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Evaluation of the Limitation of Operational Parameters of the IEEE 802.11 ac Network in the 20MHz Channel

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Abstract*—IEEE 802.11 wireless network technologies are widely used to create corporate and personal local networks for data exchange and access to Internet resources. The main principle of operation of IEEE 802.11 networks is the principle of competitive access, according to which all wireless network users have the same access rights to the information transmission environment. This method of access leads to the occurrence of collisions in networks with a large number of users, which complicates the process of network functioning and leads to the degradation of quality indicators. The purpose of the study is to estimate the limit values of the operational characteristics of the IEEE 802.11 ac wireless network in the mode with the highest transmission rate (MCS8) in a frequency channel of 20 MHz with one spatial stream, provided that the network has a significant number of active stations with a saturated load. An alternative model of processes in IEEE 802.11 networks based on the concept of a virtual competitive window is used for research. According to the concept of virtual contention window (VCW), the process of data transmission in a network with competitive access is considered as a quasi-stationary process. Numerical data were obtained and graphs of channel bandwidth, transmission delay, and delay non-uniformity were given in the presence of one to sixteen active stations with a saturated load in the network, in the case of transmission of frames with a data volume of 512 or 1500 bytes. The maximum possible bandwidth of the channel with a frequency band of 20 MHz (68.387 bit/s) was determined, in the case of using frames with the maximum load (11454 bytes) provided by the standard. Estimated data on the number of collisions occurring in a network with a saturated load and the number of frames transmitted at various stages of channel access are also provided. The frame transmission delay increases almost proportionally to the number of active stations and varies from 0.605 ms to 5.293 ms, in the case of loading all data frames of 512 bytes, and from 0.785 to 6.41 ms, in the case of a load of 1500 bytes, for changes in the number of active stations in the network from 2 to 16. The unevenness of the delay exceeds the average delay and grows non-linearly, in the case of an increase in the number of active stations from 1 to 6 (CW_{min}=15), and linearly — with a further increase in the number of stations (over 6). The obtained results are useful for reasonable planning of wireless networks and configuration of network equipment parameters.

Keywords: wireless network; jitter; delay; bandwidth; IEEE 802.11ac standard.

I. Introduction

IEEE 802.11 standard wireless local networks (Wi-Fi) have become widely used as a means of fast data transmission between network subscribers and a means of accessing Internet resources. Since the adoption of the IEEE 802.11 standard in 1997, the technologies used in this standard have undergone significant changes in order to improve. In general, their improvements are aimed at increasing network throughput and improving quality indicators [1-4]. Within one IEEE 802.11 standard, each of its modifications is framed by a separate specification, which is an integral part of the standard. Currently, the most common specifications are 802.11 a, g, n, ac. Equipment for wireless networks according to the 802.11 ax specification is being introduced, which is significantly different from previous versions due to the use of the OFDMA multiple access system.

An important feature of IEEE 802.11 technologies is backward compatibility. That is, the equipment operating according to the new specifications is compatible with the equipment of previous versions, however, this leads to a decrease in the bandwidth of the network due to its adaptation to devices of earlier specifications. The main principle of operation of IEEE 802.11 networks is the principle of competitive access, according to which all wireless network users have the same access rights to the information transmission environment. This method of access leads to the occurrence of collisions in networks with a large number of users, which complicates the process of network functioning and leads to the degradation of quality indicators [5-10].

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The IEEE 802.11 ac specification is an evolutionary development of the IEEE 802.11 n specification. This specification provides: the mandatory ability of network equipment to use a frequency band of 80 MHz instead of 40 MHz (160 MHz is optional), an increase in the number of spatial streams to eight instead of four in IEEE 802.11n, the use of a higher modulation frequency (256-QAM instead of 64-QAM) carrier frequencies of OFDM symbols [1, 2].

Many works are devoted to research and modeling of processes in IEEE 802.11 n/ac wireless networks, for example [11-15]. The works are aimed at researching the impact of individual improvements on operational characteristics and service quality parameters. In particular, the work [11] investigated the processes of data transmission in a mixed network, and the main attention was paid to the influence of low-speed stations on the speed of data transmission by high-speed stations. At the same time, the impact of collisions on the functioning of the network remains neglected. The work [12] is devoted to the study of the influence of aggregation functions and MIMO on the bandwidth of the IEEE 802.11 ac network, on the value of packet transmission delay and on the value of the unevenness of this delay (jitter). This work also does not take into account the process of the occurrence of collisions, and uses scenarios of network functioning that are quite dubious (200, 400, 600 active stations per one access point). In [13], the results of field tests of the spectral characteristics of signal flows in the uplink and downlink radio frequency channels of IEEE 802.11 ac networks are given. In [14], the results of the study of the operating characteristics of the IEEE 802.11 ac network using the currently most common mathematical model of a wireless channel are presented. This model based on the time slot concept, which has significant limitations regarding the probability of collisions in a wireless channel. In particular, we are talking about the limited probability of transmitting a data frame τ in a randomly selected time slot. In the model mentioned above, this probability is determined by the ratio [14]:

$$\tau = \frac{2(1-p_c)}{(1-2p_c)(W-1)+pW\left(1-(2p_c)^m\right)} \qquad (1)$$

where p_c is the probability of a collision; W is the minimum value of the competitive window (CW_{min}); m is the number of the stage of access to the environment.

It is obvious that in the case when $p_c = 0.5$, the denominator of formula (1) becomes zero, and the expression itself loses its meaning. But with this probability of collisions, in reality the probability of transmitting a data frame is not zero, and the data frame will be transmitted. The above-mentioned model can be used for scenarios of network operation with a low probability of collisions and a small number of stations.

The effect of different types of encryption (WEP, WPA, WPA2) on the bandwidth of the IEEE 802.11 ac local network was investigated in [15]. The network in which the information flow from the server is transmitted to the image playback device through an access point has been investigated. This work does not indicate which mode of the network was investigated (what is the width of the frequency band, the number of spatial streams, MCS, the amount of data in one frame). Additionally, in [15] it is not taken into account that during the transmission of a frame from the sender to the recipient, the channel is used twice: from the server to the AP and from the AP to the recipient.

Although in general the number of publications devoted to the functioning of IEEE 802.11 ac networks is quite large, however, a detailed analysis of the processes associated with competitive access to the channel is approximate. Taking into account the great interest of users in the use of IEEE 802.11 wireless networks and in particular the IEEE 802.11 ac specification, further research of processes in these networks is an urgent task.

The purpose of this study is to evaluate the performance of an IEEE 802.11 ac wireless network in the highest transmission rate (MCS8) mode in a 20 MHz frequency channel with a single spatial stream, under the condition that the network has a significant number of active stations with a saturated load. An alternative model of processes in IEEE 802.11 networks based on the concept of a virtual contention window was used for the research. The obtained results are useful for reasonable planning of wireless networks and configuration of network equipment parameters.

II. RESEARCH METHODOLOGY

The study of processes in the 802.11 ac wireless network was carried out using the concept of a virtual competitive window [17], which does not have the disadvantages of the time slot concept mentioned above. According to the concept of virtual contention window (VCW), the process of data transmission in a network with contention is considered as a quasi-stationary process. The scenario of the operation of the network is considered, in which a frequency channel of 20 MHz in the 5 GHz range is used, N stations with a saturated load are active in the network at the same time, all stations transmit data blocks of the same size with a volume of 512 or 1500 bytes. During the study, the following parameters were determined: the bandwidth of the wireless network, the average delay in the transmission of data frames, the unevenness of the delay, depending on the number of active stations with a saturated load in the network, and some related characteristics. The study considered scenarios with the participation of two to sixteen active stations in the network.

The limitation of the maximum number of stations is caused by a significant degradation of the quality indicators of the network, if the number of stations with a saturated load exceeds the value of the minimum competitive window.

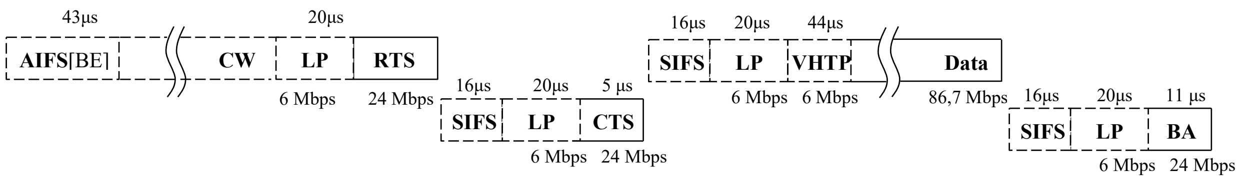

Fig. 1 Time distribution in the mode of station access to the medium for data block transmission [1]

III. BANDWIDTH OF A WIRELESS CHANNEL IN THE ABSENCE OF COMPETITION

First, let's determine the bandwidth of the wireless channel when there is one active station with a saturated load in the network, transmitting data towards the access point for a long time. We assume that the station accesses the channel according to the general rules and every time after completing the transmission of the current data frame, it loads the countdown counter with a random number from the set 0, ..., CW_{min} to form access with a delay provided by the standard procedure. Choosing any number from the specified range is equally likely, so if a large number of frames are transmitted, the average CW delay due to the countdown counter will be $CW_{min}/2$.

To determine the bandwidth of the channel, we will use the common ratio:

$$S = \frac{E[PL_1]}{E[T_{PL1}]} \tag{2}$$

where $E[PL_1]$ – average payload of one frame (512 or 1500 bytes); $E[T_{PL1}]$ – average time of transmission of one data frame.

To determine $E[T_{PL1}]$, let's use the obvious ratio (2), which corresponds to the distribution of time intervals in the cycle of access to the channel, Fig. 1.

In Fig. 1, traditional notations are used: AIFS – interframe arbitration interval, CW – contention window, LP – preamble of previous specifications, RTS – transmission request frame, SIFS – short interframe interval, VHTP – preamble of high-speed mode, Data – data block, BA – confirmation frame of the received data frame.

Taking into account the average delay $CW = CW_{min}/2$ = 7.5σ before the start of RTS frame transmission, the formula for determining the data frame transmission time by one station will take the form:

$$E[T_{PL1}] = 7{,}5\sigma + T_{RTS} + SIFS + T_{CTS} + \\ + SIFS + T_{MPDU} + SIFS + T_{ACK} + DIFS. \tag{3}$$

For a correct calculation, it is necessary to specify the duration of the intervals shown in Fig. 1. Instead of the arbitration interval AIFS[BE], we consider the usual interframe interval DIFS = 34 μs. The duration of the time slot used to measure the delay interval is σ = 9 μs. It is also necessary to take into account all service information and user data, which are transmitted using OFDM multi-frequency modulation with a duration of one symbol of 4 μs. That is, the duration of each frame is a multiple of 4 μs. The duration of the RTS and CTS frames together with the preamble transmitted at 24 Mbit/s (one of the possible standard rates from the set of 6, 12, 24 Mbit/s) will be 28 μs. The duration of the answer frame (BA) together with the preamble will be 32 μs.

Separately, we will calculate the duration of the data frame, namely: that part of it that will be transmitted at the highest speed (86.7 Mbit/s). In the high-speed mode (VHT) in the IEEE 802.11 ac network, a short guard interval (0.4 μs) is used in the OFDM symbol to transmit a block of data and, as a result, the duration of the symbol is not 4 μs, but 3.6 μs. Let's take into account that in the frequency channel of 20 MHz it is provided by standard to use a grouping of 56 OFDM carrier frequencies, of which 52 carrier frequencies are intended for transmitting useful data, and four carriers for pilot signals [2]. Let's determine the duration of the interval of only data frame transmission. The duration of the preamble of the data frame, Fig. 1, in the case of using one spatial stream, is minimal and amounts to 44 μs [1]. For further calculations, it is necessary to determine the time of transmission of the data block (Data).

We will give the calculation for the case when the data block contains 512 bytes. We assume that the UDP protocol is used at the transport level. During the calculation, the most general case was considered, in which 8 bytes are added to the data packet at the network level with accordance to the SNAP subnet access protocol, and 8 bytes of UDP service information are added at the MAC level. Then 528 bytes or 4224 bits will have to be transmitted through the channel. For transmission, we will use the fastest mode MCS 8 provided for the 20 MHz channel: QAM-256 (eight bits per carrier frequency), CR=3/4 (convolutional code speed). Separately, it can be noted that the highest speed MCS 9 modulation and coding scheme for the 20 MHz channel is not provided by the standard. Taking into account the forward coding, one data frame will contain 4224·4/3 =

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5632 (bits). One OFDM symbol can transmit 8·52 = 416 (bits). Thus, to transmit the entire block containing 512 bytes of useful data, it will be necessary to use 5632:416=13.54→14 (characters) without taking into account the preamble. The duration of the data block transmission interval will be 3.6 µs ·14=50.4 µs. If user data blocks of 1500 bytes are transmitted, the total number of bits will be (1500+16)·8·4/3=16171. To transmit this number of bits, 16171:416=38.87→39 (symbols) are needed. The duration of the transmission of these symbols will be 140.4 µs.

Taking into account the duration of the time intervals (3), the duration of the cycle of transmission of a frame with 512 bytes of user data will be 331.9 µs. And in the case when the block of user data is 1500 bytes will be 421.9 µs.

The bandwidth of the channel will be S1_512 = 512·8:331.9 = 12.34 (Mbit/c), if 512 bytes of information are transmitted in one frame and S1_1500= 1500·8:421.9 = 28.44 (Mbit/c), in case of transfer of 1500 bytes of information.

To determine the maximum possible transmission speed between the station and the access point, we will make a calculation for the scenario in which the station continuously transmits frames with the maximum possible data blocks (11454 bytes) during a certain time interval. To transmit such a block of data, 294 symbols with a duration of 3.6 µs will be required. The data block transmission time will be, together with the preamble, 44+1058.4=1102.4 (µs). Taking into account the control frames and the waiting interval, the duration of the transmission cycle, Fig. 1, of the largest data frame is 1339.9 µs. In this scenario, the bandwidth of the channel is S1_11454=68.387 Mbit/s.

For comparison, we note that speed of data block transmission in the MCS 8 mode considered by us is 86.7 Mbit/s. That is, the effective bandwidth of the channel in case of maximum load of the data frame is 78.88% of the signal speed.

We will use the value of the received channel bandwidth as a reference point for evaluating the influence of the number of active stations on the quality characteristics of the channel.

IV. NETWORK CHARACTERISTICS IN CONTENTION ACCESS MODE

Now let's analyze the bandwidth of the channel and determine the quality indicators of the network, assuming the simultaneous activity of N stations in the network. We will assume that all stations have the same technical characteristics and transmit their packets in BE mode (best attempt), that is, without prioritization.

In the event of a fight for access to the channel in competitive mode, collisions will occur due to the simultaneous transmission of packets by two or more stations. According to the 802.11 ac specification, the minimum and maximum values of the competitive window are, respectively, CW_{min} = 15, CW_{max} = 1023 [18]. The CW_{min} value defines the initial set {0,1,2,…, CW_{min}} from which the active network stations randomly select a number to load the countdown counter. If the active station will continuously collide, it can make seven consecutive attempts to access the channel and each time it will randomly

select a number for the countdown from the doubled set of numbers according to the algorithm CW: = 2(CW+1)-1. This contention mechanism of Distributed Coordination Function (DCF) is the primary contention mechanism in IEEE 802.11 networks. From the logic of operation of the 802.11 ac network in DCF mode, it follows that a collision can occur only during the transmission of an RTS frame.

To find the limit values of the quality indicators in a network with a large number of active stations, we first determine the value of the virtual contention window VCW for cases where there are two to sixteen active stations with a saturated load in the IEEE 802.11 ac network.

The virtual contention window VCW is a stochastic parameter of a Wi-Fi wireless network in a saturated load mode, which is quantitatively equal to the average number of elementary time intervals (time slots) during which the countdown counter counts down the delay interval after the completion of the transmission of the previous frame until the start of the transmission of the next data frame [19].

According to the concept of a virtual competitive window, the process of functioning of a wireless network channel with a saturated load is considered as a quasi-stationary process.

An important characteristic of the above mode is the probability of a pc collision that a station that has access to the channel for transmitting a block of data can get into. In [17], an approximate calculation ratio for the probability of collisions between two network stations is substantiated:

$$p_c^{(R)} = 1-\left(1-p_{c1}\right)^{N(R)-1} \tag{4}$$

where $p_{c1} = 1/(CW_{\min}+1) = 1/CW_1$ is the probability of a collision between this station and this one from other stations of the network; $N(R)$ – the number of active network stations that can compete for access to the channel after the end of the current time interval, taking into account collisions; R is the number of retries in case of collisions during frame transmission (R = 6).

During further calculations, we consider that $N(R) \approx N$, since the number of active stations directly participating in the competition for access to the channel changes slightly [17].

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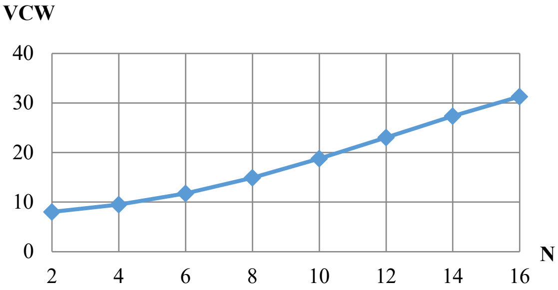

Fig. 2 Value of VCW in units of time slots as a dependence of N

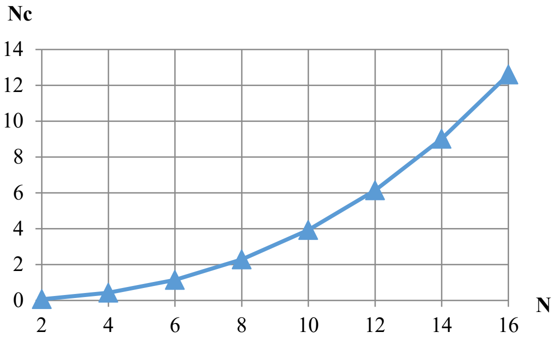

Fig. 3 The number of collisions during the implementation of one virtual competitive window

The size of the virtual competitive window can be determined by the formula:

$$VCW = \frac{CW_1 \cdot (1-p_c)}{2} \cdot \sum_{i=1}^{R+1} (2p_c)^{i-1} . \quad (5)$$

The bandwidth of the channel in the specified mode can be determined by the ratio:

$$S = \frac{N \cdot E[PL_1] \cdot P_s}{T_{VCW}} \quad (6)$$

where $P_S = 1 - p_c^{R+1}$ is the probability of successful data frame transmission.

The time of the contention window realization is defined as:

$$T_{VCW} = N \cdot \overline{T}_{PL} + N_c \cdot \overline{T}_c + n_{id} \cdot \sigma \quad (7)$$

where N_c is the number of collisions during the implementation of the virtual contention window; $\overline{T}_{PL}$ and $\overline{T}_c$ is the duration of the transmission cycle of one data frame and the duration of the collision, respectively; $n_{id} = VCW$ is the number of free time slots during the implementation of the virtual contention window.

The number of collisions that will occur during the virtual window is determined by the formula [17]:

$$N_c = p_c \cdot \frac{N}{2} \cdot \frac{1-p_c^{R+1}}{1-p_c} \quad (8)$$

The results of calculations of the characteristics of the wireless channel of the IEEE802.11 ac network with a frequency band of 20 MHz in the saturated load mode using the MCS8 modulation and coding scheme are given in Table 1.

The graphical dependences of $VCW = f1(N)$ and $N_c = f2(N)$ are shown in Fig. 2 and Fig. 3 respectively.

Estimated graphs of the dependence of the bandwidth of the wireless network, depending on the number of active stations with a saturated load, are shown in Fig. 4, Fig. 5 for a uniform load of data frames of 512 and 1500 bytes, respectively. Lines S1_512 and S1_1500 indicate the bandwidth of a wireless channel 802.11 ac in which one station continuously transmits frames with a payload of 512 bytes or 1500 bytes, respectively.

The average delay of the arrival of data frames will be equal to the implementation time of the virtual competitive window (7). The numerical values of this delay, in the case of a uniform load of 512 bytes in each frame, are given in the Table 1, and the graphic dependence in Fig. 6.

Now let's define the non-uniformity of the delay (jitter). To determine the unevenness of the delay, we will use the relations given in [2]. Based on the definition of jitter $\sigma^{(\tau)}$ as the averaged difference between the maximum $\tau^{(max)}$ and minimum delay $\tau^{(min)}$, it can be defined as twice the root mean square deviation of a random variable:

$$\sigma^{(\tau)} = \tau^{(max)} - \tau^{(min)} = 2\sqrt{D(\tau)} \quad (9)$$

The delay variance $D(\tau)$ is proposed to be calculated using the values determined within the virtual competitive window for successfully transmitted frames at each stage of channel access.

Table 1 IEEE 802.11ac 20 MHz wireless channel characteristics

N	p_c	VCW	Nc	T_{VCW}^{512}, µs	S_{512}, Mbps	T_{VCW}^{1500}, µs	S_{1500}, Mbps
2	0,0625	8,036	0,067	605,255	13,535	785,254	30,563
4	0,1760	9,519	0,427	1169,764	14,006	1529,722	31,377
6	0,2758	11,772	1,142	1763,176	13,932	2302,24	31,260
8	0,3635	14,905	2,282	2390,852	13,674	3104,312	30,853
10	0,4406	18,779	3,925	3056,364	13,304	3930,445	30,308
12	0,5083	23,067	6,149	3761,613	12,841	4768,249	29,679
14	0,5679	27,367	9,023	4507,34	12,296	5600,975	28,989
16	0,6202	31,307	12,602	5293,491	11,676	6410,825	28,245

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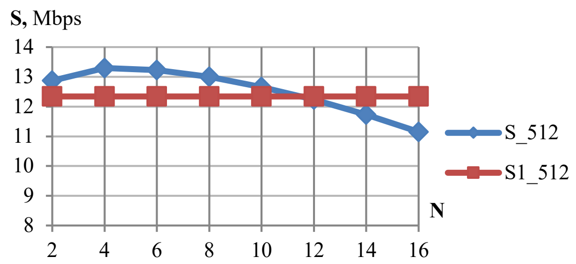

Fig. 4 The bandwidth of the channel (S_512) in the case of a frame payload of 512 bytes

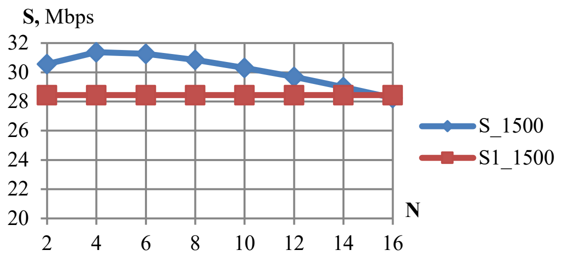

Fig. 5 The bandwidth of the channel (S_1500) in the case of a frame payload of 1500 bytes

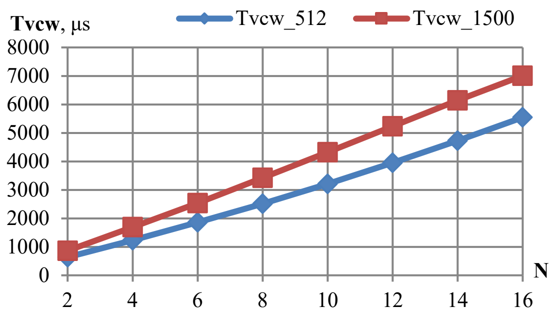

Fig. 6 The dependences of frame delay, in the case of a uniform load 512 or 1500 bytes

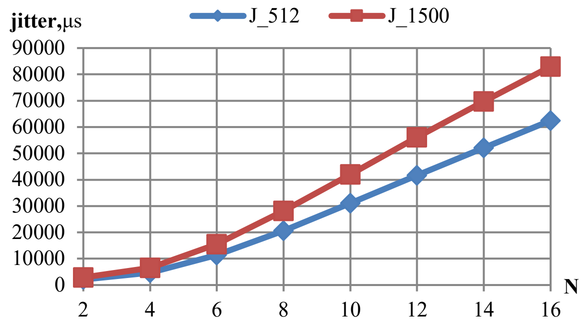

Fig. 7 Dependence of jitter on the number of active stations for two values of payload in frames

$$D(\tau)=\frac{1}{N^{(b)}}\sum_{j=1}^{m+1} N_j\cdot(\tau_j^*-\bar{\tau})^2 \qquad (10)$$

where $N^{(b)}$, N_j are the total number of transmitted data frames and the number of frames transmitted during the *j*-th attempt during the implementation of the virtual contention window; τ_j^* is the maximum delay in case of successful data frame transmission during the *j*-th attempt to access the wireless channel, $\bar{\tau}$ is the average delay.

$$\tau_j^*=(N\cdot P_s\cdot\bar{T}_{PL}+N_c\cdot\bar{T}_c)\cdot \frac{2^{j-1}\cdot(CW_{\min}+1)-1}{VCW}+ +\sigma\cdot 2^{j-1}\cdot((CW_{\min}+1)-1) \qquad (11)$$

Formula (11) allows you to determine the maximum delay τ_j^* for a frame that will fall into (j-1) collision and the station that transmits it will load into the countdown counter the maximum number from the set obtained according to the binary exponential law.

The graph of the dependence of the unevenness of the delay on the number of active stations in the network for the case when each station transmits a data frame with 512 bytes of user data is shown in Fig. 7.

In the Table 2 shows as an example the results of calculating the number of frames and the maximum delay of transmitted frames at various stages of access to the channel.

TABLE 2 CHARACTERISTICS OF SUCCESSFUL FRAME TRANSMISSION ATTEMPTS AT DIFFERENT STAGES OF CHANNEL ACCESS

N	2		8		12		14		16	
j	N_j	τ_j^*, µs	N_j	τ_j^*, µs	N_j	τ_j^*, µs	N_j	τ_j^*, µs	N_j	τ_j^*, µs
1	1,875	720,02	5,092	1503,159	5,9004	1523,82	6,0494	1509,28	6,0768	1510,85
2	0,1171875	1488,04	1,850942	3106,51	2,999173	3149,24	3,435454	3119,18	3,768831	3122,44
3	0,0073242	3024,08	0,6728174	6313,23	1,524499	6400,06	1,950994	6338,98	2,337429	6345,60
4	0,0004579	6096,16	0,2445691	12726,67	0,774893	12901,72	1,10797	12778,58	1,449677	12791,93
5	2,861E-05	12240,33	0,0889009	25553,55	0,393878	25905,02	0,629216	25657,77	0,899088	25684,581
6	1,7881E-06	24528,66	0,0323155	51207,30	0,200208	51911,63	0,357332	51416,17	0,557614	51469,886
7	1,1176E-07	49105,32	0,0117467	102514,82	0,101766	103924,84	0,202929	102932,95	0,345832	103040,49
Σ	1,9999999		7,9932916		11,89479		13,7333		15,435268	

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V. Analysis of the obtained results

The bandwidth of a wireless channel of 20 MHz for the payload is significantly different from the physical rate of transmission of useful data, due to significant waste of time for channel maintenance. Thus, in the case of a payload in a data frame of 512 bytes, the maximum calculated payload transmission rate is 12.879 Mbit/s (four active stations with a saturated load), which is 14.86% of the maximum physical data transmission rate provided for one spatial channel. In the case when the payload in the data frame is 1500 bytes, the maximum bandwidth of the channel is 28.705 Mbit/s, which is 33.11% of the maximum physical data transfer rate.

The average delay in the transmission of data frames increases with the increase in the number of active stations in wide range. Thus, in the case of loading one data frame of 512 bytes, the average delay with two active stations in the network is 605 µs, and with 16 active stations – 5293 µs, and it increases linearly with an increase in the number of stations, Fig. 6. As the payload increases to 1500 bytes, the average delay changes from 785 µs for two stations to 6410 µs for sixteen stations.

Depending on the number of active stations in the network, the non-uniformity of the frame delay varies in a wide range, Fig. 7. The non-uniformity of the delay exceeds the average delay by about ten times.

With the increase of active stations in the network, the probability increases that not all stations will be able to transmit their frames using the seven provided attempts, table.2, which will lead to an increase in the heterogeneity of the delay.

Conclusions

The application of the IEEE 802.11 ac wireless network parameter calculation method, based on the concept of a virtual competitive window, made it possible to obtain a quantitative assessment of networks operational parameters.

As the number of active stations in a wireless network increases, the total throughput increases in the interval from one to four stations, due to the reduction of the average value of the waiting interval before accessing the channel, and then decreases, the faster, the more stations in the network, due to collisions.

The frame transmission delay increases almost proportionally to the number of active stations and varies from 0.605 ms to 5.293 ms, in the case of frames payload equal to 512-byte data frames, and from 0.785 to 6.41 ms, in the case of a payload equal to 1500 bytes, for changes in the number of active stations in the network from 2 to 16. The delay unevenness exceeds the average delay and increases non-linearly when the number of active stations increases from one to six (CWmin = 15), and then increase linearly when the number of active stations increases beyond six.

Based on the obtained results, it is possible to generalize that when evaluating the bandwidth of a wireless network, it is necessary to take into account the structure of the flow (sizes of data blocks) and the structure of the connection. If data is transferred between a station and an access point, then the maximum data transfer rate will take place, and if data is transferred between two stations of the same network, then the maximum possible transfer rate is halved, since there are two connections, and two acts of transfer must be performed using the same channel: from the sender's station to the AP and from the AP to the receiver's station.

Further research should be directed to the modeling of processes in networks with several spatial flows, modeling of processes in an environment with obstacles and interferences, as well as to the evaluation of the effectiveness of the application of multimedia traffic prioritization algorithms.

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Дослідження обмежень робочих параметрів мережі IEEE 802.11 ас в каналі 20 МГц

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***Анотація*—Метою дослідження є оцінити граничні значення експлуатаційних характеристик безпроводової мережі IEEE 802.11 ас в режимі з найбільшою швидкістю передавання (MCS8) у частотному каналі 20 МГц з одним просторовим потоком, за умови наявності в мережі значної кількості активних станцій з насиченим навантаженням. Для дослідження застосовано альтернативну модель процесів у мережах IEEE 802.11, що ґрунтується на концепції віртуального конкурентного вікна. Отримано числові дані й наведено графіки залежності пропускної здатності каналу, затримки передавання та нерівномірності затримки за наявності в мережі від однієї до шістнадцяти активних станцій з насиченим навантаженням, у разі передавання кадрів з обсягом даних 512 або 1500 байтів. Визначено максимально можливу пропускну здатність каналу з частотною смугою 20 МГц (68,387 біт/с), у разі застосування кадрів з максимально великим навантаженням (11454 байти), передбаченим стандартом. Наведено також розрахункові дані про кількість колізій, що має місце в мережі з насиченим навантаженням і кількість кадрів, переданих на різних етапах доступу до каналу. Одержані результати корисні для обґрунтованого планування безпроводових мереж і налаштування параметрів мережного обладнання.**

Ключові слова: бездротова мережа; джитер; затримка; пропускна здатність; стандарт IEEE 802.11 ас.