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EVALUATING THE EFFICIENCY OF MECHANISMS FOR FRAME BLOCKS TRANSMISSION IN NOISY CHANNELS OF IEEE 802.11 NETWORKS

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ABSTRACT

Context. Aggregating frames into blocks when transmitting information in wireless IEEE802.11 networks helps to significantly reduce overhead costs and increase the transmission rate. However, the impact of noise reduces the efficiency of such transmission due to an increased probability of distortion of longer messages. We compared the efficiency of data transmission by variable and constant size blocks formed from frames using VBS and FBS mechanisms correspondingly under conditions of noise varying intensity.

Objective. The purpose of this article is a comparative study of VBS and FBS mechanisms used for the formation and transmission of different sizes frame blocks under medium and high noise intensity.

Method. A simple model used in IEEE 802.11 networks to determine the DSF throughput for transmitting frames in infrastructure domains was modified by us to transmit frame blocks of different sizes under conditions of medium and high intensity noise affecting the transmission process. 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 frame. The scale factors of the model for the number of frames in a block $k = 6–40$ at an average noise level corresponding to BER = 10^{-6} and $k = 4–15$ for high-intensity noise at BER = 10^{-5} are determined. The algorithm for calculation of the network throughput has been generalized. The investigation of the dependences of the throughput on the number of frames in the VBS blocks showed the presence of local maxima in dependences, located in the region of average values of the frames number. These maxima are more pronounced at increased data transfer rates.

Results. It is shown that with a small number of frames in a block ($k = 6–9$) and high-intensity noise, the efficiency of the FBS mechanism exceeds the efficiency of the VBS block formation mechanism. However, at the same noise level, an increase in the number of frames in a block ($k \geq 10$) makes the use of the VBS mechanism more preferable. This advantage is explained by the fact that the VBS mechanism at each subsequent stage of transmission forms a block from frames distorted at the previous stage, therefore the size of the blocks at subsequent stages decreases, increasing the number of frames successfully transmitted to the AP (due to the increase in the probability of transmitting shorter blocks). At the same time, the constant and small probability of successful transmission of a constant size block at each stage makes the probability of transmission of frames distorted at the previous stages low. The situation changes for noise of medium intensity. Here the transmission of each subsequent block in the range of up to 25 frames per block using the VBS method requires the use of two stages. The application of the FBS method in these conditions shows that only the first set of frames requires the use of two stages for its complete transmission. Then, due to the accumulation of frames at the previous stages, each subsequent stage of transmission completes the formation of the corresponding set in the memory of AP. Thus, when the noise intensity decreases to BER = 10^{-6} and below, the use of the FBS mechanism becomes more effective. The obtained results are illustrated with specific examples characterizing the formation and transmission of various frame blocks.

Conclusions. In this article, using a mathematical model modified by us, a comparative study was conducted on the efficiency of various mechanisms for forming and transmitting a frame block of different sizes under conditions of the impact of different intensity noise on the transmission process. The algorithm for calculating the network throughput was generalized, and the values of the throughput were determined when using the VBS and FBS network functioning mechanisms.

KEYWORDS: IEEE 802.11 wireless networks, throughput, noise intensity, BER, frame blocks, VBS and FBS mechanisms.

ABBREVIATIONS

AP is an access point;
STA is a station;
BER is a bit error rate;
FER is a frame error rate;
BFER is a block frames error rate;
DCF is a Distributed Coordination Function;
ACK is a frame acknowledgment;
DIFS is an inter-frame space;
SIFS is a short inter-frame space;

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MAC is a Medium Access Protocol;
BAR is a Block ACK Request;
BA is a Block ACK;
TCP is a Transfer Control Protocol;
EDCA is an Enhanced Distributed Channel Access;
VBS is a variable block size;
FBS is a fixed block size;
WLAN is a Wireless Local Area Network.

NOMENCLATURE

bE is a number of erroneous bits;
R is a data transfer rate;
t is a transmission time;
L_{data} is a length of the frame data field in bits;
E_b is an energy per bit;
N_0 is a noise power spectral density;
P_b is a bit error probability;
P_f is a frame error probability;
P_C is a probability of a data block collision in ideal channel;
P_B is a probability of a data block corruption by interference during transmission;
P_{Sr} is a relative probability of successful block transmission;
P_S is a probability of successful block transmission;
k is a number of frames in a block;
T_{DIFS} is an inter-frame space duration;
T_{SIFS} is a short inter-frame space duration;
T_{PHYhdr} is a transmission time of the frame's physical layer header;
$T_{\overline{CW}}$ is an average length of the backoff;
$CW_{\min}$ is a minimum contention window length;
T_{ACK} is an acknowledgment frame duration;
S_{id} is an ideal DCF throughput;
S_k is a real throughput when using block transmission;
δ is a propagation delay;
σ is a duration of one slot.

INTRODUCTION

The share of traffic transmitted by Wi-Fi devices in the total traffic of wireless networks over the past decade is approximately half. Wi-Fi technologies are rapidly developing, maintaining their positions in competitive activity [1, 2].

Despite significant progress in solving WLANs problems, achieved in the development of modern networks such as IEEE 802.11ac and 802.11ax, the effective throughput increases slowly, especially in dense networks operating under conditions of high external and internal noise intensity [3–5].

As noted by US Federal Communications Commission (FCC), an urgent problem for technologies using wide frequency channels (Δf = 160 MHz) is "clearing the frequency range". The effect of increasing interference is also observed with a decrease in the inter-symbol interval of transmitted data and with an increase in the number of subcarrier frequencies. The concentration of several spatial streams in one region of the channel leads to an increase in the mutual influence of signals too. This effect is further enhanced with an increase in the intensity of external noise, blurring the distinctive features of signals of different streams. Another challenge in wireless networks is the handover, which is the process of switching users from one AP to other [6].

Electromagnetic interference increases significantly when wireless networks operate in industrial environments. Sources of electromagnetic radiation such as vehicles, industrial equipment, electric motors, switching devices, high-voltage equipment, and fluorescent lamps produce intense noise.

High level of industrial interference increases BER (bit error rate) in transmission channel [7, 8]. The result is an increased loss of frames during transmission, retransmission of frame copies which in turn decreases the network throughput.

To reduce the overhead costs when transmitting data in separate frames, a block transfer mechanism was proposed [9–11]. This mechanism provides that a block of frames from one flow can be sent without acknowledging that the AP has correctly received each individual frame. After the block transmission the STA initiates a BAR frame to enquire the number of frames that have been received successfully. The AP then responds with a BA frame. The efficiency of this scheme comes from the fact that the overhead is greatly reduced, because DIFS and backoff intervals only occur before the first frame of the block and only one acknowledgment is used for all frames in the block (BA).

A similar principle is used by the TCP transport protocol when transmitting data segments in wired networks [12, 13].

The concept of EDCA used in IEEE 802.11e [14–16] provides two mechanisms for composition of frame blocks during the transmission process. A block of data can be formed using only those frames that were corrupted during the transmission of the previous block. In such a case referred to as VBS, data frames block size varies over time from one transmission stage to next. In other cases, a data block can also be composed on corrupted frames as well as newly transmitted frames, so that the data frames block size is kept at the maximum size specified at the initial stage. Thus, the data block size does not change over time and refers to this as FBS.

The object of study is the process of transmitting information in wireless networks using VBS and FBS mechanisms for the formation and transmission of frame blocks under conditions of medium and high intensity external noise.

The subject of study is the mathematical models of IEEE.802.11 BA networks using VBS and FBS operating mechanisms under conditions of noise influence on the transmission process.

The purpose of the paper is a comparative study of the efficiency of frame blocks transmission formed using the VBS and FBS mechanisms under the influence of variable intensity noise.

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1 PROBLEM STATEMENT

Interferences that have various physical natures 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 [8, 17]. An example of a simple channel model that is widely used in information theory is additive white Gaussian noise channel without fading [18].

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" [19]:

$$\mathrm{BER} = \frac{\text{number of corrupted bits}}{\text{total number of bits}} = \frac{bE}{R \cdot t}, \qquad (1)$$

where bE is the number of erroneous bits, R is the data transfer rate, t is the transmission time.

In a noisy channel, the BER is often expressed as a function of the normalized carrier-to-noise ratio denoted E_b/N_0. The Gaussian approximation of the noise in determining the BER is used to estimate the number of iterations needed to the convergence of the parity code decoder in function of the level of noise power [20]. Bit-error rate analysis of low-density parity-check codes using Gaussian approximation of a channel is considered in [21].

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 [22, 23].

Let L and P_b correspond the frame length and bit error rate (BER), respectively, and P_f correspond the frame error rate (FER). Then the probability that a frame of length L will be transmitted undistorted is equal:

$$q = (1-P_{b1})(1-P_{b2})(1-P_{b3})...(1-P_{bL}) = (1-P_b)^L, \qquad (2)$$

where $P_{b1}= P_{b2}= P_{b3}=\ldots= P_{bL}= P_b$. In this case, the probability of frame distortion is equal to

$$P_f = 1-(1-P_b)^L. \qquad (3)$$

The probability of successful (error-free) transmission of a data block by the STA to AP can be expressed as follows:

$$P_S = (1-P_C)(1-P_B) = (1-P_C)(1-P_b)^{k \cdot L}. \qquad (4)$$

The P_C is traditionally determined using Markov-chain models [24–26].

Let us analyze the influence of the intensity of external interference or, in other words, the noise level in the communication channel on the probability of the block successful transmission. At the same time, since in accordance with (4) the influence of the collision's intensity P_C and external interference P_b is carried out on P_S separately [27], it is possible, without reducing the reliability of the analysis, to fix P_C at the certain level and consider the influence P_b on the relative value of $P_{Sr}= P_S/(1–P_C)$.

Table 1 shows the dependence of P_{Sr} on k (L=12000 bits) for three levels P_b=BER=10^{-7}, 10^{-6}, 10^{-5}.

If we assume that P_C is zero, then $P_{Sr}= P_S$ and from Table 1 it follows that the probability of a block successful transmission in case BER=P_b=10^{-5} decreases significantly with increasing k.

In the ideal case, the channel is regarded as perfect, i.e. neither error not collisions occur, and in any transmission cycles there is only one active STA which always has backlogged frame in queue between the MAC and its upper layer waiting to be transmitted. The receiver (AP – in infrastructure network) only responds with ACK (ACKnowledgment) and the other STAs just sense the channel and wait. Then the ideal DCF throughput S_{id} taking into account [9, 28] can be defined as

$$S_{id} = \frac{L_{data}}{T_{DIFS} + T_{C\overline{W}} + T_F + T_{ACK} + 2\delta}, \qquad (5)$$

where $T_{C\overline{W}} = \frac{\sigma \cdot (CW_{\min}-1)}{2}$ and $T_F = T_{PHYhdr} + \frac{L_{data}}{R} + T_{SIFS}$. Each frame includes a common physical header whose duration T_{PHYhdr} has to be added to the frame transmission time [10].

The block transmission scheme in protected mode is illustrated in Fig. 1.

Table 1 – Dependences of P_{Sr} on k for different values of noise intensity P_b

BER=P_b=10^{-7}											
P_{Sr}	0.999	0.998	0.996	0.995	0.994	0.993	0.990	0.988	0.982	0.976	0.965
k	1	2	3	4	5	6	8	10	15	20	30
BER=P_b=10^{-6}											
P_{Sr}	0.988	0.976	0.965	0.953	0.942	0.931	0.908	0.887	0.835	0.787	0.697
k	1	2	3	4	5	6	8	10	15	20	30
BER=P_b=10^{-5}											
P_{Sr}	0.887	0.787	0.697	0.619	0.549	0.487	0.383	0.301	0.165	0.09	0.03
k	1	2	3	4	5	6	8	10	15	20	30

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DIFS	backoff	PHY_{hdr}	frame	SIFS	ACK	SIFS	PHY_{hdr}	frame	SIFS	•••

PHY_{hdr}	frame	SIFS	BAR	SIFS	BA

Figure 1 – The scheme of data frames block transmission

The transmission speed can be significantly increased by combining frames into blocks and transmitting them using the VBS and FBS mechanisms. It is of considerable interest to conduct a comparative analysis of the efficiency of these mechanisms when changing the sizes of transmitted blocks and in the presence of Gaussian noise of varying intensity in the transmission channel.

2 REVIEW OF THE LITERATURE

Supporting real-time communications over IEEE 802.11 WLANs is very important yet challenging due to limited channel capacity, unstable channel conditions and a low transmission delay requirement of real-time traffic [29]. In [30] the authors provided a closed formula, based on some approximations, for the configuration of the parameters $CW_{\min}$ and $CW_{\max}$, where CW is the contention window in backoff mechanism of a frame transmission. In [31] the authors built an analytical model to derive an average delay estimate for the traffic of different priorities in the unsaturated 802.11e WLANs.

The majority of analytical works on the delay performance of IEEE 802.11 focuses on predicting only the mean MAC delay, although higher layer application and protocols are interested in the total performance of the MAC layer. The analysis presented in [32] applies to the priority schemes of the of the EDCA mechanism of the IEEE 802.11e standard. However, by using an appropriate parameter setting, the results presented are also applicable to the legacy 802.11 DCF. In [33] authors note that for analytical tractability and simplicity, most exiting performance models of transmission opportunity (TXOP) have been restricted to unrealistic working scenarios where the traffic follows a Poisson process, which is unable to capture to heterogeneous characteristics of multimedia traffic. IEEE 802.11e EDCA induces service differentiation by appropriate joint turning of for adjustable contention parameters.

In [3] authors consider the situation in which a transmitter attempts to communicate reliably over a discrete memoryless channel. In [34] authors analyze additive white Gaussian noise at both the receiver and the warden for covert communication. The next generation of wireless communication technologies is accelerating the transformation of industrial Internet of things (IIoT) [4]. In [5] authors consider adversary's noise and channel uncertainties and analyze their impact on throughput of covert messages.

Congestion is the main cause of losses in wired networks, but in today's heterogeneous networks, loss events can also be introduced due to higher error rates on wireless channels, host mobility and frequent handovers [35]. Interference is the main performance-limiting factor in most wireless networks [36]. The interference ranges in a mentioned literature are set without fully considering the effect of the networks. The setting of the interference range is rather heuristic and remains an open problem [37].

In the case of collision, at least two stations (STAs) start transmission in the same slot, each of them sends out a whole block and BAR frame and then waits for the BA frame. The access point (AP) shall not send back the BA frames when it detects a collision. The STAs can't receive the BA frames successfully, and then they have to retry their transmission again.

In the erroneous case due to interference STA sends to AP a whole block and BAR frame as usual. The AP then sends back a BA frame to indicate which frames are corrupted.

The authors of article [10] justify the expediency of using the frame block protection mechanism during transmission. In this case, successful transmission of the first frame in a block is notified via immediate ACK. Otherwise, even if the first frame in a block collides with other frames transmitted by other stations, the transmitting station will continue to transmit the next frames in a block since it cannot determine such a collision. This can lead to severe performance degradation.

The BA frame contains information about the reception of the whole block through a corresponding bitmap. Both the BAR and BA frames are transmitted at the same rate used for the data frame transmission. After each BA the STA transmits the corrupted frames composed in a subsequent block.

Network performance is affected by two different states: the probability of having successful channel access and the channel utilization efficiency [24]. The first state depends on the number of competing stations. The second state depends on the overhead, in terms of headers, control frames and retransmissions required for the data delivery, and it is a function of the frame error rate.

3 MATERIALS AND METHODS

If the mechanism of variable blocks size (VBS) is used when transmitting data, then after receiving frame BA the next block is formed only from frames distorted at the previous state. Let's analyze the operation of this mechanism at average noise intensity BER=P_b=10^{-6} using the example of a block with k=20. The corresponding transmission scheme using the protection mode is shown in Fig.2.

In the fields of the scheme in Fig. 2, designated by the letter F, we integrate the physical layer header PHY_{hdr}, the frame itself and the short inter-frame interval SIFS.

The probability of successful transmission of a separate frame F1, which performs the block protection function, is equal to P_S=0.988, and we assume that this frame will be successfully transmitted. The probability of suc-

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cessful transmission of an entire block consisting of 20 frames at BER=P_b=10^{-6} is equal to

$$P_{S,k=20} = (1 - P_b)^{L_0 \cdot k} = 0.787 , \qquad (6)$$

that is, we can assume that statistically approximately 16 frames from a block successfully passed to the AP, and 4 distorted frames (for example F3, F7, F11, F15), as shown in Fig.2, are transmitted at the second stage. In this case, taking into account (5), the throughput is

$$S_{k=20} = \frac{21 \cdot L_{data}}{2(T_{DIFS} + T_{\overline{CW}} + T_{ACK}) + 4T_{SIFS} + 25 \cdot T_F + 2T_{BAR} + 2T_{BA} + 8\delta} . \qquad (7)$$

DIFS	backoff	F1	ACK	SIFS	F2	F3	F4	F5	F6	F7	•••	F21	BAR	SIFS	BA

DIFS	backoff	F3	ACK	SIFS	F7	F11	F15	BAR	SIFS	BA

Figure 2 – The VBS transmission scheme for a block containing k = 20 frames at BER = P_b = 10^{-6}

For forty frames in a block (k = 40) with the same level of interference in the channel (BER = P_b = 10^{-6}), the transmission scheme is shown in Fig. 3.

DIFS	backoff	F1	ACK	SIFS	F2	F3	F4	F5	F6	F7	•••	F41	BAR	SIFS	BA

DIFS	backoff	F2	ACK	SIFS	F4, F7, F10, F13, F16, F19, F21, F24, F27, F30, F33, F36, F38, F40	BAR	SIFS	BA

DIFS	backoff	F4	ACK	SIFS	F21	BAR	SIFS	BA

Figure 3 – The VBS transmission scheme for a block containing k = 40 frames at BER = P_b = 10^{-6}

The probability of successful transmission of a block, consisting of k = 40 frames, calculated similarly to (6), is equal to $P_{S,k=40}$ = 0.619. Thus, it can be assumed that statistically approximately 25 frames from a block successfully passed to the access point, and 15 frames (for example F2, F4, F7, F10, F13, F16, F19, F21, F24, F27, F30 F33, F36, F38 and F40), as shown in Fig. 3, are transmitted at the second stage. The probability of successful transmission of a block formed at the second stage and containing 14 frames at BER=P_b=10^{-6} is $P_{S,k=14}$=0,845. From this number, statistically 12 frames will successfully reach the access point, and 2 frames (for example F4, F21) will be distorted and will be transmitted already at the third stage. In this case, the throughput is

$$S_{k=40} = \frac{41 \cdot L_{data}}{3(T_{DIFS} + T_{\overline{CW}} + T_{ACK}) + 6T_{SIFS} + 58 \cdot T_F + 3T_{BAR} + 3T_{BA} + 12\delta} . \qquad (8)$$

Similar calculations were carried out for blocks with k = 6, 10, 15, 25 and 30. The resulting throughput values for blocks of different lengths when changing the data transfer rate R are shown in Table 2. The following parameters were used in the calculations [9, 38]: T_{SIFS}=16 µs, σ = 9 µs, T_{DIFS}=34 µs, T_{PHYhdr} = 20 µs, $CW_{\min}$=16, 2δ=0,7 µs, T_{BAR}=21,8 µs, T_{BA}=31 µs, L_{data}=12000 bit.

Graphical dependencies of throughput S_k on the number of frames in a block k at different data transfer rates R are shown in Fig.4. As can be seen from the figure, the curves are characterized by the presence of a maximum in the area of average k values. As data rates increase, these maximums become more pronounced.

Let's analyze the effect of high-intensity noise with BER=P_b=10^{-5} on the process of block data transmission using the VBS mechanism. The process of transmitting a block with k=15 frames in protected mode is described schematically in Fig. 5.

Table 2 – The throughput values S_k at different k and R when BER=P_b=10^{-6}

k	S_k							
		R, Mbps						
	108	162	216	270	324	378	432	486
6	67.8	85.8	98.9	108.8	116.7	123.0	128.2	132.6
10	63.0	79.9	92.3	101.8	109.3	115.4	120.4	124.6
15	62.6	80.0	93.0	102.9	110.9	117.3	122.7	127.2
20	61.5	79.5	93.1	103.8	112.3	119.4	125.3	130.3
25	60.9	79.2	93.2	104.3	113.3	120.7	126.9	132.2
30	56.6	73.6	86.6	96.9	105.2	112.1	117.9	122.8
40	53.7	70.2	82.9	93.0	101.2	108.0	113.8	118.7

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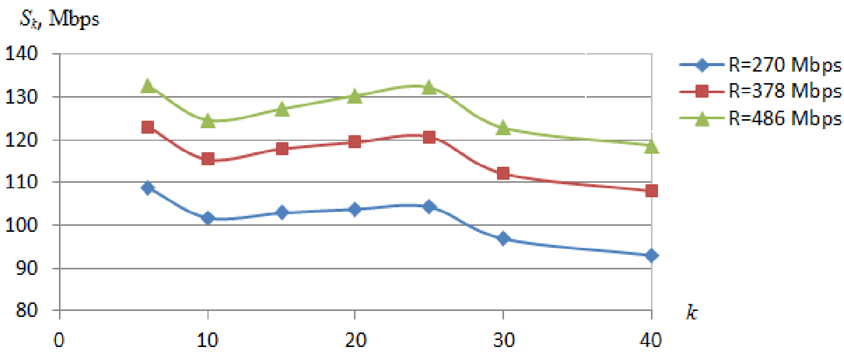

Figure 4 – Dependence of network throughput S_k on the number of frames k in a block. Data transfer is carried out using the VBS method at BER=P_b=10^{-6}

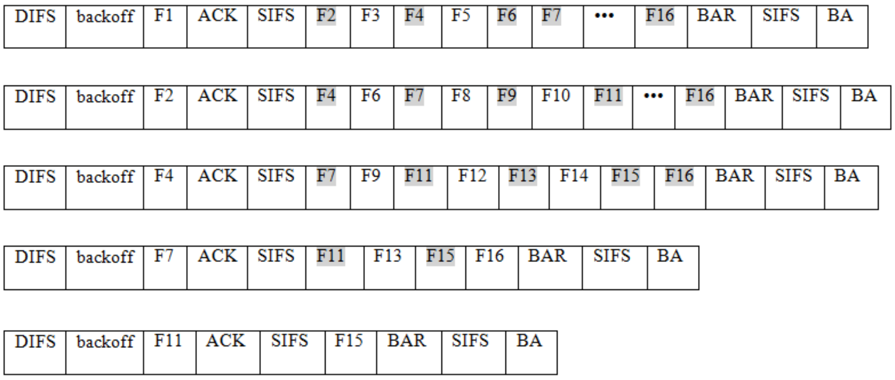

Figure 5 – The VBS transmission scheme for a block containing k = 15 frames at high interference intensity (BER=P_b=10^{-5})

The probability of successful transmission of a fifteen frames block when BER=P_b=10^{-5} is equal to

$$P_{S,k=15} = (1-P_b)^{L_0\cdot k} = 0.165, \tag{9}$$

that is, at the first stage statistically 2 frames successfully pass through the channel, and 13 are distorted (F2, F4, F6, F7, F8, F9, F10, F11, F12, F13, F14, F15, F16 in the designation of the blocks of the scheme in Fig. 5).

These frames are transmitted at the second stage, with F2 acting as a diagnostic frame, and a last 12 forming a block. The probability of successful transmission of this block is 0,237, therefore we assume that at this stage 3 frames successfully pass through the channel (F6, F8 and F10), and 9 are distorted (F4, F7, F9, F11, F12, F13, F14, F15, F16).

The indicated 9 frames are transmitted at the third stage, with F4 acting as a diagnostic frame, and a last 8 forming a block. The probability of successful transmission of this block is 0.383, so we assume that at this stage on average 3 frames successfully pass through the channel (F9, F12 and F14), and 5 are distorted (F7, F11, F13, F15, F16).

These frames are transmitted at the fourth stage, with F7 acting as a diagnostic frame, and a last 4 forming a block. The probability of successful transmission of this block is 0,619, therefore we assume that at this stage on average 2 frames successfully pass to the access point (F13 and F16), and 2 are distorted (F11 and F15). As shown in the scheme, they are successfully transmitted at the fifth stage.

In this case, the network throughput is calculated as follows:

$$S_{k=15} = \frac{13\cdot L_{data}}{5(T_{DIFS}+T_{\overline{CW}}+T_{ACK})+10T_{SIFS}+45\cdot T_F+5T_{BAR}+5T_{BA}+20\delta}. \tag{10}$$

Similar calculations were carried out for blocks with k = 4, 6, 8, 10, and 12. The throughput values for all these blocks when changing the data transfer rate R are shown in Table 3.

Graphs of the throughput S_k on k dependences for R = 270, 378, and 436 Mbps are shown in Fig. 6.

As can be seen from figure 6, the curves characterized by the presence of a local maximum in the vicinity of k=10. The values of these maxima, as well as the absolute values of the throughput at high noise level BER=P_b=10^{-5} are significantly smaller compared to the previous case described in section 4.1 where BER=P_b=10^{-6}.

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Table 3 – The throughput values S_k at different k and R when BER=P_b=10^{-5}

k		S_k						
		R, Mbps						
	108	162	216	270	324	378	432	486
4	41.5	50.5	56.7	61.2	64.6	67.3	69.5	71.3
6	38.9	48.0	54.3	58.9	62.5	65.3	67.6	69.5
8	36.2	45.2	51.7	56.5	60.2	63.2	65.6	67.6
10	35.5	44.9	51.8	57.0	61.1	64.4	67.2	69.5
12	32.0	40.2	46.2	50.7	54.2	57.0	58.1	61.3
15	25.1	32.0	37.2	41.2	44.3	46.9	49.1	50.9

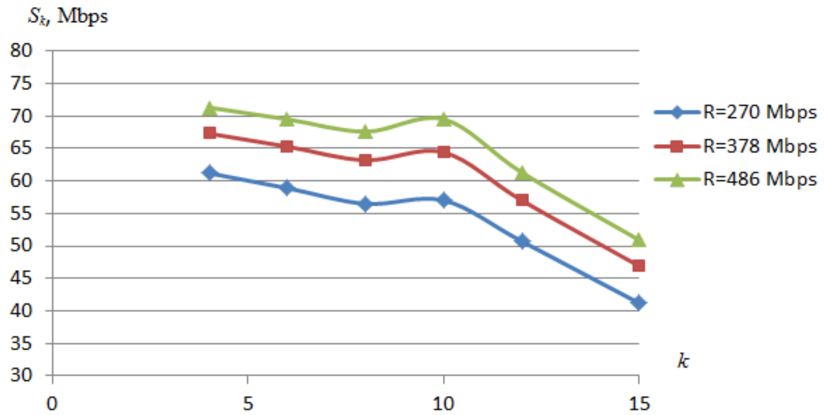

Figure 6 – Dependence of network throughput S_k on the number of frames k in a block. Data transfer is carried out using the VBS method at BER = P_b = 10^{-5}

In this work, to study the efficiency of data transmission using the VBS method under noise, we modified expression (1), which was originally proposed to calculate the throughput of a WLAN in ideal case of no noise. Keeping the simplicity of the original model, we propose to determine the influence of noise within the framework of the following model:

$$S_k = \frac{(k+1)\cdot L_{data}}{\alpha(T_{DIFS} + T_{\overline{CW}} + T_{ACK}) + \beta T_{SIFS} + \gamma T_F + \eta(T_{BAR} + T_{BA}) + \lambda\delta}. \quad (11)$$

The values of the coefficients α, β, γ, η, and λ for all k involved in calculation and two noise levels (BER) are collected in Tab.4. The dependences of the coefficient γ on k for different noise levels are shown in Fig. 7.

Table 4 – Values of coefficients in model (11)

Noise level, BER	Number of frames in each block k	Model coefficients				
		α	β	γ	η	λ
10^{-6}	6	1	2	7	1	4
	10	2	2	12	1	6
	15	2	4	18	2	8
	20	2	4	25	2	8
	25	2	4	32	2	8
	30	3	4	41	2	10
	40	3	6	58	3	12
10^{-5}	4	2	4	7	2	4
	6	3	4	11	2	10
	8	3	6	16	3	12
	10	3	6	21	3	12
	12	4	8	29	4	16
	15	5	10	45	5	20

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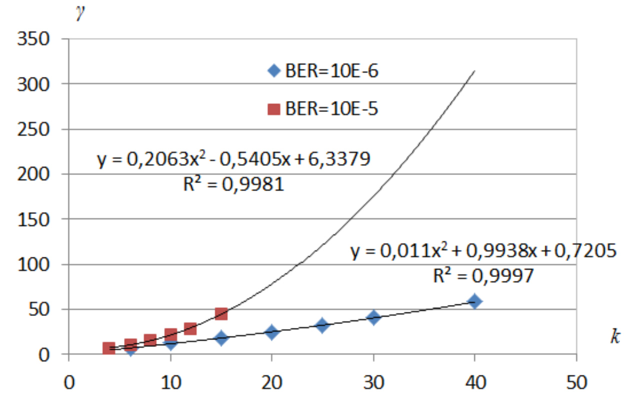

Figure 7 – Dependences of coefficient γ in (11) on the number of frames in block k for different noise levels

Let us generalize the algorithm for determining the network throughput.

1. At the first stage, using the noise level BER=P_b and the total data length of the frame's block $L_0 \cdot k$ we calculate the probability of successful block transmission $P_S^{(1)}$ using formulas (6). By multiplying the resulting probability $P_S^{(1)}$ by the number of frames in the block k and going to the nearest integer, we will obtain the average number of frames that will be successfully transmitted to the access point AP:

$$k_{AP}^{(1)} = [k \cdot P_S^{(1)}], \qquad (12)$$

where [] denotes going to the nearest integer value.
If the number of frames $k_{AP}^{(1)}$ is less, than the number of frames in the block k, then they difference indicates frames distorted by interference, which, in accordance with the VBS method, will form a new block for transmission in the second stage:

$$k_D^{(2)} = [(k - k_{AP}^{(1)})]. \qquad (13)$$

2. One is subtracted from the obtained value $k_D^{(2)}$ (10) (one frame performing the channel diagnostic function is transmitted before the block and its delivery is confirmed by a separate receipt ACK), the remaining number of frames is subjected to a procedure similar to (12):

$$k_{AP}^{(2)} = [(k_D^{(2)} - 1) \cdot P_S^{(2)}] = [(k_D^{(2)} - 1) \cdot (1 - P_b)^{L_0 \cdot (k_D^{(2)} - 1)}]. \qquad (14)$$

In this case, the number of frames distorted during transmission at the second stage and intended for transmission at the third stage is

$$k_D^{(3)} = (k_D^{(2)} - 1) - k_{AP}^{(2)}. \qquad (15)$$

3. These frames form the corresponding block at the third stage and the procedure is repeated:

$$k_{AP}^{(3)} = [(k_D^{(3)} - 1) \cdot P_S^{(3)}] = [(k_D^{(3)} - 1) \cdot (1 - P_b)^{L_0 \cdot (k_D^{(3)} - 1)}], \qquad (16)$$

$$k_D^{(4)} = (k_D^{(3)} - 1) - k_{AP}^{(3)}. \qquad (17)$$

Continuing this algorithm, we obtain its generalization in the following form:

$$k_{AP}^{(i)} = [(k_D^{(i)} - 1) \cdot P_S^{(i)}] = [(k_D^{(i)} - 1) \cdot (1 - P_b)^{L_0 \cdot (k_D^{(i)} - 1)}], \qquad (18)$$

$$k_D^{(i+1)} = (k_D^{(i)} - 1) - k_{AP}^{(i)}. \qquad (19)$$

Here symbol i denotes the number of transmission stages in the VBS method.

4 EXPERIMENTS

Let us first consider the transmission of blocks of a fixed size under conditions of high-intensity noise BER=P_b=10^{-5}. Let's assume that the transmitted block contains 6 frames of standard length (see section 3). The probability of successful transmission of the entire block is equal to $P_{S,k=6}$ =0.487, that is, approximately half of the frames of this block will be distorted (for example F2, F4, and F6).

But, unlike the VBS method, now, in order to maintain the constant block size, these frames are complemented with four new frames with the following numbers in order, forming the block – F2$_d$, F4$_d$, F6$_d$, F8, F9, F10, and F11 (the symbol d hereinafter denotes distorted frames; at the first stage, frames from 1 to 7, inclusive, took part in the transmission process and F1 diagnoses transmission environment). From the frames distorted at the first stage of transmission, we select a frame that will be diagnostic at the second stage, for example F2$_d$. This frame is separately confirmed by a receipt, and according to Section 3.2, the probability of its successful transmission is 0,887, that is, it is sufficiently high. Thus, at the second stage, the following block is formed for transmission: F4$_d$, F6$_d$, F8, F9, F10, and F11.

We assume that, as in the first stage, three frames are successfully transmitted to the access point, and three are distorted. Let's estimate the probability that copies of frames F4$_d$, F6$_d$ will be included in the number of successfully transmitted frames at the second stage. For this,

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we will use the well-known formula of a probability theory [17]:

$$P_A = \frac{C_M^m \cdot C_{N-M}^{n-m}}{C_N^n}. \quad (20)$$

Here

$$C_N^n = \frac{N(N-1)(N-2)...1}{[n(n-1)(n-2)...1]\cdot[(N-n)(N-n-1)(N-n-2)...1]}. \quad (21)$$

In these formulas N is the number of frames in the sent block ($N = 6$); n is the total number of frames that were distorted during transmission ($n = 3$); M is the number of copies of distorted frames included in the block for transmission at the second stage ($M = 2$); m is the number of frame copies that are planned as successfully transmitted to the AP. In our case, for $m = 2$, $P_A = 0.2$, i.e. successful transfer at the second stage of copies $F4_d$ and $F6_d$ is the rare event. However, for $m = 1$, $P_A = 0.6$, i.e. successful transmission of $F4_d$ or $F6_d$ can be accepted. Let's assume that it is $F4_d$.

Thus, frame $F6_{dd}$ is included in the block for transmission at the third stage, as well as, for example, frames $F8_d$ and $F10_d$. From among these frames, a frame diagnosing the transmission environment in protected mode is selected. The probability of choosing the $F6_{dd}$ frame out of three is 1/3, and the total probability for the third and fourth stages of transmission is 2/3. Therefore, it can be assumed that the $F6_{dd}$ frame will be sent at one of these stages, and all 7 frames of the first set (F1 – F7) will finally be collected in the buffer memory of the AP. At the same time, it will be possible to form this set of frames in the required sequence and send it to the network. In the best case, this will be done after the third stage of transfer, in more likely – after the fourth stage. In the case of using the VBS method (see subsection 3.2), the formation of the entire first set in the desired sequence of frames took place immediately after the third stage of transmission.

But it should be taken into account that in the third and fourth stages, the frames of other sets will also be stored in the memory of the AP, which characterizes the potential possibility of forming complete sets for transmission over the network in the following stages. Let's consider this.

After the first stage of transmission, the access point will receive frames $F1_1$, $F3_1$, $F5_1$, $F7_1$, from the first set. It will not be able to send these frames to the network until this set is received completely and its frames are formed in the required sequence.

After the second stage of transmission, copies of frames $F2_d$ and $F4_d$ are added to the first set, and frames F9 and F11 from the second set are added to the access point.

After the third stage of transfer, frame $F6_{dd}$ is not added to the first set (the most realistic option is selected), and 3 frames are added to the second and third sets, for example $F10_d$, F13 to the second and F15 to the third block.

After the fourth stage of transmission, a copy of the $F6_{ddd}$ frame is finally added to the first set, completing its formation, and two more frames enter the memory of the AP, for example, $F14_d$ to the second block and F17 to the third block.

As a result, after the end of the fourth stage of transmission, the access point contains: a fully formed first set of frames (F1 – F7), as well as 5 frames of the second and 2 frames of the third set, which in total is equivalent to a complete set of frames.

Thus, under the considered conditions: a significant intensity of external noise – BER $=10^{-5}$ and a small block length ($k = 6$–9 frames), it can be assumed that the efficiency of the FBS method exceeds the efficiency of the VBS method, which was studied in the previous section.

Let's analyze for comparison the option of transmitting longer blocks of frames ($k = 10$) with the same significant noise intensity BER$=10^{-5}$.

At the first stage, the following set of frames is prepared for transmission: F1, F2, F3, F4, F5, F6, F7, F8, F9, F10, F11. The probability of successful transmission of a ten frames block (F2–F11) is $P_{S,k=10}=0.301$, which assumes the successful delivery of three frames plus a diagnostic frame F1. Suppose it will be F3, F5, F7.

Then, in the second stage, frames $F2_d$, $F4_d$, $F6_d$, $F8_d$, $F9_d$, $F10_d$, $F11_d$, F12, F13, F14, F15 will be prepared for transmission. Seven frames from this set were distorted in the process of the first stage of transmission, so copies of they were prepared for transmission, which were supplemented to a complete block by four new frames with consecutive numbers. A copy of the distorted frame is chosen as the diagnostic frame due to the higher probability of such a choice.

From the composition of this block, three frames will be successfully delivered to the access point. Due to the large number of the frame's copies in the set, we believe that there will be two copies and one frame from among the added ones, for example $F4_d$, $F8_d$ and F13. Thus, after the second stage of transmission, frames F1, $F2_d$, F3, $F4_d$, F5, F7, $F8_d$ from the first block and F13 from the second block will be accumulated in the buffer memory of the access point.

At the third stage of transmission, copies of distorted frames $F6_{dd}$, $F9_{dd}$, $F10_{dd}$, $F11_{dd}$, $F12_d$, $F14_d$, $F15_d$ will be used to form a block, which will be supplemented with frames F16, F17, F18, F19. The BA frame sent by the AP will contain information about distorted frames. Considering, that 4 out of 7 frames were distorted in the first stage, and in the second it was repeated with their copies, it is reasonable to choose a diagnostic frame from among them, let it be $F6_{dd}$. Then, in the third stage, will be sent the next set of frames: $F6_{dd}$_ $F9_{dd}$, $F10_{dd}$, $F11_{dd}$; $F12_d$, $F14_d$, $F15_d$; F16, F17, F18, F19. Three groups of frames, separated by the sign ";" are approximately equal in number, so let's assume that frames $F10_{dd}$, $F14_d$, F17, one from each group, will reach the AP undistorted. Thus, after the third stage of transmission, 9 frames of the first set will be accumulated in the memory of AP (two frames are missing from the full set, according to our example,

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these are F9 and F11), as well as frames F13, F14, F17 from the second set.

Copies of frames $F9_{ddd}$, $F11_{ddd}$; $F12_{dd}$, $F15_{dd}$; $F16_{d}$, $F18_{d}$, $F19_{d}$ will be included to block in the fourth stage of transmission; which will be supplemented with frames F20, F21, F22, F23. The distorted frames form three, approximately equal groups, so it is more reasonable to expect that $F9_{ddd}$ or $F11_{ddd}$ will be used as a diagnostic frame at the fifth stage. The probability of successful delivery of one of these frames to the AP is 1/10, that is, it should not be expected to be delivered in the near stages. Replenishment of the second set of frames in the memory of the AP at the fourth stage will most likely take place with three frames; at the fifth stage a maximum of two is possible. The process then becomes more and more delayed, since the fewer unsent frames of a given set remain, the less likely it is that they will be among those successfully delivered.

At the same time, it should be noted that according to the calculation carried out when $k = 10$, using the VBS method allows us to fully form the first set in AP after the third stage of transmission.

5 RESULTS

Thus, it can be concluded that in conditions of significant interference intensity (BER = 10^{-5}) and an increase in the length of the transmitted block beyond $k = 10$, the VBS method is preferable for use. This advantage is due to the fact that when using the VBS method, at each subsequent stage of transmission, the length of the transmitted block is reduced and, accordingly, the absolute number of successfully delivered frames increases (due to the increase in the probability of delivery) from this already reduced block. The convergence of the algorithm is accelerated.

In the case of FBS, the large block length results in a low delivery probability value that remains constant at each transfer stage. Therefore, the number of successfully delivered frames at each stage of transmission is small and, as calculations show, this is not compensated by the successful delivery and accumulation of frames from subsequent sets.

Let's compare these two methods when working in conditions of medium interference intensity (BER = 10^{-6}).

According to subsection 4.1, when VBS mechanism works for $k = 10$, the completion of the first set formation in access point is observed after the second stage of transmission. And then the transmission of the frames of the second set begins. The same is true for subsequent sets of frames. Two stages of transmission are required to transmit each block here. A similar situation is observed for blocks containing up to $k = 25$ frames.

For the FBS method at the first stage of transmission, the set of frames looks like: F1_F2, F3, F4, F5, F6, F7, F8, F9, F10, F11. The probability of successful block transfer is $P_{S,k=10}$=0.887, so statistically approximately 9 frames from the set F2–F11 will be successfully delivered, and, for example, F3 will be unsuccessful.

At the second stage we will receive the following set: $F3_{d}$_F12, F13, F14, F15, F16, F17, F18, F19, F20, F21 and from this block (F12–F21) approximately 9 frames will be successfully delivered to the AP too.

Thus, if we use the FBS method in these conditions, after the second stage in memory of the AP the first complete set of frames F1–F11 will be located, as well as 9 frames of the following second set, which will be formed on the third stage. By conducting a similar analysis, we find that sets 1, 2 and 3 will be formed in the AP after the fourth stage of transmission, and the entire set 4 will be added to them after the fifth stage, and so on.

Under these conditions, the use of the FBS method is more preferable.

6 DISCUSSION

We compared the efficiency of data transmission by variable and constant size blocks formed from frames using VBS and FBS mechanisms under conditions of noise varying intensity. It is shown that with a small number of frames in a block ($k = 6$) and high-intensity noise (BER = 10^{-5}), the efficiency of the FBS mechanism exceeds the efficiency of the VBS block formation mechanism. However, at the same noise level, an increase in the number of frames in a block ($k \geq 10$) makes the use of the VBS mechanism more preferable. This advantage is explained by the fact that the VBS mechanism at each subsequent stage of transmission forms a block from frames distorted at the previous stage, therefore the size of the blocks at subsequent stages decreases, increasing the number of frames successfully transmitted to the access point (due to the increase in the probability of transmitting shorter blocks). At the same time, the constant and small probability of successful transmission of a constant size block at each stage makes the probability of transmission of frames distorted at the initial stages low. This is due to both the low probability of transmission of the rather long blocks themselves and the relatively small number of copies of frames in the block that have already been distorted several times at previous stages of transmission. The above factors complicate the formation of a correct and complete sequence of frames of a given information message, significantly slowing down this process.

For medium-intensity noise (BER = 10^{-6}), the transmission of each subsequent block in the range of up to 25 frames per block using the VBS method requires the use of two stages. The application of the FBS method in these conditions shows that only the first set of frames requires the use of two stages for its complete transmission. Then, due to the accumulation of frames at the previous stages, each subsequent stage of transmission completes the formation of the corresponding set in the memory of access point. Thus, when the noise intensity decreases to BER = 10^{-6} and below, the use of the FVS mechanism becomes more effective.

The obtained results are illustrated with specific examples characterizing the formation and transmission of various frame blocks.

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These studies were conducted under the condition of a fixed probability of collisions. In the future, it is planned to continue comparing the efficiency of various mechanisms for forming frame blocks under conditions of different noise intensities, taking into account the change in the number of collisions in 802.11 networks.

CONCLUSIONS

1. A simple model used in IEEE 802.11 networks to determine the DSF throughput for transmitting frames in infrastructure domains was modified by us to transmit frame blocks of different sizes under conditions of medium and high intensity noise affecting the transmission process. The scale factors of the model for the number of frames in a block $k = 6$–40 at an average noise level corresponding to $BER = 10^{-6}$ and $k = 4$–15 for high-intensity noise at $BER = 10^{-5}$ are determined. The algorithm for calculation the network throughput has been generalized.

2. For the first time, comparative studies of VBS and FBS mechanisms used for the formation and transmission of different sizes frame blocks under medium and high noise intensity were conducted.

3. The process of step-by-step dynamic transmission of blocks with a decreasing number of frames from stage to stage, formed within the VBS mechanism, in an environment with medium and high noise intensity was studied.

The investigation of the throughput dependences on the number of frames in the FBS blocks showed the presence of local maxima, located in the region of average values of the frames number. These maxima are more pronounced at increased data transfer rates.

4. It is shown that with a small number of frames in a block ($k = 6$) and high-intensity noise ($BER = 10^{-5}$), the efficiency of the FBS mechanism exceeds the efficiency of the VBS block formation mechanism. However, at the same noise level, an increase in the number of frames in a block ($k \geq 10$) makes the use of the VBS mechanism more preferable. When the noise intensity decreases to $BER = 10^{-6}$ and below, due to the accumulation of frames at the previous stages of transmission the use of the FVS mechanism provides a wider throughput and therefore becomes more effective.

The scientific novelty of obtained results consists in determining the throughput of wireless computer networks IEEE 802.11 using the mechanisms of VBS and FBS for the formation and transmission of frame blocks under the influence of variable-intensity noise on the transmission process. The study of the dependence of through put on the number of frames in VBS blocks showed the presence of local maxima of the dependences, which are located in the region of average values of the frames number. These maximums are observed in the range of medium and high noise intensities and are more pronounced at higher data transfer rates.

The practical significance of obtained results consists in the possibility of a reasonable choice of a suitable mechanism for the formation and transmission of frame blocks in accordance with the noise level in the data transmission environment and the determination of the optimal number of frames in the block corresponding to the maximum throughput under given transmission conditions.

Prospects for further research are to study the possibility of using congestion control algorithms in fiber-optic TCP networks, when transmitting data segments using sliding windows, for use in wireless networks with the implementation of automatic regulation of the length of transmitted frame blocks and adaptation to the noise level in the transmission medium. The model created by these studies must also take into account the impact of collisions caused by active frame generation by other stations in the wireless domain.

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ОЦІНКА ЕФЕКТИВНОСТІ МЕХАНІЗМІВ ПЕРЕДАЧІ БЛОКІВ ФРЕЙМІВ В ЗАШУМЛЕНИХ КАНАЛАХ IEEE 802.11 МЕРЕЖ

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АНОТАЦІЯ

Актуальність. Об'єднання фреймів у блоки при передаванні інформації в бездротових мережах IEEE 802.11 допомагає суттєво зменшити накладні витрати і підвищити швидкість передачі. Одночасно з цим, вплив шуму зменшує ефективність такої передачі внаслідок підвищення імовірності викривлення більш довгих повідомлень. Ми порівнювали ефективність передачі даних з використанням змінного та постійного розмірів блоків з фреймів, що формуються з використанням VBS та FBS механізмів, в умовах дії шуму змінної інтенсивності.

Мета роботи. Метою цієї статті є порівняльні дослідження VBS та FBS механізмів, що використовуються для формування і передачі блоків фреймів різного розміру в умовах середньої та високої інтенсивності шуму.

Метод. Проста модель, що використовується в IEEE 802.11 мережах для визначення DCF пропускної здатності при передаванні фреймів в інфраструктурних доменах була модифікована нами для передачі блоків фреймів різного розміру в умовах середньої та високої інтенсивності шуму, що впливає на процес передачі. Ми використовуємо для передачі дискретний у часі Гаусовий канал без пам'яті. У такому каналі бітові помилки є незалежними і рівномірно розподіленими серед бітів фрейму. Визначені масштабуючі коефіцієнти моделі для кількості фреймів в блоці $k = 6–40$ при середньому рівні шуму, що відповідає $\mathrm{BER} = 10^{-6}$, і $k = 4–15$ для високого рівня шуму при $\mathrm{BER} = 10^{-5}$. Узагальнено алгоритм для розрахунку пропускної здатності мережі. Дослідження залежностей пропускної здатності від кількості фреймів у VBS блоках показало наявність локальних максимумів залежностей, які розташовані в області середніх значень кількості фреймів. Ці максимуми є більш вираженими при підвищених швидкостях передачі даних.

Результати. Показано, що при невеликій кількості фреймів в блоці ($k = 6–9$) і високоінтенсивному шумі ефективність FBS механізму перевищує ефективність VBS механізму формування блоків. Проте, при такому ж рівні шуму, підвищення кількості фреймів в блоці ($k \geq 10$) робить використання VBS механізму кращим. Ця перевага пояснюється тим фактом, що VBS механізм на кожній наступній стадії передачі формує блок з фреймів, викривлених на попередній стадії, при цьому розмір блоків на наступних стадіях передачі зменшується, підвищуючи число фреймів, успішно переданих AP (внаслідок підвищення імовірності передачі більш коротких блоків). Одночасно з цим, постійна і невелика імовірність успішної передачі блоків постійного розміру на кожній стадії робить імовірність передачі фреймів, пошкоджених на попередніх стадіях, низькою. Ситуація змінюється для шуму середньої інтенсивності. Тут передача кожного наступного блоку в діапазоні до 25 фреймів на блок з використанням методу VBS потребує двох етапів. Застосування ж методу FBS в цих же умовах показує, що тільки перший набір фреймів потребує використання двох стадій для його повної передачі. Потім, внаслідок накопичення фреймів попередніх стадій, на кожній наступній стадії передачі завершується повне формування відповідного набору в пам'яті AP. Таким чином, коли інтенсивність шуму зменшується до $\mathrm{BER} = 10^{-6}$ і нижче, використання FBS механізму стає більш ефективним. Одержані результати ілюструються специфічними прикладами, які характеризують формування і передачу різних блоків фреймів.

Висновки. У цій статті, використовуючи модифіковану нами математичну модель, проведені порівняльні дослідження ефективності механізмів формування і передачі блоків фреймів різного розміру в умовах впливу шуму різної інтенсивності на процес передачі. Узагальнено алгоритм для розрахунку пропускної здатності, визначені величини пропускної здатності при використанні VBS та FBS механізмів функціонування мережі.

КЛЮЧОВІ СЛОВА: IEEE 802.11 бездротові мережі, пропускна здатність, інтенсивність шуму, BER, блоки фреймів, VBS та FBS механізми.

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