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The Method of DCF Simulation and Analysis for Small Wi-Fi Networks

Summary

WLAN networks have become very popular at home and in small offices. The wireless network users need the high throughput, but this throughput is decreased by many factors. These factors include primarily interference from another wireless devices and Wi-Fi protocol legacy. The authors analyse Mac layer factors which diminish the network throughput. The DCF algorithm is analysed in details, too. The simulations incorporating Monte Carlo method have been performed to simulate Wi-Fi network in the time domain. The 5 GHz band network with a variable number of stations is examined to check how the station number affects DCF parameters. The dead time is calculated for different data rates to analyse how this parameter reduces the maximum network throughput.

Key words: WLAN network, 802.11n, DCF, MAC sublayer, access to media in Wi-Fi network.

JEL codes: C61

Introduction

WLAN (Wireless LAN) networks, based on IEEE 802.11n standard (IEEE 802.11 2012), have become very popular in such different types of networks like the big corporate networks and small office and private home networks. And in these both types of networks users need the high throughput in their networks. The users exchange a huge amount of data in the corporate networks, using databases and data consuming applications. But the users of small home networks also need to achieve high throughput, because of downloading many multimedia files from the Internet, using video on demand and social networks to exchange films, video blogs and photos with their friends.

From its beginning 802.11 standard has still been evolved up today. The network throughput and coverage were increased by every successive standard amendment, starting from 802.11b through 802.11a and 802.11g until to 802.11n, 802.11ac, 802.11ad (IEEE 802.11 2012). The 802.11n version is the most popular nowadays. In this version the MIMO (Multiple Input Multiple Output) communication system was introduced. It means that receiver and transmitter can use one, two, three or four antennas and transmit up to four spatial streams of data. Another improvement is channel width of 40 MHz. In previous versions the 20 MHz channel has been used. All these improvements results in very high throughput (IEEE 802.11 2012, Juniper 2011). The theoretical possibility is up to 600 Mbit/s for MIMO schema of 4x4 antennas and 40 MHz channel. But on the other hand, the real home networks use 1x1 SISO (Single Input Single Output) schema or at most 2x2 MIMO schema. The most popular are laptops, tablets or mobile phones with one antenna and PCs with two antennas nowadays. So in home networks MIMO schema higher than 2x2 are not achievable in practice now. Such limitation causes that maximum achievable throughput in home wireless network build on 802.11n standard is 65 MHz for SISO model with 20 MHz channel and 135 Mbit/s for SISO model with 40 MHz channel. The third improvement, introduced in 802.11 amendment is the possibility of using shorter guard intervals between symbols, what increased the throughput a little – up to 72.20 MHz and 150 MHz in mentioned above schemas. If we consider 2x2 transmission schema (two spatial streams) one can achieve respectively 130 Mbit/s in 20 MHz channel and 270 Mbit/s in 40 MHz channel. The shorter guard intervals using increases the network speed up to 144 Mbit/s and 300 Mbit/s respectively.

The very basic problem with wireless networks is that the throughput defined in the standard is the maximum theoretical throughput. WLAN network features (Dolińska et al. 2014) causes that the practical throughput, i.e. throughput achieved in real networks, is about the half of the theoretical and what is important also – the maximum throughput can be achieved only in very good transmission conditions (Ni 2004; Ha 2011; Ha 2012). The shorter guard intervals can be used only in good channel conditions, what is rarely fulfilled in buildings, i.e. in home networks. Furthermore high speed communication demands advanced modulation schemas, what is also achievable in good radio channel conditions. But one of the most important speed limitation property of 802.11 standard is MAC communication schema. In DCF schema (basic for WLANS) the obligatory time intervals between frames must be used. The IFS (interframe spaces) named SIFS and DIFS are shown in Fig. 1. The TBO (backoff time) before every data frame is also obligatory (Fig. 1). Both this additional time separators further reduces the practical network throughput.

In this article the authors present the analysis of the factors in MAC layer, that reduce the high theoretical throughput. The method of simulation, based on the Monte Carlo method is utilized, which allows to simulate systems using random sampling (TBO value is random) and real parameter values. The article describes DCF (Distributed Coordination Function) algorithm in details and simulation assumptions. 802.11n standard can work in band of 2,4 GHz and 5 GHz, but the second one is advised for many reasons. The analysis is performed for WLAN working in 5 GHz band. The simulation result and analysis are presented. The summary of the paper is included in the last section.

DCF analysis methods

DCF method was introduced in the first version of 802.11 and has been used until today (IEEE 802.11 2012). This media access method was the subject of analysis, researches and improvement proposals from its beginning (e.g. Bharghavan 1994, Natkaniec 2000, Manshaei and Hubaux 2007). One of the first improvement propositions was the MACAW protocol (Bharghavan et al. 1994), which introduced improved MACA access method with RTS-CTS message exchange. MACAW method proposed new backoff method, which used the same backoff counter by all stations in the wireless network, because backoff counter should reflect the level of contention. In its author's opinion this solution improved the fairness of contending stations. Unfortunately, this method was too difficult to be implemented in real network protocol. In Wi-Fi networks all the stations are independent from each other and copying the backoff counter to the each station is difficult.

The another issue of DCF, which was investigated by the researchers, was the problem of contention window minimum (CWmin) and maximum (CWmax) values choosing. This problem was developed inter alia by Natkaniec and Pach (Natkaniec and Pach 2000). The standard specifies separately the values of CWmin and CWmax for each kind of physical layer. The analysis was performed for 802.11b standard with 2 Mbit/s throughput. The authors analyzed effective throughput and mean delay versus offered load. It turned out that these parameters depend not only on the contention window length but also on the number of stations in the network.

The backoff algorithm was also analyzed by many other researchers. The new backoff algorithm was proposed by Deng et al. (Deng et al. 2004). Their proposition is named Linear/Multiplicative Increase and Linear Decrease (LMILD). It uses linear contention window (CW) decrease mechanism to avoid channel domination, instead of the reset mechanism of the BEB (Binary Exponential Backoff) scheme. Then stations use the additional piece of information, i.e. they must listen for collision. The proposed method lies in the fact that colliding nodes increase their contention windows multiplicatively, while other nodes overhearing the collisions increase their contention windows linearly. After a successful transmission, all nodes decrease their contention windows linearly. The key is to select proper coefficient by which CW is increased. The fairness in the wireless network depends on these coefficient values.

The next article (Suhane et al. 2011) analyses a performance of mobile ad hoc network. The network performance is decreased by the BEB algorithm and fast-growing retransmission delays for the backlog traffic.

All these mentioned analysis were performed for previous versions of Wi-Fi network, like 802.11b, 802.11a or 802.11g. It would be interesting to analyze DCF method in 802.11n WLANs.

DCF simulation assumptions and algorithm

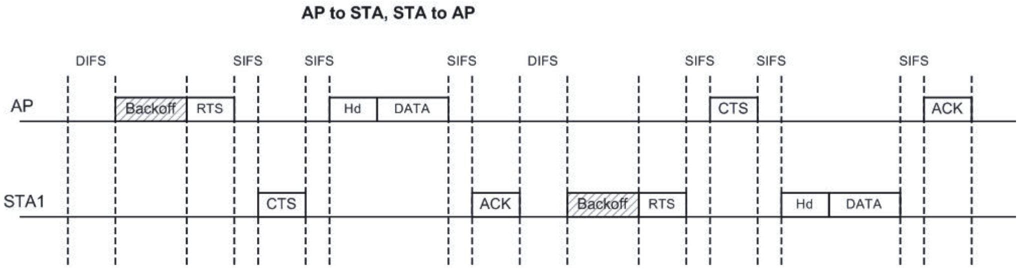
To prepare calculations of dead time in Wi-Fi networks the authors prepared simulations incorporating Monte Carlo method. This method relies on repeated random sampling to obtain numerical results (Dolińska et al. 2014).

Simulation assumptions

The authors prepared simulations of DCF method as with some assumptions made to make this simulation manageable and workable. We simulate DCF communication scheme, which is the basic MAC access method in Wi-Fi networks. In our simulations we take into account only data frames and some necessary control frames, like RTS, CTS and ACK (obligatory acknowledge frame). We do not use management frames.

Fig. 1

The example of communication in simple network



Source: own preparation.

One communication session includes RTS and CTS frames exchange, one data frame transmission and obligatory ACK frame transmission. The example of such session is presented in Fig. 1. Data frame time (T_{FR}) includes time needed for sending data and additional PHY header. All frames are separated by obligatory IFSs: DIFS (or EIFS) and additional backoff time TBO before RTS, SIFS before CTS, data and ACK frames. TBO is the result of multiplying of value drawn from (0, CW) interval and slot time for 802.11n standard (IEEE 802.11 2012, Natkaniec and Pach 2000):

$$\mathrm{TBO = INT(\ random\_value\_from\_interval(0, CW)) * Slot\_time} \qquad (1)$$

CW changes from CWmin equal to 15 to CWmax equal to 1023 (IEEE 802.11 2012). One successful communication session lasts T_{tots} time, which is equal the sum of the following time intervals: one DIFS, TBO, three SIFSs and time needed for RST, CTS, data frame and ACK sending (Dolińska et al. 2014). When two or more stations draw the same minimum TBO value, the collision occurs. In this case of communication scheme RTS frames collide with each other, but the stations must wait for lack of CTS answer to recognize collision. So in the case of collision the session lasts T_{totc} time, which is equal the sum of the following time intervals: DIFS, TBO, SIFS and time needed for RST and CTS frames sending

(Dolińska et al. 2014). The time T_{totc} is shorter than in the case of communication without RTS/CTS frames exchange. All these time intervals are presented on Fig. 1. So the analysis were conducted for DCF with RST/CTS communication schema. One communication cycle has contained 200 sessions.

The next assumptions concern the packet exchange: the packet throughput and packet length in one communication simulation is constant. In this case T_{ACK} value is constant and depends on the packet rate. T_{FR} is constant also and depends on packet rate and packet length. In the DCF method all IFSs are constant also for chosen standard amendment (IEEE 802.11 2012). In our simulations we use two frame lengths. The first one is typical Ethernet frame of length 1540 bytes (with Wi-Fi frame header) and the second is aggregated frame of length 3880 bytes. In this article we describe simulation prepared for 802.11n, working on 5 GHz band with 20 MHz channel width. All radio channel parameters and IFS values are collected in Table 1.

Table 1

Radio channel parameters and IFS values

Parameter name	Parameter value
Band	5 GHz
Radio channel width	20 MHz
Antenna configuration	SISO, MIMO 2x2
Slot time	9 [μs]
SIFS	16 [μs]
DIFS	34 [μs]
EIFS	99 [μs]
CW range	15-1023

Source: IEEE 802.11 (2012).

In our simulation we used different values of throughput with SISO and MIMO 2x2 antenna model, it means both stations can have one antenna or two antennas. Parameters assigned with throughput, like packet transmission time are collected in Table 2.

The simulated network is structural type of network, i.e. one of this stations is AP. This network consists of 2 to 11 stations. In DCF communication schema AP has the same rights of access to media like another stations, i.e. AP has no additional privileges during communication session.

For simulation purpose we assumed that every station has always data to send. We do not use sending data without backoff time in the first session, because we assumed that communication session starts immediately after previous hypothetic session, i.e. the communication in the network have been lasted from some time.

Table 2

Frame rates and transmission times

Frame type	Antenna configuration	Rate [Mbit/s]	Transmission time [µs]
RTS	SISO	6.5	56,62
CTS	SISO	6.5	49,23
ACK	SISO	6,50	49,23
ACK	SISO	19,50	37,74
ACK	SISO	39,00	34,87
ACK	SISO	58,50	33,91
ACK	MIMO	13,00	48,62
ACK	MIMO	39,00	42,87
ACK	MIMO	78,00	41,44
ACK	MIMO	117,00	40,96
1540[1]	SISO	6,50	1927,38
1540	SISO	19,50	663,79
1540	SISO	39,00	347,90
1540	SISO	58,50	242,60
1540	MIMO	13,00	987,69
1540	MIMO	39,00	355,90
1540	MIMO	78,00	197,95
1540	MIMO	117,00	145,30
38802	SISO	6,50	4807,38
3880	SISO	19,50	1623,79
3880	SISO	39,00	827,90
3880	SISO	58,50	562,60

Data frame transmission time includes preamble.
1/2/ data frames
Source: own preparation.

In our simulation sheet we can write down, if the session was successful or not, which station had collision or which was the winner. Using Monte Carlo method we can calculate real time values for every communication session, we can calculate dead time and percentage participation of every component of communication session.

For the purpose of analysis some parameters have been defined to describe phenomenon on the timeline. Let value n describes the number of communication sessions, n_1 the number of success sessions, and n_2 the number of collisions, so $n = n_1 + n_2$. The basic information is the dead time, i.e. time, when all users are waiting, but the radio channel is idle, which can be defined as follows (Dolińska et al. 2014):

$$\begin{aligned} T_{DEAD}(n) &= \sum_{i=1}^{n_1} T_{DEADD2i} + \sum_{i=1}^{n_2} T_{DEADC2i} = \\ &= n_1(T_{DIFS} + 3 \cdot T_{SIFS}) + \sum_{i=1}^{n_1} T_{D2BOi} + n_2(T_{DIFS} + T_{SIFS}) + \sum_{i=1}^{n_2} T_{C2BOi} \end{aligned} \tag{2}$$

In the case of communication sessions the dead time is the sum of T_{DIFS}, 3 T_{SIFS} and T_{BO} (see Fig. 1). In the case of collisions dead time is the sum of T_{DIFS}, T_{SIFS} and T_{BO}, so is a little shorter. Second parameter defines the percentage of dead time in one communication cycle and could be described as follows (Dolińska et al. 2014):

$$T\%_{DEAD}(n) = \frac{T_{DEAD}(n)}{\sum_{i=1}^{n_1} T_{D2i} + \sum_{i=1}^{n_2} T_{C2i}} \tag{3}$$

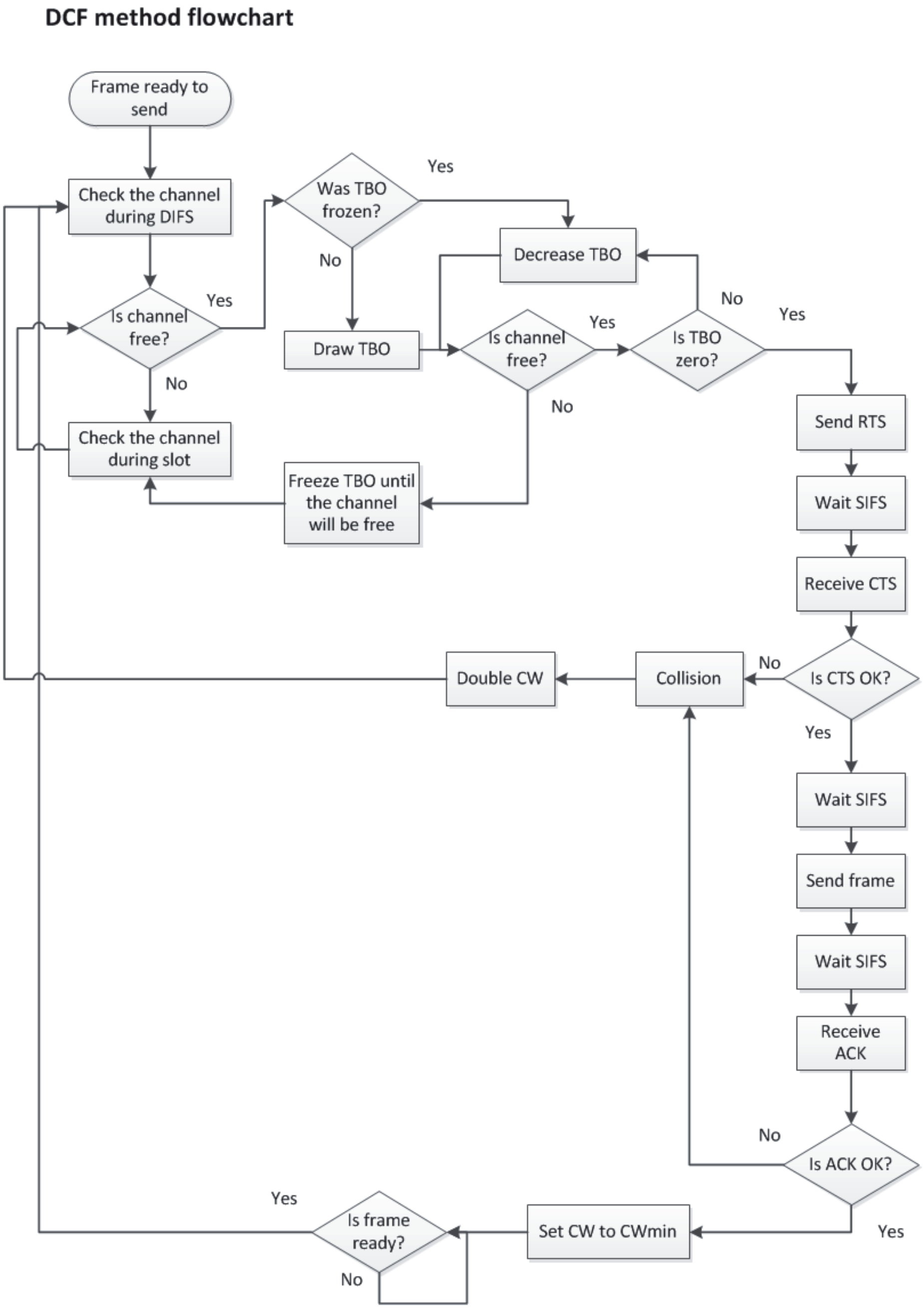
when T_{D2i} means the time of one successful session and T_{C2i} means the time of one collision session. The third parameter is the collision number in relation to the throughput and number of stations.

DCF simulation algorithm

In the simulation algorithm we model DCF scheme with few additional constraints to make the algorithm robust. The simulated algorithm is presented in Fig. 2. Like it was mentioned above, we do not use sending data without backoff time in the first session. When the frame is ready to send the station must check, if the channel is free during DIFS time. When the channel is free all this time, the station must draw random value. In the first session we select minimum CW (15) for first draw for all stations, so we make first draw from the interval 0 to 15. From second session we enlarge CW exponentially in the case of collision (until CWmax, i.e. 1023) and decrease to CWmin in the case of successful transmission (according to the standard). TBO value for every station is stored to the next session for stations, which did not have collision or did not have successful transmission. The new random

Fig. 2

WLAN network flowchart



Source: own preparation, basing on IEEE 802.11 (2012).

value of backoff time must be drawn for the stations, which had collision or transmission in the previous session. TBO for each station is calculated using the formula (1). After TBO calculating, stations refrain transmission and are listening to the channel again, decreasing TBO after every slot time (Fig. 2). The station, which draws the shortest TBO time, start transmission, the rest of the stations must wait until the transmission will be finished and the channel will be free again.

To simulate this step of algorithm, after calculating a backoff time for each station we must find the minimum value and check, if only one station has this minimum value. If this condition is true, this station is a winner and this information is stored . This information will also be needed in the next session to decrease CW of this station to minimum value.

If two or more stations have the same minimum value of TBO, it means that collision occurs. The collision mark for each of these station is set. This information is stored also for statistical purposes and will be used in the next session to enlarge CW by 2 in the next session. In this case we must check, if the CW don't exceed the CWmax value. If yes, the CW is not enlarged.

Simulation results and analysis

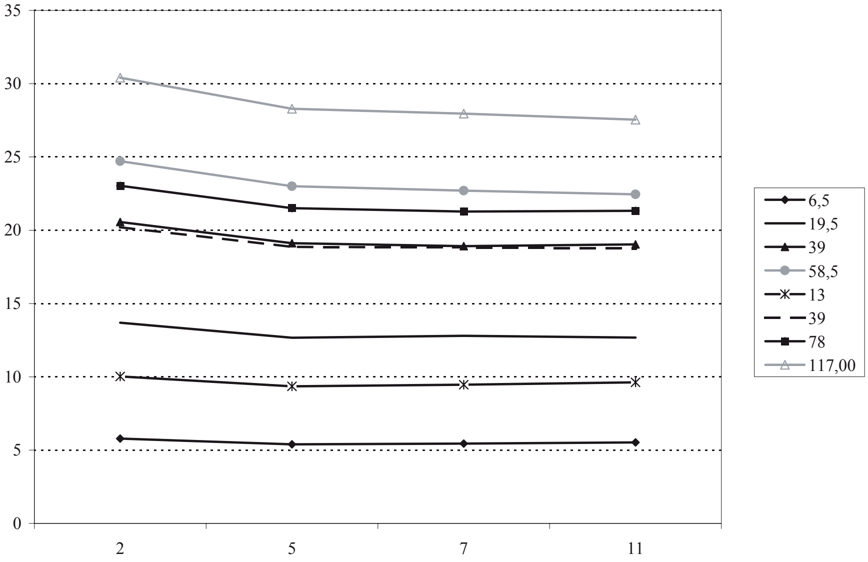
The simulations were performed using the spreadsheet to simulate the network, with some assumptions and restrictions, as described in the sec. 3.1. As it was mentioned above, one communication cycle has contained 200 sessions. All examined parameters was calculated as the arithmetic average from 20 communication cycles.

Firstly the dead time was calculated for different number of stations (2 to 11) and different network throughputs (see Table 2). Percentage values of the dead time in relation to station number for different throughputs are presented in Fig. 3. The percentage values of dead time depend on the throughput values and not depend on the number of stations in the network. For different station numbers, working in network, these values are quite stable (Fig. 3). The higher the throughput the higher is the percentage of dead time, because in relation to amount of data send the dead time elongates. The percentage of dead time values for the 39 Mbit/s throughput, Ethernet frame and SISO model (about 20%, see Fig. 3a) is similar to this obtained in simulations performed for 2,4 GHz band and for throughput 26 MHz (Dolińska et al. 2014). The detailed values are different, because the individual components of the dead time (SIFS, DIFS) have different values for both bands. When aggregation is used, the dead time values are more than half shorter than for Ethernet frame, what can be seen in Fig. 3a and 3b. The longer are the frames the less time is wasted for interframe separators. Using frame aggregation improves the transmission efficiency and this growth is proportional to aggregation level. In this simple example the dead time decreases more than halve, and in the same proportion the transmission throughput increased.

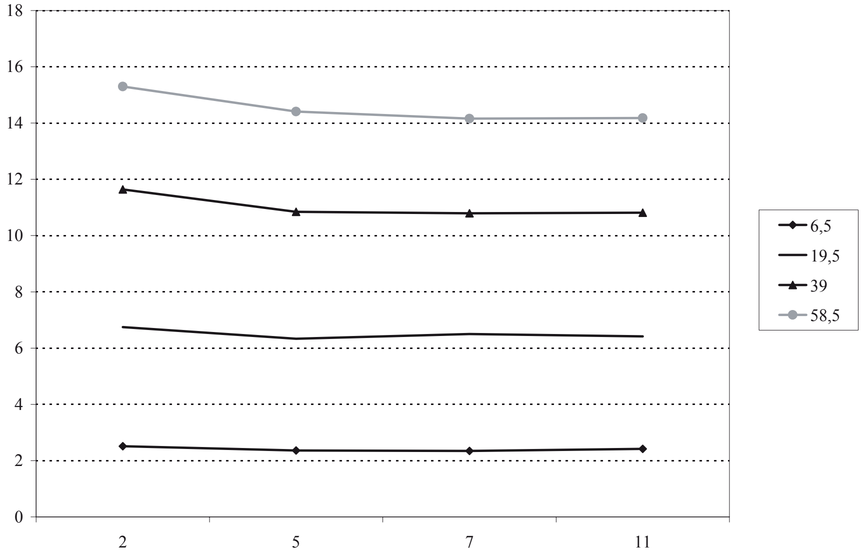
Fig. 3

Percentage of dead time for two types of frames in relation to station number for different throughputs

a) Ethernet frame



b) aggregated frame

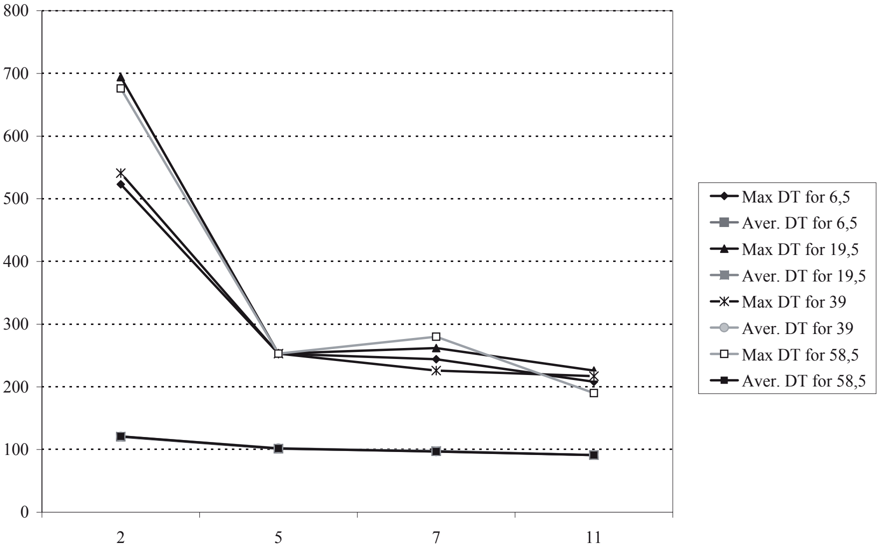


Source: own preparation.

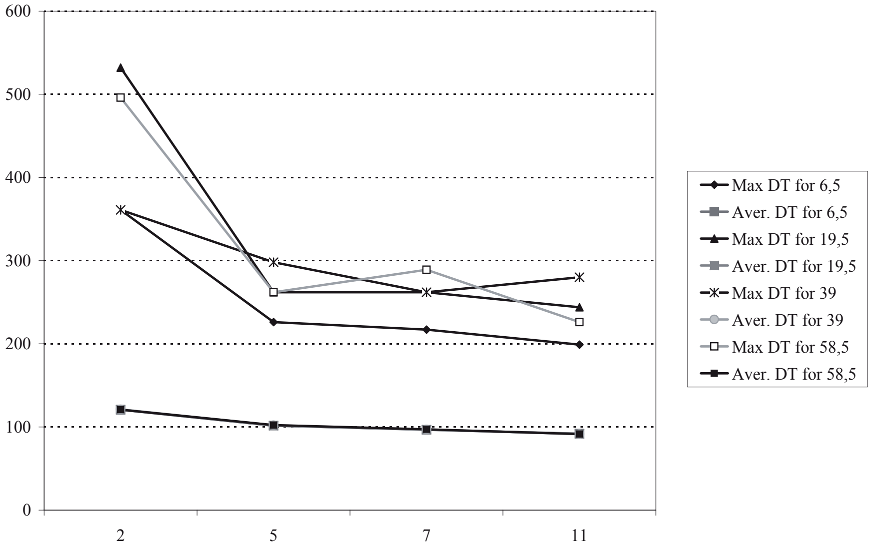
Fig. 4

Maximum and average values of dead time for two types of frames (SISO model) in relation to station number for different throughputs

a) Ethernet frame



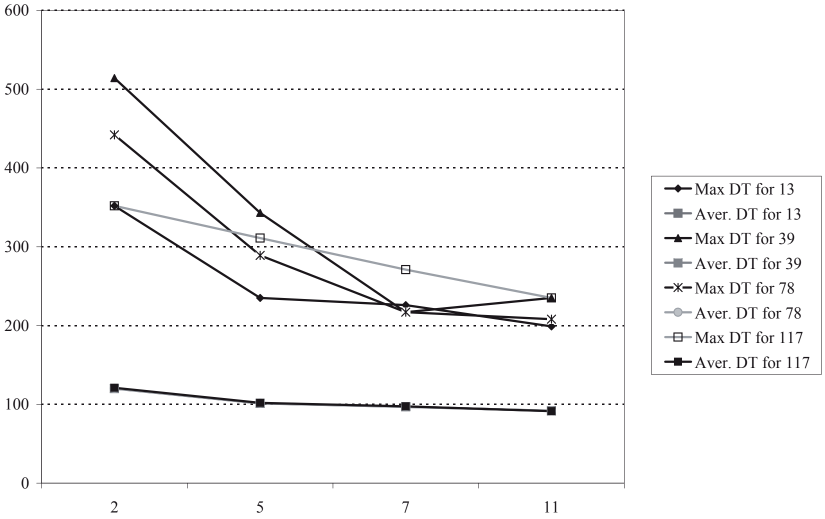
b) aggregated frame



Source: own preparation.

Fig. 5

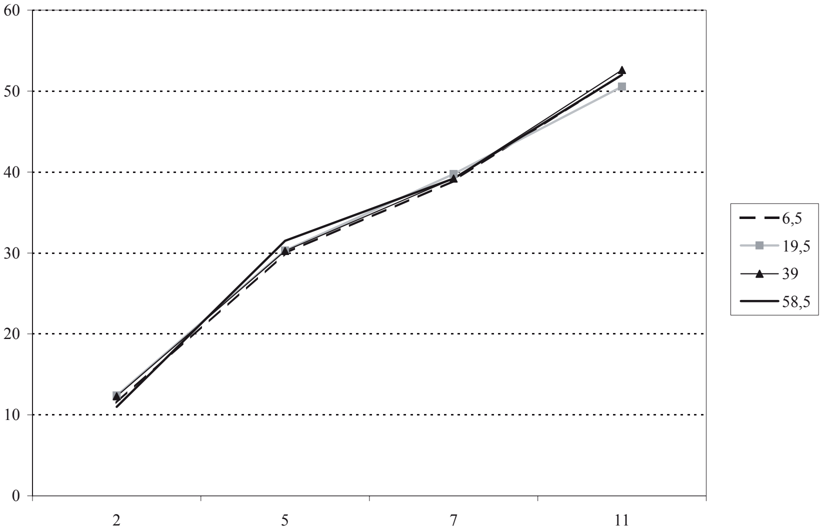
Maximum and average values of dead time for Ethernet frame (MIMO model) in relation to station number for different throughputs



Source: own preparation.

Fig. 6

Collision number for Ethernet frame (SISO model) in relation to station number for different throughputs



Source: own preparation.

The average and maximum value of the dead time was also calculated in relation to station number for different throughput values. As shown in Fig. 4, the average dead time values are similar for simulation using Ethernet frames and aggregated frames. The result of simulation for MIMO model is also similar, what is shown in Fig. 5. The maximum values of the dead time are higher for smaller networks and decreases with increasing number of stations. Maximum dead time values had almost 700 µs for Ethernet frame transmission and about 500 µs for aggregated frame transmission simulation and Ethernet frame with MIMO. The average dead time value is almost stable and depends on the station number only. It is from about 120 µs for 2 station network to about 90 µs for 11 station network. It means, that such high values of dead time, like 700 µs or 500 µs, happen not very often. But these long values of the dead time makes transmission conditions not stable and not predictable. Sometimes station is able to send its frame quickly, but from time to time transmission is delayed.

The next simulations were performed to check collision number in relation to the station number and for different throughput. The obtained result for Ethernet frame in SISO model is presented on Fig. 6. In another simulation cases (Ethernet MIMO model and aggregated frame) the result was almost the same. The collision number depends on the number of stations in the network only. We obtained about 10 collision in the smallest network up to 52 collisions in the biggest one. Taking into account that communication cycle consist of 200 transmissions, we have from about 5 % collisions to about 26% collisions in simulate networks. The collision number increase almost linear in relation to the station number.

Conclusions

The analysis of the factors in MAC layer, that reduce the high theoretical throughput is presented in this article. The method of simulation, based on the Monte Carlo method was used, which allows to simulate systems using random sampling (TBO value is random) and real parameter values. The 5 GHz Wi-Fi network with variable number of stations (from 2 to 11) was simulated. The simulation were performed for SISO and MIMO communication model and for two frame lengths: Ethernet frame (1540 bytes) and aggregated frame (3880 bytes). The dead time, described in sec. 3.1 and collision number was investigated.

Simulation results shows that:

- Percentage values of the dead time increase when the throughput increases, but for different station numbers in network these values are quite stable.
- The maximum values of the dead time are higher for smaller networks and decreases with increasing number of stations.

- The average dead time value is almost stable and depends on the station number only.
- The collision number depends on the number of stations in the network only, and not depends on the throughput.

The dead time instability problem requires optimization. It should be interesting to adjust the time separator values to the number of station or to the network theoretical throughput. The collision problem requires optimization also. The RTS/CTS method was introduced to decrease collision number and the wasted time, but this method in such fast networks is insufficient.

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Metoda symulacji i analizy zdyskontowanych przepływów pieniężnych dla małych sieci

Streszczenie

Sieci WLAN stały się bardzo popularne w domu i w małych biurach. Użytkownicy sieci bezprzewodowych potrzebują wysokiej wydajności, lecz wydajność ta jest zmniejszana przez wiele czynników. Czynniki te obejmują przede wszystkim interferencję ze strony innych urządzeń bezprzewodowych i spuścizny protokołu Wi-Fi. Autorzy analizują czynniki w warstwie MAC, które zmniejszają przepustowość sieci. Dokonano również szczegółowej analizy algorytmu DCF. Przeprowadzono symulacje z zastosowaniem metody Monte Carlo w celu dokonania symulacji sieci Wi-Fi w domenie czasowej. Zbadano sieć w paśmie 5 GHz przy zmiennej liczbie stacji w celu sprawdzenia, jak liczba stacji wpływa na parametry DCF. Obliczono czas martwy dla różnych szybkości transmisji danych dla zbadania, jak parametr ten zmniejsza maksymalną przepustowość sieci.

Słowa kluczowe: sieć WLAN, 802.11n, DCF, podwarstwa MAC, dostęp do mediów w sieci Wi-Fi.

Kody JEL: C61

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