fragmentation of a standard frame. The comparison showed that the use of the fragmentation mechanism is more beneficial both when throughput is stabilized under conditions of increased noise intensity and when the throughput is increased under conditions of high and very high noise intensity.

**Conclusions.** In this article, a mathematical model has been modified for direct calculation of the wireless network throughput. Using this model, we studied the changes in throughput over a wide range of BER and a number of operation stations for various values of the transmitted frame fragmentation factor. The conditions for increasing the throughput are determined.

**KEYWORDS:** IEEE 802.11 wireless networks, DCF, throughput, infrastructure domain, BER, frame, fragmentation factor, collision.

## ABBREVIATIONS

AP is an access point;

BER is a bit error rate;

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

DCF is a Distributed Coordination Function;

FCC is a Federal Communication Commission;

MAC is a Medium Access Protocol;

MIMO is a Multiple Input Multiple Output;

STA is a station;

Wi-Fi is a Wireless Fidelity;

WLAN is a Wireless Local Area Network.

## NOMENCLATURE

*ACK* is a frame acknowledgment;

*DIFS* is an interframe space;

*SIFS* is a short interframe space;

*bE* is a number of erroneous bits;

$H$ is a frame header transmission time;

$E_b$ is an amount of energy per bit;

*FER* is a frame error rate i.e. probability of frame distortion;

$k$ is a fragmentation factor;

$L$ is length of the frame data field in bits;

$L_0$ is an initial length of the frame data field in bits;

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

$m$ is a number of window doubling allowed;

$N_0$ is a noise power spectral density;

$n$ is a number of competing stations;

$P_b$ is a bit error probability;

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

$P_S$ is a probability of successful frame transmission;

$p$ is the collision probability;

$R$ is a data transfer rate;

$S$ is a network throughput;

$T_c$ 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;

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$t$ is a transmission time;
$W_0$ is a minimum value of contention window;
$\alpha$ is a multiplicative constant coefficient;
$\beta$ is a power constant coefficient;
$\delta$ is a propagation delay;
$\eta$ is a number of empty slots;
$\sigma$ is a duration of one slot;
T is a probability of successful frame transmission over the channel without errors.

## INTRODUCTION

In the last few decades, we have witnessed an exponential growth of the demand for wireless networks that provide reliable communications and ensure ubiquitous coverage, high spectral efficiency, and low latency [1, 2]. From 2012 to 2017, mobile networks have been a seventeen-fold cumulative growth, registering an increment in 71% in data traffic from 2016 to 2017 alone. Recent studies also show, that 54% of the traffic, generated by devices that support cellular and Wi-Fi connectivity was offloaded via Wi-Fi in 2017 and is expected that this number increases up to 59% by 2022 [3, 4].

The 802.11 DCF WLANs (Wi-Fi networks) work on the basic of the well-known carrier-sense multiple access with collision avoidance (CSMA/CA) protocol. In distributed WLAN's environment a common wireless medium is shared by a number of associated stations without any centralized coordination. Whenever a given station has a frame to transmit, it waits until the channel becomes idle for a given amount of time (DIFS interval), and then accesses the channel following exponential backoff rules. If a successful reception occurs the access point responds after a SIFS – interval with an ACKnowledgment frame. The management of the common medium is specified by two aspects: (1) multiple access resolution, i.e. the rules that govern how a given station acquires the right to use the channel; and (2) channel transmission operations, i.e. the rules that govern how a station that wins a contention performs transmissions without losing control over the channel.

Despite significant progress in solving these and other WLANs problems, achieved in the development of next-generation networks such as 802.11ac and 802.11ax, the effective throughput increases quite slowly, especially in dense networks operating under conditions of high interference intensity. A high noise level is usually caused by the presence of both external interference and interference specific to a given data transmission technology, usually caused the need to increase the transmission rate [5].

As noted by US Federal Communications Commission (FCC), an urgent problem for technologies using channels with a width $\Delta f$ = 160 MHz, operating in the range with a central frequency $f$ = 5 GHz, is "clearing the frequency range". The effect of noise increases as the channel bandwidth expands. A similar effect is also observed with a decrease in the inter-symbol interval of transmitted data and with an increase in the number of subcarrier frequencies used in modern wireless technologies. Being closer to each other adjacent subcarriers are more sensitive to noise and mutual interference [6].

In the presence of a significant number of obstacles in the signal propagation area, multiple reflected signals lose their initial energy and arrive to wireless router with a certain delay. To struggle the negative influence of multipath propagation, several antennas are used on the sender side and on the receiver side of the channel (MIMO scheme). This also allowed the formation of several parallel spatial data streams. In 802.11ac technology, which uses 8 antennas in the router, a directional signal formation mode (Beamforming) has been created. This mode is used, for example, between two routers in the backbone of the wireless network. At the same time, the concentration of several spatial streams in one region of the channel, even despite, for example, different polarization of signals transmitted in each stream, leads to an increase in the mutual influence of signals. This effect is further enhanced with an increase in the intensity of external noise, blurring the distinctive features of signals of different streams.

**The object of study is** the process of data transmission in wireless networks with heavy traffic at high intensity of external interference.

**The subject of study** is the mathematical models of IEEE.802.11 DCF networks operation under conditions of collisions and external interference combine influence.

**The purpose of the paper** is to study the possibility of increasing the throughput of a dense wireless network at high noise intensity due to the fragmentation of transmitted frames.

## 1 PROBLEM STATEMENT

In conditions of increased interference intensity, the probability of successful frame transmission from the station to the access point can be defined as [7, 8]

$$P_S = T \cdot (1 - FER)\,. \tag{1}$$

The probability T is traditionally determined using Markov-chain models in the form of the function $F(p, W_0, m)$, where $p$ is the collision probability, which in turn depends on T; $W_0 = CW_{\min}$ is the minimum contention window; $m$ is the number of window doublings after every next collision [9–11].

Collisions coming from WLAN's nodes using the same MAC protocol, and interference coming from devices outside the network, waste valuable transmission time and radiated power, having a negative impact on the energy efficiency, throughput, and delay of the system [12]. Network nodes cannot distinguish one type of loss from another because the symptoms are the same – not receiving the acknowledgment from the access point. The increase in the level of interference leads to the increase in the loss of information frames during transmission, which in turn decreases the network throughput.

Rational for improving the reliability of WLANs is to avoid losing frames due to occurrence of channel induced errors, collisions etc. The STA needs to retransmit the

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whole frame even if it contains only one bit error. When the channel error rate is significantly high to get the frame through would require a large number of retransmissions. To mitigate this, fragmentation was proposed whereby big frames are sent in small fragments which are individually acknowledged or retransmitted. Doing this in case the error the STA needs to retransmit only the error fragment which takes short time compared to retransmitting the whole initial frame. If the medium is significantly noisy, a fragment has a higher probability to get through without errors because it can be fitted between error bursts [13, 14]. By operating this way, the STA increases its chances of successful frame transmission in bad channel conditions.

At the same time, it should be considered that fragmentation increases the amount of service information needed to transfer a given amount of data, which leads to a decrease in network throughput.

The purpose of this work is to expand the mathematical model proposed by us in article [15], which in an explicit analytical form describes the impact of collisions and external noise on the operation of IEEE 802.11 networks, for the case of frames fragmentation, and to study the possibility of increasing network's throughput due to fragmentation under conditions of high intensity of external interference.

## 2 REVIEW OF THE LITERATURE

The basic for the theoretical analysis of the frame transmission probability in IEEE 802.11 DCF wireless networks for more than the last two decades are Markov chain models [9–11, 16–20]. In the widely known work published by Bianchi [9] which was further developed by Tinnirello, Bianchi, and Xiao [10] the authors use the chain model for ideal channel conditions. The probability that a station accessed a channel depends on when the channel was idle or busy in a previous time slot. These aspects were studied in [16]. In article [17] a Markovian agent model is used to represent the behavior of wireless nodes based on CSMA/CA access method.

In articles using the Markov model, it is often assumed that traffic is saturated [18–21]. In these conditions nodes can be modeled as being equally likely to send in any slot, and this assumption also holds in the first approximation for unsaturated traffic which nearly Poisson [22].

Work [23] is devoted to study of the optimization problem of retransmission number on transmission performance. The number of stations in the network is 20, 40, and 80. The author provides an analytical model on the performance of real-time applications transmission over WLAN. The analytical model evaluates the random-access performance of real-time services based on two-dimensional Markov-chain model by taking into account the impact of the maximum optimal retransmission number on the service time of the packet transmissions. Modelling and performance evaluation of the IEEE 802.11 DCF for real-time control is also carried out in article [24].

Electromagnetic interference that reduces the efficiency of wireless networks occurs both due to external sources and depends on the architecture and operating conditions of the network itself. Sources such as automobiles, aircrafts, ignition electric motors and switching gear, high voltage wires and fluorescent lamps cause industrial noise. Electromagnetic interference is a disturbance generated by these external sources that affects an electrical circuit of electromagnetic induction, electrostatic coupling, discharging process or conduction disorder.

The problem of interference arises when more APs of wireless network are placed near each other and the coverage area of these APs starts to overlap, which causes degradation of the bandwidth and the service received by the recipients. Another challenge in wireless networks is the handover, which is process of switching users from one AP to other [25].

Significant interference in the process of information transmission in some cases introduced the effect of multipath signal propagation. This effect is also known as multipath interference or multipath distortion. Notable consequences of this are envelope fading and inter-symbol interference [26]. If the propagation delay of the rays is small compared to the channel symbol duration, then only wave interference occurs, leading to the fading. Due to the time difference between the base signal and the multiple reflected copies, the access point may have problems demodulating the received signal. In this case, the serious problem is the overlapping of information bits on each other, as a result of which the data is damaged. This effect is called inter-symbol interference.

Interferences that have a various physical nature differ in their spectral composition. At the same time, it is important to study the general patterns of the interference influence on data transmitted in wireless networks over a radio channel. For this purpose, it is advisable to use Gaussian noise as the most general noise model that describes a wide range of noise sources and their superposition quite well [27].

An example of a simple channel model that is widely used in information theory is additive white Gaussian noise channel without fading [27, 28]. In [29], Tianji et al analyze the throughput performance of the Block ACK scheme over a noisy channel. In [30] authors present a new discrete time Markov chain model to estimate the packet transmission probability. They propose an enhancement of the IEEE 802.11 RTS/CTS scheme to recognize the reason of transmission failure (collision or noise errors).

One of the changes that modern digital communication systems have brought to radio engineering is the need to end-to-end performance evaluations. The measure of that performance is usually bit error rate (BER), which quantified the reliability of the radio system from “bits in” to “bits out” [31],

$$\text{BER} = \text{number of corrupted bits} / \text{total number of bits} = bE / (R \cdot t). \tag{2}$$

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In a noisy channel, the BER is often expressed as a function of the normalized carrier-to-noise ratio denoted $E_b / N_0$ (energy per bit to noise power spectral density) [28]. The Gaussian approximation of the noise in determining the BER is used to estimate the number of iterations needed to the convergence the parity code decoder in function of the level of noise power [32]. Bit-error rate analysis of low-density parity-check codes using Gaussian approximation of a channel is considered in [33].

In general, errors at different locations of an information sequence of length $L$ can occur with different probabilities. In this article, we use for transmission a time-discrete channel without memory with white Gaussian noise. A channel of this type is characterized by the fact that the bit errors in it are independent and equally distributed over the bits of the frame data [27].

## 3 MATERIALS AND METHODS

Improving the transmission reliability of a frame can be achieved by reducing the size of its data field [28, 30, 34]. At the same time, this leads to an increase in the relative contribution of the time spent on the transmission of the MAC protocol information of the 802.11 standard, which is necessary to ensure a successful transmission process. Let us study this process under conditions of high noise intensity.

In work [15], we have expressed in an explicit analytical form the dependence of the throughput of the IEEE 802.11 DCF wireless computer network on the number of stations operation in saturation mode and the value of BER, which is determined by the intensity of interference in the radio path. This dependence can be represented in the following form:

$$S = \frac{2nqL}{2nq(T_{SC} - T_C) + (Q+1-2q)[T_C(\frac{Q+1}{Q+1-2q})^n + \eta\sigma]}. \quad (3)$$

In expression (3)

$$T_{SC} - T_C = SIFS + ACK + \delta, \quad (4)$$

$$T_C = PHY_{hdr} + MAC_{hdr} + \frac{L}{R} + DIFS + \delta, \quad (5)$$

$$Q = \frac{W_0 \cdot 2^{\beta(n-1)}}{1+\alpha(n-1)}. \quad (6)$$

In accordance with the justification given in the previous section, bit errors occurring in the noisy channel are independent and equally distributed over the bits of the frame data field. Then the probability that a frame with a data field of length $L$ will be transmitted undistorted is equal to

$$q = (1-P_{b1})(1-P_{b2})(1-P_{b3})...(1-P_{bL}).$$

And since the probabilities of distortion of individuals bits are the same, then

$$q = (1-P_b)^L. \quad (7)$$

Using expressions (3)–(7), we calculated the dependences $S(n, P_b)$ for different values of $L$. The probability of an error of one bit in a frame was taken equal to $P_b = 10^{-5}$, $5 \cdot 10^{-5}$, $10^{-4}$ which corresponds to increased and high interference intensity. We took the initial length of the frame data field equal to $L_0 = 12000$ bits.

To calculate the dependences $S(n, L)$ for different values of $P_b$, we used the following data [15, 35, 36]:

$SIFS = 16$ µs, $DIFS = 34$ µs, $\delta = 0{,}33$ µs (the distance between the station and AP was taken equal 100 m), $\sigma = 9$ µs, $ACK = 38{,}66$ µs, $H = PHY_{hdr} + MAC_{hdr} = 68$ µs, $R = 54$ Mbps, $\alpha = 0{,}05$, $\beta = 0{,}2$, $W_0 = 16$.

## 4 EXPERIMENTS

Tables 1, 2 and 3 for $P_b = 10^{-5}$, $5 \cdot 10^{-5}$ and $10^{-4}$ respectively show the values of the throughput $S$ depending on the number of simultaneously operating stations $n$ and the length of the frame data field $L$.

In [36] the authors carried out the numerical study of the well-known bi-dimensional Markovian mathematical model [9, 10] under ideal channel conditions using the ns-3 discrete-event network simulator. Comparison of the throughput values $S$ obtained by them with our data determined during the transmission in a noisy channel with a relatively low noise level $P_b = 10^{-5}$ (Table 1) showed acceptable results. For example, for $n = 10$, the decrease in the value of $S$ in our case is 27%, for $n = 10$ – 26%.

Analyzing the numerical dependences presented in Table 1, the following can be noted. With an increase in the number $n$ of stations competing for access to the communication channel, the value of the throughput $S$ monotonically decreases. This is due to the growth of the collision intensity of simultaneously operating stations. Reducing the length of the transmitted frames data field from 12000 bits to 6000 bits and further to 3000 bits allows you to increase the probability of the frame successful transmission $q$ in expression (3). So, at $L = L_0$ $q = 0{,}887$, at $L = L_0/2$ $q = 0{,}942$, at $L = L_0/4$ $q = 0{,}97$. However, despite this, in Table 1 we observe a decrease in the value of $S$ with a decrease in the length of transmitted frames. This is due to the fact that with a decrease in amount of transmitted data $L$, the relative part of the overhead costs, i.e., service information that ensures the process of the frames transmitting increases.

The probabilities of successful frame transmission for Table 2 are: at $L = L_0$ $q = 0{,}549$, at $L = L_0/2$ $q = 0{,}741$, at $L = L_0/4$ $q = 0{,}86$.

The probabilities of successful frame transmission for Table 3 are: at $L = L_0$ $q = 0{,}30$, at $L = L_0/2$ $q = 0{,}549$, at $L = L_0/4$ $q = 0{,}74$.

Using Tables 1, 2 and 3 we determined the relative decrease in the throughput value with a growth of interference intensity for various lengths of the frame data field.

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Table 1 – Results of throughput $S$ calculations for $P_b = 10^{-5}$

| $n$ | | 5 | 7 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 80 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S. Mbps | $L = L_0$ | 19.440 | 19.300 | 19.220 | 18.690 | 18.100 | 16.130 | 13.410 | 7.430 | 3.210 | 1.180 | 0.130 |
| | $L = L_0 / 2$ | 12.550 | 12.470 | 12.430 | 11.980 | 11.480 | 9.960 | 8.020 | 4.200 | 1.400 | 0.630 | 0.068 |
| | $L = L_0 / 4$ | 7.350 | 7.310 | 7.290 | 6.980 | 6.640 | 5.640 | 4.450 | 2.240 | 0.910 | 0.330 | 0.035 |

Table 2 – Results of throughput $S$ calculations for $P_b = 5 \cdot 10^{-5}$

| $n$ | | 5 | 7 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 80 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S. Mbps | $L = L_0$ | 16.80 | 16.79 | 16.76 | 16.11 | 15.27 | 12.86 | 10.08 | 5.07 | 2.07 | 0.74 | 0.08 |
| | $L = L_0 / 2$ | 11.57 | 11.55 | 11.53 | 11.05 | 10.47 | 8.81 | 6.90 | 3.45 | 1.40 | 0.50 | 0.05 |
| | $L = L_0 / 4$ | 7.03 | 7.01 | 6.98 | 6.67 | 6.31 | 5.28 | 4.10 | 2.02 | 0.82 | 0.29 | 0.03 |

Table 3 – Results of throughput $S$ calculations for $P_b = 10^{-4}$

| $n$ | | 5 | 7 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 60 | 80 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S. Mbps | $L = L_0$ | 12.61 | 12.59 | 12.55 | 11.96 | 11.07 | 8.79 | 6.51 | 2.99 | 1.16 | 0.41 | 0.04 |
| | $L = L_0 / 2$ | 10.16 | 10.15 | 10.12 | 9.66 | 9.04 | 7.37 | 5.59 | 2.66 | 1.05 | 0.37 | 0.04 |
| | $L = L_0 / 4$ | 6.59 | 6.58 | 6.56 | 6.25 | 5.87 | 4.83 | 3.70 | 1.78 | 0.71 | 0.25 | 0.03 |

Let the number of simultaneously operating stations $n = 20$. Then for $L = L_0$ an increase in $P_b$ from $10^{-5}$ to $5 \cdot 10^{-5}$ leads to a decrease in the value of $S$ by 15,6%, and a further increase in $P_b$ from $5 \cdot 10^{-5}$ to $10^{-4}$ by another 27,5% relative to the level at $P_b = 5 \cdot 10^{-5}$. Similar calculations for $n = 30$ give $\Delta S_{12} / S_1 = 24{,}8\%$ and $\Delta S_{23} / S_2 = 35{,}4\%$, where 1, 2 and 3 are the Tables numbers. For $n = 40$ $\Delta S_{12} / S_1 = 31{,}8\%$ and $\Delta S_{23} / S_2 = 41\%$.

When the length $L_0$ of the frame data field is halved, we get the following data: for $n = 20$ $\Delta S_{12} / S_1 = 8{,}8\%$ and $\Delta S_{23} / S_2 = 13\%$; for $n = 30$ $\Delta S_{12} / S_1 = 14\%$ and $\Delta S_{23} / S_2 = 19\%$; for $n = 40$ $\Delta S_{12} / S_1 = 17{,}9\%$ and $\Delta S_{23} / S_2 = 22{,}9\%$. By reducing the length $L_0$ of the frame data field by four times, we get the following data: for $n = 20$ $\Delta S_{12} / S_1 = 5\%$ and $\Delta S_{23} / S_2 = 7\%$; for $n = 30$ $\Delta S_{12} / S_1 = 7{,}9\%$ and $\Delta S_{23} / S_2 = 9{,}8\%$; for $n = 40$ $\Delta S_{12} / S_1 = 9{,}9\%$ and $\Delta S_{23} / S_2 = 11{,}9\%$.

The performed calculation shows that with a decrease in the length $L$ of the transmitted frame data field from 12000 bits to 6000 bits and further to 3000 bits, the throughput $S$ becomes less susceptible to an increase in the noise intensity. So, for example, for $n = 20$, an increase in the error probability $P_b$ from $10^{-5}$ to $5 \cdot 10^{-5}$ leads for $L = 12000$ bits to a decrease in the value of $S$ by 15,6%, for $L = 6000$ bits – by 8,8%, for $L = 3000$ bits – by 5%. In the zone of more intensive noise increase in $P_b$ from $5 \cdot 10^{-5}$ to $10^{-4}$ leads for $L = 12000$ bits to a decrease in $S$ by 27,5%, for $L = 6000$ bits – by 13%, for $L = 3000$ bits – by 7%. Similar results are observed for other values of $n$.

Qualitatively different results are obtained in the region of very high interference intensity, at $P_b = 2 \cdot 10^{-4}$. Corresponding dependences $S(n)$ at $L = L_0$, $L = L_0 / 2$ and $L = L_0 / 4$ are shown in Fig. 1.

As can be seen from the graphs, the dependence $S(n)$ at $L = L_0 / 2$ is located significantly higher than the similar dependence at $L = L_0$. Thus, in the region of high-intensity noise, a two-fold decrease in the length of the frame data field made it possible to significantly increase the throughput $S$ compared to the original one. Reducing $L$ to 3000 bits also allows, although to a lesser extent, to increase the throughput compared to the original.

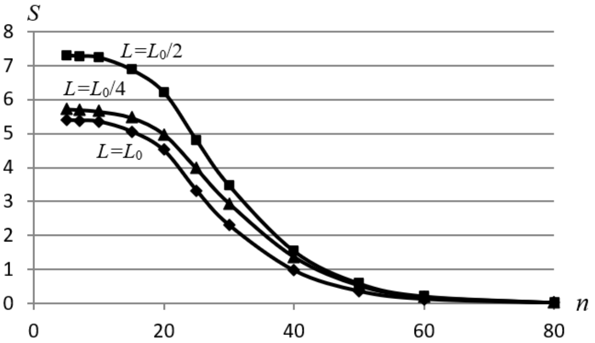

Figure 1 – Throughput $S$ versus the number of competing stations $n$ at different length of the frame data field $L$ for BER = $2 \cdot 10^{-4}$, $L_0 = 12000$ bits

## 5 RESULTS

The increase in throughput within the framework of the fragmentation mechanism can be achieved by reducing the overhead that is spent on a frame transmission. In the overhead, we also include the time spent on the retransmissions of frames distorted by interferences.

Reducing the length of the data field $L$ of the transmitted frames decreases the probability of its distortion by external interference and can, at the same time, increase throughput by reducing the number of retransmissions. It follows from the results of the previous section that this effect is more pronounced in the range of very high noise intensity. Let us study this process under the condition of a constant total length of the data field of the frame transmitted using the fragmentation mechanism.

We will divide the standard original frame with data field of length $L_0 = 12000$ bits into fragments so that the sum of the data fragments is $L_0$. In the basic DCF scheme, only first fragment in a transmitted frame contends for a channel access, the other fragments are transmitted after differing a SIFS interval and after each fragment an ACK is sent back by access point [14, 19, 34]. When creating a model for studying the throughput, we assumed that channel errors don't corrupt ACK frames. Since the ACK frames are usually transmitted at lower transmission rate than the data frames, this should be a reasonable assumption in many practical environments [37]. For all these conditions, and taking into account the fragmentation factor $k$, expression (3) is transformed to the following form:

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$$S=\frac{2nL_0(1-P_b)^{\frac{L_0}{k}}}{2n(1-P_b)^{\frac{L_0}{k}}(T_{SC}-T_C)_k+[Q+1-2(1-P_b)^{\frac{L_0}{k}}]\{T_{Ck}[\frac{Q+1}{Q+1-2(1-P_b)^{\frac{L_0}{k}}}]^n+\eta\sigma\}}, \qquad (8)$$

where

$$T_{Ck}=PHY_{hdr}+k\cdot MAC_{hdr}+\frac{L_0}{R}+DIFS+k\delta, \qquad (9)$$

$$(T_{SC}-T_C)_k=k\cdot(SIFS+ACK+\delta). \qquad (10)$$

Dependences $S(n)$ calculated in accordance with expressions (8)–(10) at different values of $k$ for conditions of increased noise intensity (BER = $5\cdot10^{-5}$), high intensity (BER = $10^{-4}$) and very high intensity (BER = $2\cdot10^{-4}$) are shown in Fig. 2, 3 and 4, respectively.

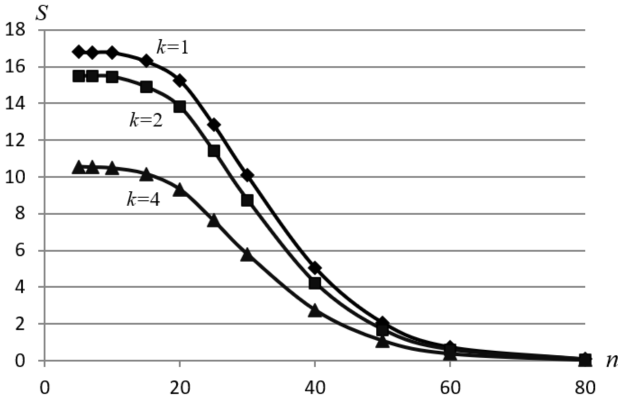

Figure 2 – Throughput $S$ versus the number of competing stations $n$ at different value of fragmentation factor $k$ for BER = $5\cdot10^{-5}$

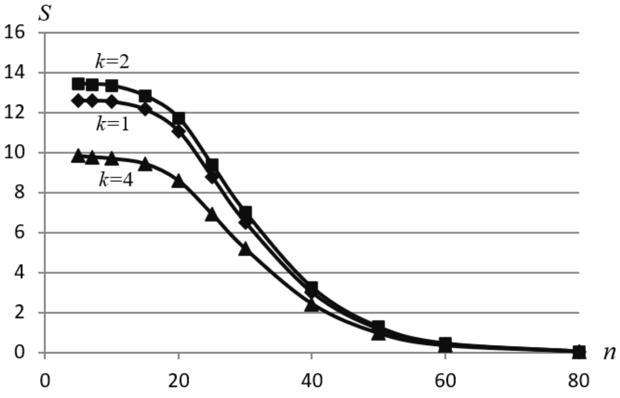

Figure 3 – Throughput $S$ versus the number of competing stations $n$ at different value of fragmentation factor $k$ for BER = $10^{-4}$

As follows from the graphs shown in Fig. 2–4, if for BER = $5\cdot10^{-5}$ with an increase in the fragmentation factor $k$, the values of $S$ decrease for all values of $n$ due to the predominant influence of an increase in overhead costs, then for BER = $10^{-4}$ and especially for BER = $2\cdot10^{-4}$ we observe the opposite effect. This is most characteristically for fragmentation with $k = 2$, in which the throughput values in relation to the initial frame increase most significantly for all values of $n$.

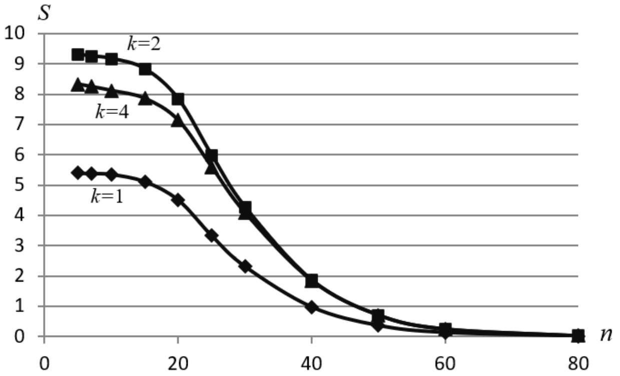

Figure 4 – Throughput $S$ versus the number of competing stations $n$ at different value of fragmentation factor $k$ for BER = $2\cdot10^{-4}$

## 6 DISCUSSION

Based on the Markov chain model, which is used by many researchers as the basic for studying the behavior of wireless networks of IEEE 802.11 DCF standard, we expressed in an explicit analytical form the dependence of the throughput of the network infrastructure domain on the number of operating stations, the value of BER, which is determined by the interference intensity in radio path, and the size of the transmitted frames. This allowed us to investigate these dependencies for different lengths of the frame data field.

The initial length of the data field is taken equal to the standard – 12000 bits. The calculations were carried out with the error probabilities in one bit of data $10^{-5}$, $5\cdot10^{-5}$, $10^{-4}$, $2\cdot10^{-4}$. The first two values correspond to the probabilities 0.887 and 0.549 of standard-length frame successful transmission and correspond to increased noise intensity. The third and fourth values correspond to the probabilities 0.3 and 0.09 of successful transmission. We can assume that they correspond to high and very high noise levels, respectively. Reducing the length of the frame data field to 3000 bits made it possible to increase the probability of successful transmission to 0.97; 0.86; 0.74 and 0.55, respectively.

Analyzing the obtained dependencies, it should be noted that in the range of increased and high noise intensity, a decrease in the length of the frame data field from the standard length of 12000 bits to 3000 bits is accompanied by a decrease in the throughput for all values of the number of competing stations. This is because as the

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amount of the transmitted data decreases, and the relative overhead increases. At the same time, it can be seen from the above tables that as the amount of the frame data decreases from 12000 bits to 6000 bits and further to 3000 bits, the throughput becomes less susceptible to an increase in the noise intensity. So, for example, for 20 stations, an increase in the error probability in one bit from $5\cdot10^{-5}$ to $10^{-4}$ leads to a decrease in the throughput by 27,5 % for 12000 bits, by 13% for 6000 bits, and by 7% for 3000 bits. Similar results are also observed for a different number of operating stations.

Qualitatively different results are obtained in the region of very high interference intensity. A significant increase in the probability of frame transmission in this region observed with a decrease in the standard length of the frame data field by 2 and 3 times, made it possible to increase the throughput compared to the original one. This effect is especially pronounced when the length is halved.

Consider the process of sending a frame with data of standard length but divided into a several fragments. In the basic DCF scheme, only the first fragment of the transmitted frame contends for access to the communication channel with the access point, each subsequent fragment is transmitted after the separating SIFS interval and is acknowledged by the ACK frame.

For these conditions, previously obtained by us expression for the throughput is transformed taking into account the number of transmitted fragments. As follows from the calculations, if for $\text{BER} = 5\cdot10^{-5}$ with an increase in the fragmentation factor, the throughput values decrease over the entire range of the number of simultaneously operating stations, due to the predominant influence of the increase in the overhead costs, then already in the region of high ($\text{BER} = 10^{-4}$) and, accordingly, very high ($\text{BER} = 2\cdot10^{-4}$) noise intensity we have the opposite effect. The throughput increases the most at a fragmentation factor of two.

It is of interest to compare the results obtained in sections 3 and 4 of this article at different noise levels.

For $\text{BER} = 5\cdot10^{-5}$, a simple decrease in the frame data field from 12000 bits to 6000 bits and further to 3000 bits, for example, for 25 stations, leads to a decrease in the throughput by 1.46 and 2.44 times, respectively. In the case of using fragmentation, an increase in the fragmentation factor from $k = 1$ to $k = 2$ and further to $k = 4$ with the same number of the operating stations leads to a decrease in the throughput by 1.13 and 1.69 times, respectively, i.e., significantly less than in the previous case.

At $\text{BER} = 10^{-4}$ for the same conditions, in the first case, a decrease in the throughput by 1,19 and 1,82 times is observed, and in the second case, for fragmentation, with an increase in $k$ from 1 to 2, an increase in the throughput by 1,07 times is observed, and with an increase in $k$ from 1 to 4 – a decrease in the throughput, but only by 1,27 times.

For $\text{BER} = 2\cdot10^{-4}$ at 25 stations, reducing the frame data field from 12000 to 6000 bits leads to an increase in the throughput by 1,44 times, and when reducing from 12000 to 3000 bits to an increase in the throughput by 1.19 times. When fragmenting the data field of a standard length of 12000 bits, the transition from $k = 1$ to $k = 2$ gives an increase in the throughput by 1,8 times, and from $k = 1$ to $k = 4$ – by 1,68 times.

Thus, it can be stated that the fragmentation mechanism under conditions of increased and high noise intensity is more beneficial in terms of stabilization or increase in throughput than simply reducing the length of the frame data field.

## CONCLUSIONS

**The scientific novelty.** Using an approach based on the Markov chains modeling of the operation of IEEE 802.11 DCF wireless networks, we first expressed in an explicit analytical form the dependence of the infrastructure domain throughput on the number of operating stations, the value of BER, which is determined by the level of interference in the domain space, and the fragmentation factor of the transmitted frame data field.

It is shown that despite the increase the noise immunity, a decrease in the length of the transmitted frame data field is accompanied by reduce in throughput in the range $\text{BER}=10^{-5} – 10^{-4}$. And only at a very high noise intensity, corresponding to $\text{BER} = 2\cdot10^{-4}$, a decrease in the frame size leads to an increase in the throughput.

The study of the process of the standard frame transmitting, but with a fragmented data field, showed that if for $\text{BER} = 5\cdot10^{-5}$ with an increase in fragmentation factor, the throughput values decrease in the entire range of the number of stations due to the predominant increase in overhead costs, then in the region of high ($\text{BER} = 10^{-4}$) and very high noise intensity ($\text{BER} = 2\cdot10^{-4}$) we have the opposite effect. To the greatest extent, the throughput increases when the frame data is transmitted in two equal fragments.

For the first time, a comparison was made of the network throughput determined by simply reducing the length of the frame data field and using fragmentation of a standard frame. The comparison showed that the use of the fragmentation mechanism is more beneficial both when throughput is stabilized under conditions of increased noise intensity and when the throughput is increased under conditions of high and very high noise intensity.

**The practical significance** of this work lies in the fact that the results obtained in it make it possible to determine the optimal value of the fragmentation factor of the frame data field transmitted in the wireless network, depending on the number of operating in the domain stations and the intensity of electromagnetic interference.

One of the priorities of wireless networks is their use for the automation of production processes in a number of industries. A common factor that reduces their efficiency is the high electromagnetic interference level in the shops of industrial enterprises, due to the operation of technological equipment. Studying the possibilities of increasing the networks throughput in such conditions, with

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$BER = 10^{-5} – 2\cdot10^{-4}$, is of significant practical importance.

**Prospects for further research** are to study the reveal regularities of the joint influence of collisions and noise on the transmission efficiency of fragmented frames in the conditions of further development of modern wireless network technologies.

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## REFERENCES

1. Giordani M., Polese M., Mezzavilla M. et al. Toward 6G Networks: Use Cases and Technologies, *IEEE Communications Magazine*, 2022, Vol. 58, No. 3, pp. 55–61, DOI: 10.1109/MCOM.001.1900411.
2. Chien T. V., Ngo H. Q., Chatzinotas S. et al. Reconfigurable Intelligent Surface-Assisted Cell-Free Massive MIMO Systems Over Spatially-Correlated Channels, *IEEE Transactions on Wireless Communications*, 2022, Vol. 21, No. 7, pp. 5106–5128. DOI: 10.1109/TWC.2021.3136925.
3. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update : 2017–2022, 2019, pp. 1–33. Document ID 1486680503328360.
4. Dianne S. V. Medeiros, Helio N. Cunha Neto, Martin Andreoni Lopez et al.] A survey on data analysis on large scale wireless networks: online stream processing, trends and challenges, *Journal of Internet Services and Applications*, 2020, Vol. 11, No. 1. DOI: 10.1186/s13174-020-00127-2.
5. 802.11ac: The Fifth Generation of Wi-Fi. Technical White Paper [Electronic resource]. Access mode: https://www.cisco.com/c/dam/en/us/products/collateral/wireless/aironet-3600-series/white-paper-c11-713103.pdf.
6. IEEE 802.11ax: The Sixth Generation of Wi-Fi. White Paper [Electronic resource]. Access mode: https://www.cisco.com/c/en/us/products/collateral/wireless/white-paper-c11-740788.html.
7. Lee H., Tinnirello I., Yu J. et al. Throughput and Delay Analysis of IEEE 802.1le Block ACK with Channel Errors, *2nd International Conference on Communication Systems Software and Middleware, Bangalore, 7–12 January 2007 : proceeding*. IEEE, 2007, pp. 1–7. DOI: 10.1109/COMSWA.2007.382498.
8. Youngsoo K., Sunghyun Ch., Kyunghun J. et al.Throughput enhancement of IEEE 802.11 WLAN via frame aggregation, *IEEE 60th Vehicular Technology Conference : VTC2004-Fall, Los Angeles, 26–29 September 2004 : proceeding*, IEEE, 2004, Vol. 4, pp. 3030–3034. DOI: 10.1109/VETECF.2004.1400617.
9. Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function, *IEEE Journal on Selected Areas in Communications,* 2000, Vol. 18, No. 3, pp. 535–547. DOI: 10.1109/49.840210.
10. Tinnirello I., Bianchi G., Xiao Y. Refinements on IEEE 802.11 Distributed Coordination Function Modeling Approaches, *IEEE Transactions on Vehicular Technology*, 2010, Vol. 59, No. 3, pp. 1055–1067, DOI: 10.1109/TVT.2009.2029118.
11. Tay Y. C., Chua K. C. A capacity analysis for the IEEE 802.11 MAC protocol, *Wireless Networks,* 2001, Vol. 7, No. 2, pp. 159–171. DOI: 10.1023/A:1016637622896.
12. Vermeulen T., Reynders B. , Rosas F. E. et al. Performance analysis of in-band collision detection from dense wireless networks, *EURASIP Journal on Wireless Communications and Networking*, 2021. Article number: 87, DOI: 10.1186/s13638-021-01940-4.
13. Tourrilhes J. Fragment adaptive reduction: coping with various interferers in radio unlicensed bands, *IEEE international conference of communications (ICC’01).* Helsinki, 11–14 June 2001, proceeding, IEEE, 2001, pp. 239–244.
14. Mafole P., Aritsugi M. Analysis and performance assessment of a fragment retransmission scheme for energy efficient IEEE 802.11 WLANs, *Springer Plus*, 2016, Vol. 5, No. 1. DOI: 10.1186/s40064-016-3023-6.
15. Khandetsky V. S., Karpenko N. V. Modeling of IEEE 802.11 Computer Networks at Increased Interference Intensity, *Radio Electronics, Computer Science, Control,* 2022, No. 2, pp. 132–139. DOI 10.15588/1607-3274-2022-2-13.
16. Foh C. H., Tantra J. W. Comments on IEEE 802.11 saturation throughput analysis with freezing of backoff counters, *IEEE Communications Letters,* 2005, Vol. 9, No. 2, pp. 130–132. DOI: 10.1109/LCOMM.2005.02008.
17. Scarpa M., Serrano S. A New Modelling Approach to Represent the DCF Mechanism of the CSMA/CA Protocol, *24th International Conference on Analytical and Stochastic Modelling Techniques and Applications, ASMTA 2017. Lecture Notes in Computer Science, Newcastle-upon-Tyne, 10–11 July 2017, proceeding.* Springer, Cham, 2017, Vol. 10378, pp. 181–195. DOI: 10.1007/978-3-319-61428-1_13.
18. Krishman M. N., Pollin S., Zakhor A. Local Estimation of Collision Probabilities in 802.11 WLANs with Hidden Terminals : Technical Report No. UCB/EECS-2009-2, January 2009, *Electrical Engineering and Computer Sciences University of California at Berkeley*, 11 p. [Electronic resource]. – Access mode: https://www2.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-2.pdf.
19. Sweedy A. M., Semeia A. I., Sayed S. Y. et al. The effect of frame length, fragmentation and RTS/CTS mechanism on IEEE 802.11 MAC performance, *10th International Conference on Intelligent Systems Design and Applications.* Cairo, 29.11.2010-1.12.2010 : proceeding, IEEE, 2010, pp. 1338–1344, DOI: 10.1109/ISDA.2010.5687095.
20. Liao R., Bellalta, Barcelo J. et al. Performance analysis of IEEE 802.11ac B. wireless backhaul networks in saturated conditions, *EURASIP Journal of Wireless Communications and Networking*, 2013. Article number 226, pp. 1–14. DOI: 10.1186/1687-1499-2013-226.
21. Ugwu G. O., Nwawelu U. N., Ahaneku M. A. et al. Effect of service differentiation on QoS IEEE 802.11e enhanced distributed channel access: a simulation approach, *Journal of Engineering and Applied Science,* 2022, Vol. 69, No. 1, pp. 1–18. DOI: 10.1186/s44147-021-00055-3.
22. Malone D., Duffy K., Leith D. Modeling the 802.11 Distributed Coordination Function in Nonsaturated Heterogeneous Conditions, *IEEE/ACM Transactions on Networking*, 2007. Vol. 15, No. 1, pp. 159–172. DOI: 10.1109/TNET.2006.890136.
23. Bozkurt A. Optimal delay analysis for real-time traffics over IEEE 802.11 wireless LANs, *EURASIP Journal of Wireless*

DOI 10.15588/1607-3274-2023-3-15

*Communications and Networking*, 2016, Article number 52, pp. 1–13. DOI: 10.1186/s13638-016-0545-0.
24. Tian G., Tia Y.-C. Modelling and performance evaluation of the IEEE 802.11 DCF for real-time control, *Computer Networks*, 2012, Vol. 56, No. 1, pp. 434–447. DOI: 10.1016/j.comnet.2011.10.001.
25. Aldbaibani O. A., Raschella A., Mohi-Ud-Din G. et al. A User Prioritization for Horizontal Handover in Dense WLAMs, *International Journal of Wireless Information Networks*, 2022, Vol. 29, pp. 130–142. DOI: 10.1007/s10776-021-00544-5.
26. Matthew Gast. 802.11 Wireless Networks: The Definitive Guide. O’ Reilly Media, Inc, 2005, 630 p.
27. Cover T. M., Thomas J. A.. Elements of Information Theory. Second Edition. Hoboken, New Jersey, Wiley, 2006, 774 p.
28. Proakis J. G., Salehi M. Digital Communications. Fifth Edition. McGrow-Hill Education, 2007, 1150 p.
29. Li T., Ni Q., Turletti T. et al. Performance analysis of the IEEE 802.11e block ACK scheme in a noisy channel, *2nd International Conference on Broadband Networks, Boston, 7 October 2005 : proceeding, IEEE*, 2005, Vol. 1, pp. 511–517. DOI: 10.1109/ICBN.2005.1589655.
30. Yazid M., Aissani D., Bouallouche-Medijkoune L. et al. Modelling and enhancement of the IEEE 802.11 RTS/CTS scheme in an error-prone channel, *Formal Aspects of Computing,* 2015, Vol. 27, No. 1, pp. 33–52. DOI: 10.1007/s00165-014-0300-4.
31. Breed G. Bit error rate: fundamental concepts and measurement issues, *High Frequency Electronics*, 2003, Vol. 2, No. 1, pp. 46–48.
32. Ghani B., Launay F., Pousset Y. et al. Low complexity hybrid interference cancellation for sparse code multiple access, EURASIP Journal of Wireless Communications and Networking, 2022,Article number 95, pp. 1–26, DOI: 10.1186/s13638-022-02162-y.
33. Tan B. S., Li K. H., Teh K. C. Bit – error rate analysis of low-density parity-check codes with generalized selection combining over a Rayleigh-fading channel using Gaussian approximation, *IET Communication,* 2012, Vol. 6, No. 1, pp. 90–96. DOI: 10.1049/iet-com.2011.0271.
34. Yazid M., Bouallouche-Medikoune L., Aissani D. et al. Analytical analysis of applying packet fragmentation mechanism on IEEE 802.11b DCF network in non-ideal channel with infinite load conditions, Wireless Networks, 2014, Vol. 20, pp. 917–934. DOI: 10.1007/s11276-013-0653-2.
35. Chang Z., Alanen O., Huovinen T. et al. Performance Analysis of IEEE 802.11ac DCF with Hidden Nodes, *IEEE 75th Vehicular Technology Conference (VTC Spring), Yokohama, 6–9 May 2012 : proceeding*, IEEE, 2012, pp. 1–5. DOI: 10.1109/VETECS.2012.6240054.
36. Patidar R., Roy S., Henderson T. R. et al. Validation of Wi-Fi network simulation on ns-3 : Technical Report : August 7, 2017, University of Washington. Seattle, 2017, 19 p.
37. Lee H., Tinnirello I., Yu L. et al. A performance analysis of block ACK scheme for IEEE 802.11e networks, *Computer Networks,* 2010, Vol. 54, No. 14, pp. 2468–2481. DOI: 10.1016/j.comnet.2010.04.001.

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# АНАЛІЗ ФУНКЦІОНУВАННЯ БЕЗДРОТОВИХ КОМП’ЮТЕРНИХ МЕРЕЖ В УМОВАХ ВИСОКОЇ ІНТЕНСИВНОСТІ ЗАВАД

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## АНОТАЦІЯ

**Актуальність.** Зниження імовірності успішної передачі фрейму в інфраструктурному домені бездротової мережі стандарту IEEE 802.11 DCF обумовлено як впливом інтенсивності колізій так і дією зовнішніх завад у радіоканалі. Використовуючи в якості базового підходу той, що, заснований на використанні Марківських ланцюгів, ми в явній аналітичній формі виразили залежність пропускної здатності мережі від кількості працюючих станцій, швидкості бітових помилок (BER) і коефіцієнта фрагментації фрейму.

**Мета роботи.** Метою даної статті є дослідження впливу інтенсивності шуму на величину пропускної здатності домену бездротової мережі в широкому діапазоні кількості працюючих станцій, під час передачі фреймів різної довжини за відсутності та із застосуванням механізму фрагментації.

**Метод.** Математичне моделювання показало, що в діапазоні підвищеної та високої інтенсивності шуму ($BER = 10^{-5} - 10^{-4}$), зменшення довжини поля даних фрейму, що передається, від стандартних 12000 біт до 3000 біт супроводжується зниженням пропускної здатності для будь-якої кількості конкуруючих станцій. Одночасно з цим слід відмітити, що пропускна здатність стає менш сприятливою до збільшення інтенсивності шуму. В області дуже високої інтенсивності завад ($BER = 2 \cdot 10^{-4}$) одержані результати, які якісно відрізняються. Значне збільшення імовірності передачі фрейму в цій області, яке спостерігається зі зменшенням стандартної довжини поля даних в 2–3 рази, дозволило підвищити пропускну здатність порівняно з початковою. Цей ефект є особливо вираженим у випадку, коли довжина зменшується вдвічі.

**Результати.** Дослідження процесу передачі фрейму стандартного розміру але з фрагментованим полем даних показало, що для $BER \leq 5 \cdot 10^{-5}$ зі збільшенням коефіцієнту фрагментації значення пропускної здатності знижуються на всьому діапазоні кількості працюючих станцій переважно за рахунок впливу зростання накладних втрат. Однак в області високої ($BER = 10^{-4}$) і надвисокої ($BER = 2 \cdot 10^{-4}$) інтенсивності шуму ми маємо зворотний ефект. Найбільше зростання пропускної здатності спостерігається, коли дані фрейму передаються двома рівними фрагментами. Ми провели порівняння пропускної

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здатності мережі, визначеної при простому зменшенні довжини поля даних фрейму і для передачі фрейму з даними стандартної довжини, розділеними на декілька фрагментів. Порівняння показало, що використання механізму фрагментації є більш вигідним як при стабілізації пропускної здатності в умовах підвищеної інтенсивності шуму, так і при збільшенні пропускної здатності в умовах високої і надвисокої інтенсивності шуму.

**Висновки.** У даній статті була модифікована математична модель, що дозволяє безпосередньо обчислювати пропускну здатність бездротової мережі. Використовуючи цю модель, ми дослідили зміну пропускної здатності в широкому діапазоні BER і кількості працюючих станцій, для різних значень коефіцієнта фрагментації фрейму, що передається. Визначено умови підвищення пропускної здатності.

**КЛЮЧОВІ СЛОВА:** бездротові мережі IEEE 802.11, DCF, пропускна здатність, інфраструктурний домен, BER, фрейм, коефіцієнт фрагментації, колізія.

## ЛІТЕРАТУРА

1. Toward 6G Networks: Use Cases and Technologies / [M. Giordani, M. Polese, M. Mezzavilla et al.] // IEEE Communications Magazine. – 2022. – Vol. 58, No. 3. – P. 55–61. DOI: 10.1109/MCOM.001.1900411.
2. Reconfigurable Intelligent Surface-Assisted Cell-Free Massive MIMO Systems Over Spatially-Correlated Channels / [T. V. Chien, H. Q. Ngo, S. Chatzinotas et al.] // IEEE Transactions on Wireless Communications. – 2022. – Vol. 21, No. 7. – P. 5106–5128, DOI: 10.1109/TWC.2021.3136925.
3. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update : 2017–2022. – 2019. – P. 1–33. – Document ID 1486680503328360.
4. A survey on data analysis on large scale wireless networks: online stream processing, trends and challenges / [Dianne S. V. Medeiros, Helio N. Cunha Neto, Martin Andreoni Lopez et al.] // Journal of Internet Services and Applications. – 2020. – Vol. 11, No. 1. – DOI: 10.1186/s13174-020-00127-2.
5. 802.11ac: The Fifth Generation of Wi-Fi. Technical White Paper [Electronic resource]. – Access mode: https://www.cisco.com/c/dam/en/us/products/collateral/wireless/aironet-3600-series/white-paper-c11-713103.pdf.
6. IEEE 802.11ax: The Sixth Generation of Wi-Fi. White Paper [Electronic resource]. – Access mode: https://www.cisco.com/c/en/us/products/collateral/wireless/white-paper-c11-740788.html.
7. Throughput and Delay Analysis of IEEE 802.1le Block ACK with Channel Errors / [H. Lee, I. Tinnirello, J. Yu et al.] // 2nd International Conference on Communi-cation Systems Software and Middleware, Bangalore, 7–12 January 2007 : proceeding. – IEEE, 2007. – P. 1–7, DOI: 10.1109/COMSWA.2007.382498.
8. Throughput enhancement of IEEE 802.11 WLAN via frame aggregation / [K. Youngsoo, Ch. Sunghyun, J. Kyunghun et al.] // IEEE 60th Vehicular Technology Conference : VTC2004-Fall, Los Angeles, 26–29 Septem-ber 2004 : proceeding. – IEEE, 2004. – Vol. 4. – P. 3030–3034, DOI: 10.1109/VETECF.2004.1400617.
9. Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function / G. Bianchi // IEEE Journal on Selected Areas in Communications. – 2000. – Vol. 18, No. 3. – P. 535–547, DOI: 10.1109/49.840210.
10. Tinnirello I. Refinements on IEEE 802.11 Distrib-uted Coordination Function Modeling Approaches / I. Tinnirello, G. Bianchi, Y. Xiao // IEEE Transactions on Vehicular Technology. – 2010. – Vol. 59, No. 3. – P. 1055–1067, DOI: 10.1109/TVT.2009.2029118.
11. Tay Y. C. A capacity analysis for the IEEE 802.11 MAC protocol / Y. C. Tay, K. C. Chua // Wireless Net-works. – 2001. – Vol. 7, No. 2. – P. 159–171. DOI: 10.1023/A:1016637622896.
12. Performance analysis of in-band collision detec-tion from dense wireless networks / [T. Vermeulen, B. Reynders, F. E. Rosas et al.] // EURASIP Journal on Wireless Communications and Networking. – 2021. – Article number: 87. DOI: 10.1186/s13638-021-01940-4.
13. Tourrilhes J. Fragment adaptive reduction: coping with various interferers in radio unlicensed bands / J. Tourrilhes // IEEE international conference of commu-nications (ICC'01), Helsinki, 11–14 June 2001 : proceeding. – IEEE, 2001. – P. 239–244.
14. Mafole P. Analysis and performance assessment of a fragment retransmission scheme for energy efficient IEEE 802.11 WLANs / P. Mafole, M. Aritsugi // Springer Plus. – 2016. – Vol. 5, No. 1, DOI: 10.1186/s40064-016-3023-6.
15. Khandetsky V. S. Modeling of IEEE 802.11 Com-puter Networks at Increased Interference Intensity / V. S. Khandetsky, N. V. Karpenko // Radio Electronics, Computer Science, Control. – 2022. – No. 2. – P. 132–139. DOI 10.15588/1607-3274-2022-2-13.
16. Foh C. H. Comments on IEEE 802.11 saturation throughput analysis with freezing of backoff counters / C. H. Foh, J. W. Tantra // IEEE Communications Letters. – 2005. – Vol. 9, No. 2. – P. 130–132, DOI: 10.1109/LCOMM.2005.02008.
17. Scarpa M. A New Modelling Approach to Repre-sent the DCF Mechanism of the CSMA/CA Protocol / M. Scarpa, S. Serrano // 24th International Conference on Analytical and Stochastic Modelling Techniques and Applications, ASMTA 2017. Lecture Notes in Computer Science, Newcastle-upon-Tyne, 10–11 July 2017 : pro-ceeding. – Springer, Cham, 2017. – Vol. 10378. – P. 181–195. DOI: 10.1007/978-3-319-61428-1_13.
18. Krishman M. N. Local Estimation of Collision Probabilities in 802.11 WLANs with Hidden Terminals : Technical Report No. UCB/EECS-2009-2, January 2009 / M. N. Krishman, S. Pollin, A. Zakhor / Electrical Engineer-ing and Computer Sciences University of California at Berkeley. – 11 p. [Electronic resource]. – Access mode: https://www2.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-2.pdf.
19. The effect of frame length, fragmentation and RTS/CTS mechanism on IEEE 802.11 MAC perfor-mance / [A. M. Sweedy, A. I. Semeia, S. Y. Sayed et al.] // 10th International Conference on Intelligent Systems Design and Applications, Cairo, 29.11.2010-1.12.2010 : proceeding. – IEEE, 2010. – P. 1338–1344, DOI: 10.1109/ISDA.2010.5687095.
20. Performance analysis of IEEE 802.11ac wireless backhaul networks in saturated conditions / [R. Liao, B. Bellalta, J. Barcelo et al.] // EURASIP Journal of Wire-less Communications and Networking. – 2013. – Article number 226. – P. 1–14 p. DOI: 10.1186/1687-1499-2013-226.
21. Effect of service differentiation on QoS IEEE 802.11e enhanced distributed channel access: a simula-tion approach / [G. O. Ugwu, U. N. Nwawelu, M. A. Ahaneku et al.] //

DOI 10.15588/1607-3274-2023-3-15

Journal of Engineering and Applied Science. – 2022. – Vol. 69, No. 1. – P. 1–18. DOI: 10.1186/s44147-021-00055-3.

22. Malone D. Modeling the 802.11 Distributed Coor-dination Function in Nonsaturated Heterogeneous Condi-tions / D. Malone, K. Duffy, D. Leith // IEEE/ACM Transactions on Networking. – 2007. – Vol. 15, No. 1. – P. 159–172. DOI: 10.1109/TNET.2006.890136.
23. Bozkurt A. Optimal delay analysis for real-time traffics over IEEE 802.11 wireless LANs / A. Bozkurt // EURASIP Journal of Wireless Communications and Net-working. – 2016. – Article number 52. – P. 1–13. DOI: 10.1186/s13638-016-0545-0.
24. Tian G. Modelling and performance evaluation of the IEEE 802.11 DCF for real-time control / G. Tian, Y.-C. Tia // Computer Networks. – 2012. – Vol. 56, No. 1. – P. 434–447. DOI: 10.1016/j.comnet.2011.10.001.
25. A User Prioritization for Horizontal Handover in Dense WLAMs / [O. A. Aldbaibani, A. Raschella, G. Mohi-Ud-Din et al.] // International Journal of Wireless Information Networks. – 2022. – Vol. 29. – P. 130–142. DOI: 10.1007/s10776-021-00544-5.
26. Matthew Gast. 802.11 Wireless Networks: The Definitive Guide. – O' Reilly Media, Inc, 2005. – 630 p.
27. Cover T. M. Elements of Information Theory. Second Edition / T. M. Cover, J. A. Thomas. – Hoboken, New Jersey: Wiley, 2006. – 774 p.
28. Proakis J. G. Digital Communications. Fifth Edi-tion / J. G. Proakis, M. Salehi. – McGrow-Hill Education, 2007. – 1150 p.
29. Performance analysis of the IEEE 802.11e block ACK scheme in a noisy channel / [T. Li, Q. Ni, T. Turletti et al.] // 2nd International Conference on Broadband Networks, Boston, 7 October 2005 : proceeding. – IEEE, 2005. – Vol. 1. – P. 511–517. DOI: 10.1109/ICBN.2005.1589655.
30. Modelling and enhancement of the IEEE 802.11 RTS/CTS scheme in an error-prone channel / [M. Yazid, D. Aissani, L. Bouallouche-Medijkoune et al.] // Formal Aspects of Computing. – 2015. – Vol. 27, No. 1. – P. 33–52. DOI: 10.1007/s00165-014-0300-4.
31. Breed G. Bit error rate: fundamental concepts and measurement issues / G. Breed // High Frequency Elec-tronics. – 2003. – Vol. 2, No. 1. – P. 46–48.
32. Low complexity hybrid interference cancellation for sparse code multiple access / [B. Ghani, F. Launay, Y. Pousset et al.] // EURASIP Journal of Wireless Com-munications and Networking. – 2022. – Article number 95. – P. 1–26, DOI: 10.1186/s13638-022-02162-y.
33. Tan B. S. Bit – error rate analysis of low-density parity-check codes with generalized selection combining over a Rayleigh-fading channel using Gaussian approxi-mation / B. S. Tan, K. H. Li, K. C. Teh // IET Communi-cation. – 2012. – Vol. 6, No. 1. – P. 90–96. DOI: 10.1049/iet-com.2011.0271.
34. Analytical analysis of applying packet fragmenta-tion mechanism on IEEE 802.11b DCF network in non-ideal channel with infinite load conditions / [M. Yazid, L. Bouallouche-Medikoune, D. Aissani et al.] // Wireless Networks. – 2014. – Vol. 20. – P. 917–934. DOI: 10.1007/s11276-013-0653-2.
35. Performance Analysis of IEEE 802.11ac DCF with Hidden Nodes / [Z. Chang, O. Alanen, T. Huovinen et al.] // IEEE 75th Vehicular Technology Conference (VTC Spring), Yokohama, 6–9 May 2012 : proceeding. – IEEE, 2012. – P. 1–5. DOI: 10.1109/VETECS.2012.6240054.
36. Validation of Wi-Fi network simulation on ns-3 : Technical Report : August 7, 2017 / [R. Patidar, S. Roy, T. R. Henderson et al.] / University of Washington – Seattle, 2017. – 19 p.
37. A performance analysis of block ACK scheme for IEEE 802.11e networks / [H. Lee, I. Tinnirello, L. Yu et al.] // Computer Networks. – 2010. – Vol. 54, No. 14. – P. 2468–2481. DOI: 10.1016/j.comnet.2010.04.001.

DOI 10.15588/1607-3274-2023-3-15