Throughput Modeling in IEEE 802.11 WLAN-based Wireless Networks

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***Abstract*—Wireless Local Area Networks (WLANs) are nowadays the most widely used indoor wireless networks that found a large variety of wireless applications. WLANs are widely used in both home and office networking. Due to the ability of providing high data rate access, WLANs are significant components of next generation wireless networks. Next generation wireless networks must provide a reliable communication and high data rate under various scenarios. A way of solving these tasks is the application of adaptive methods where system characteristics change according to channel conditions. A reliable model of WLAN operation is required for design and analysis of adaptive rate adaptation methods. In this work, we created a simulation model that is used for analyzing WLAN throughputs under different scenarios. It can be also applied to analyze other important performance metrics such as the delay and probability of collisions.**

Keywords*—*Adaptive rate adaptation, collisions, throughput, wireless networks.

I. INTRODUCTION

Wireless Local Area Networks (WLANs) specified by IEEE 802.11 standard are nowadays the most widely used wireless indoor networks [1]-[30]. They are applied in both home and office networking. The IEEE 802.11 specifies both the physical (PHY) and Medium Access (MAC) layers [1]. The PHY layer defines kinds of the signal modulation, and the MAC layer regulates the transmission of the data frame.

There exist a few versions of IEEE 802.11 standard that specifies the WLANs. The Orthogonal Frequency Division Multiplexing (OFDM), complementary code keying modulation (CCK) technique, and spread spectrum methods have been accepted as bases for different versions.

The original IEEE 802.11 is a sufficiently low data rate PHY (supporting only 1- and 2-Mbps data rates) along with MAC standard. This version operates at the 2.4-GHz ISM band. It proposes two types of spread spectrum signals: direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS) implementations. A version 802.11b is a PHY extension to the original 802.11 standard. It also operates at the 2.4-GHz frequency band, but it allows higher data rates of 5.5 and 11 Mbps. It uses the CCK technique. The 802.11a is another PHY extension to the 802.11 standard. It operates at the 5-GHz unlicensed frequency band and allows for data rates of 654 Mbps. The OFDM forms the basis for the PHY in this standard. The 802.11g is another version of the 802.11 standard. It operates at the 2.4-GHz ISM band and allows for data rates ranging from 1 to 54 Mbps. The 1- and 2-Mbps rates are operated in the DSSS mode whereas the 512 - and 11-Mbps rates are operated in CCK mode. Additionally, rates at 6 to 54 Mbps are operated in OFDM mode. The 802.11g standard uses the same modulation (OFDM) and data rates as the 802.11a standard but operates at the 2.4-GHz ISM band. Thus, the 802.11g can support a very high data rate, and it is compatible with the 802.11b standard.

The throughput is an important performance metric of any wireless network. In this work, we created a simulation model for the throughput analyses under various adaptive policies. The model is based on IEEE 802.11 standard. While specifying the PHY and MAC layers, the IEEE 802.11 does not define, however, techniques (protocols) that could improve multiple transmission rates. Nowadays, a large number of rate adaptation schemes were proposed, see, for example, [7]-[15] and [19]-[21].

Our simulation model was created in C++. It can be conveniently used for the analysis of the network throughputs under different scenarios, in particular, the simulation model can be successfully applied to the performance comparison of various adaptive methods. In multi-user scenarios, collisions are observed. The quality of their detection and treatment is an important factor affecting the performance of rate adaptation methods. The IEEE802.11 MAC protocol is such that the collision resolution becomes slower as the number of active stations increases. This fact motivated elaboration of MAC algorithms providing a collision avoidance. An algorithm was proposed in [13]. The authors refer the proposed protocol as a less collisions fast resolution (LCFR) MAC protocol. In this paper, we apply our simulation model to a throughput and delay comparison of IEEE 802.11 and LCFR MAC protocols.

II. OVERVIEW OF OFDM-BASED PHY LAYER

Depending on the radio channel conditions, the PHY layer supports a few modulation and coding schemes. The main parameters of the OFDM-based PHY are shown in Table I. An OFDM symbol is created via the 64-point inverse Fourier transform (IDFT). Only 48 of 64 subcarriers are used for modulation, and four subcarriers are reserved for pilot tones. The pilot tones are used at the receiver for the channel and residual phase error estimation. The remaining 12 subcarriers are empty, that is they are not used. The output of the IDFT is converted to a serial sequence and a specially constructed guard interval or cyclic prefix (CP) is added. The CP presence is essential in the OFDM modulation, although it increases

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the OFDM symbol duration and is considered as overhead. Although the CP does not carry out additional information and is removed at the receiver, it combats with the multipath propagation and facilitates the channel equalization reducing it a simple one-tap equalizer. After the CP has been added, the entire OFDM symbol is transmitted across the channel. As long as the duration of the CP is longer than the channel impulse response, the inter-symbol interference caused by the multipath propagation is eliminated. Those are OFDM basics.

TABLE I. MAIN PARAMETERS OF OFDM-BASED PHY LAYER

Data rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding rates	1/2, 9/16, 2/3, 3/4
Number of subcarriers	52
Number of pilot tones	4
OFDM symbol duration	4 μsec
Guard interval	800 ηsec, 400 ηsec (optional)
Subcarrier spacing	312.5 kHz
Signal bandwidth	16.66 MHz
Channel spacing	20 MHz

III. IEEE 802.11 AND LCFR MAC PROTOCOLS

The fundamental goal of IEEE 802.11 MAC is to provide and to facilitate the transmission of data frames for different applications between two WLAN stations, employing the support of the PHY layer. A general WLAN structure consists of three components: the station, the access point (AP), and the medium. A set of stations that communicate with one another form a basic service set (BSS).

The WLAN station transmits information by frames. There are three main parts of each frame: the frame header, the frame body, and the frame trailer (check sequence) [8].

The main IEEE 802.11 MAC method to access the medium is called the distributed coordination function (DCF) [13]-[15]. The standard specifies also another algorithm, the point coordination function (PCF), that is, however, used optionally. The DCF is a random access scheme that provides the multiple access with a collision avoidance (CSMA/CA) protocol. A brief description of the IEEE 802. 11 DCF follows [14]-[15].

A. IEEE 802.11 DCF

If a WLAN station has a new packet to be transmitted, it listens the channel activity. The station transmits if the channel is idle for a period of time equal to a distributed interframe space (DIFS). Otherwise, if the channel is recognized busy (either immediately or during the DIFS), the station continues to listen to the channel until the channel is found idle for a DIFS. Then, the WLAN station generates a random back-off interval before transmitting (this is the Collision Avoidance feature of the protocol). The main goal of the random back-off is the avoidance of collisions, that is, the minimization of the probability of collision with packets that are transmitted by other WLAN stations. Additionally, a WLAN station must wait some random back-off time between two new consecutive packet transmissions, even if the medium is sensed idle in the DIFS time. This is done in order to avoid the channel capture. The DCF uses a discrete-time back-off scale. The time that follows the idle DIFS is slotted, and the WLAN station is able to transmit only at the beginning of each slot time. The slot time size is put equal to the time required at any station to detect the transmission of a packet from any other station. The slot time size depends on a few factors such as the PHY

The DCF adopts an exponential back-off scheme: a binary exponential back-off (BEB) is used as a stability algorithm for sharing the radio channel [14]-[15]. When the WLAN attempts to transmit the packet the first time, the BEB chooses a random slot from the next contention window (CW) with an equal probability, that is CW=$\mathrm{CW}_{\min}$, where the $\mathrm{CW}_{\min}$ is the minimal CW size. If the packet transmission for the station is unsuccessful, that is, the collision is observed, its CW size is doubled until it reaches the maximal value $\mathrm{CW}_{\max}$. Thus, the size of the CW is defined as

$$\mathrm{CW} = \min\{2 \times \mathrm{CW}, \mathrm{CW}_{\max}\}. \quad (1)$$

Thus, the CW size depends on the number of transmissions failed for the packet.

The back-off time counter is decreases while the radio channel is sensed idle. If a transmission is detected, it is kept constant, and it is reactivated when the channel is sensed idle again for more than a DIFS. The transmission begins when the back-off time reaches zero.

The WLAN station resets its CW size to the $\mathrm{CW}_{\min}$ after a succesfull transmission, or in the case where the total number of packet transmission attempts reaches a limit.

The CSMA/CA algorithm does not rely on the capability of the stations to detect a collision by hearing their own transmission. Thus, an acknowledgement (ACK) is transmitted by the receiver station. The ACK indicates that the packet has been received successfully. The ACK is immediately transmitted at the end of the packet, after a period of time called short interframe space (SIFS). As the SIFS plus the propagation delay time is shorter than the DIFS, another station is not able to detect that the channel is idle for a DIFS until the end of the ACK. If the transmitting station does not receive the ACK , or it detects the transmission of a different packet on the channel, it reschedules the packet transmission according to the given back-off rules. This method of the packet transmission is called the basic access mechanism. The DCF specifies also a more complicated additional technique that can be optionally used for the packet transmission. This technique is called the request to send/clear to send (RTS/CTS). The WLAN station that wants to transmit a packet, waits until the channel is recognized idle for a DIFS, follows the above back-off rules, and then, instead of the packet, preliminarily transmits a special short frame called the RTS. When the receiving station detects the RTS frame, it responds by sending a CTS frame. after the SIFS. The transmitting station is allowed to transmit its packet only if the CTS frame is correctly received.

This mechanism is intended to avoid collisions. The RTS and CTS frames carry out the information of the length of the packet that must be transmitted. This information can be read by other stations. On the basis of this information, the network nodes update the so called network allocation vector (NAV), which contains the information about the period of time in which the channel will be busy. Thus, when the station detects either the RTS or CTS, it has enough information for a reasonable delay in the transmission. In such a way, collisions may be avoided.

Thus, the RTS/CTS algorithm helps to improve the network throughput at the expense of a higher complexity . This improvement is more evident for transmissions of large packets because the length of the frames involved in the contention process is decreased. If there are no error in channel sensing, collision may occur only when a few packets are transmitted in the same slot time. If all transmitting stations use the RTS/CTS algorithm, the collision may appear only in the RTS frames. But the collisions are quickly resolved by the transmitting stations due to the absence of the CTS responses.

B. LCFR algorithm

The described above the IEEE802.11 MAC protocol suffers from a slow collision resolution that is more evident as the number of active stations increases. This fact is also confirmed by simulation results given below.

At each contention period, any WLAN station can either transmit or be in the postponed position if it loses the contention. Any packet transmission may be either successful or result into a collision. Thus, at each contention period, the WLAN station may be only in one of three positions that are the successful packet transmission, the collision, and postponed stage. In the described above MAC algorithm, the CW size is not changed if the WLAN station is in the postponed mode, and the backo-ff timer will decrease by one slot whenever an idle slot is detected. But recently a MAC protocol was proposed where the authors suggested to change the CW size for the postponed stations and to regenerate the back-off timers for all potential transmitting stations [13]. This algorithm allows avoiding potential collisions, and the authors called this technique less collision fast resolution (LCFR) algorithm because it provides a fast resolution of possible packet collisions. It is also important that the LCFR does not increase the implementation complexity that is of the order of that in the IEEE 802.11.

We describe below the main features of the LCFR algorithm.

1) The minimal CW size , $\mathrm{CW}_{\min}$ is much smaller than that in the IEEE 802.11.

2) The back-off timers are reduced exponentially fast.

3) The maximal CW size , $\mathrm{CW}_{\max}$ is much larger than that in the IEEE 802.11.

4) Unlike the IEEE 802.11, the CW size is increased if the station is either in collision state or in the postponed state.

The implementation of points 1)-2) aims at a reduction of the average number of idle backoff slots for each contention period, and the realization of points 3)-4) increases quickly the back-off timers, which, in turn, results in a fast decrease of the collision probability.

Thus, the main difference of the LCFR algorithm from other contention based MAC protocols such as the IEEE 802.11 MAC is such that in the IEEE 802.11 MAC, the CW size of a station is increased only when it experiences a transmission failure (i.e., a collision). In the LCFR algorithm, the CW size of a station increases if it experiences a collision and also when it is in the deferring state and senses the start of a new busy period. Therefore, the LCFR algorithm forces all stations, which have packets to transmit (including those which are deferring due to back-off) to alter their CW sizes at each contention period.

A detailed description of the LCFR algorithm follows [13].

The back-off procedure is implemented in the following way. All active stations listen the radio channel. If the station senses the medium idle for a slot, then it decreases its back-off time (BT) exponentially, i.e.,

$$\mathrm{BT}_{\mathrm{new}} = \frac{\mathrm{BT}_{\mathrm{old}}}{2},$$

$$\text{if } \mathrm{BT}_{\mathrm{new}} < \mathrm{SlotTime}, \mathrm{BT}_{\mathrm{new}} = 0. \quad (2)$$

The station transmits the packet when its back-off timer reaches zero. The back-off timer decreases in two times at each idle slot until either it reaches to zero or it senses a non-idle slot, which comes first. This mechanism results in a reduction of wasted idle back-off time when a station runs out of packets for transmission.

In the case of the packet collision the LCFR algorithm forces the station to operate in the following way. If a station notices that its packet transmission has failed possibly due to packet collision (for example, it does not receive the ACK from the intended receiving station), the CW size of the station is increased and a random BT is selected from the uniform distribution $[0, \mathrm{CW}]\times$ SlotTime, that is the BT = uniform[0,CW]$\times$SlotTime, where the CW is the current contention window size.

In the case of the successful packet transmission, the LCFR operates as follows. After the station has finished the successful packet transmission, its CW size reduces to the initial (minimum) CW size, $\mathrm{CW}_{\min}$, and a random BT value will be chosen accordingly as

$$\mathrm{CW} = \mathrm{CW}_{\min},$$

$$\mathrm{BT} = \mathrm{uniform}[0, \mathrm{CW}] \times \mathrm{SlotTime}. \quad (3)$$

If the station is in deferring position and , it detects the start of a new busy period (which indicates either a collision or a packet transmission), the station increases its CW size and assigns a new random BT as

$$\mathrm{CW} = \min\{2 \times \mathrm{CW}, \mathrm{CW}_{\max}\},$$

$$\mathrm{BT} = \mathrm{uniform}[0, CW] \times \mathrm{SlotTime}. \quad (4)$$

IV. Comparison of Throughputs under IEEE 802.11 and LCFR MAC protocols

We created a C++ simulation model for analyzing the network throughputs. With the help of the model, we compared the throughputs under the IEEE 802. 11 MAC protocol using DSSS specifications and under the LCFR algorithm. In order to test this model, we used the simulation parameters given in [13]. They are shown in Table II.

With the help of our simulation model, we tested the throughputs as well delays in wireless networks with different numbers of active stations. As in [13], we also changed the

TABLE II. SIMULATION PARAMETERS

Parameter	Value
SIFS	10 μs
DIFS	50 μs
Slot time	20 μs
Bit rate	2 $Mbps$

packet length. The number of the network nodes was equal to 10, 20, and 50, and the packet length varied from 100 to 1000 bits.

In Figs. 1-3, the estimates of the throughput are shown for the respective scenarios of wireless networks with 10, 20, and 50 nodes, whereas in Figs. 4-6, the numerical estimates of the delays in packet transmission are shown. In each case, the LCFR algorithm outperforms the IEEE 802.11 MAC protocol due to a faster collision resolution. Under all scenarios, our simulation results show agree well with the results given in [13]. This fact proves the correctness of our simulation model, which is assumed to be used further for testing advanced MAC algorithms.

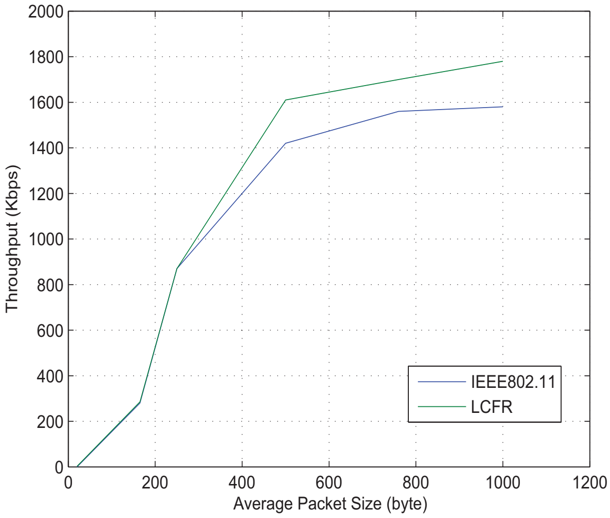

Fig. 1. Throughput, 10 network nodes

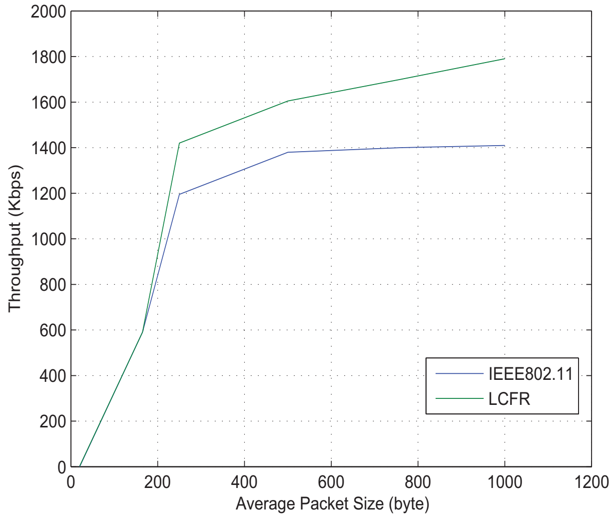

Fig. 2. Throughput, 20 network nodes

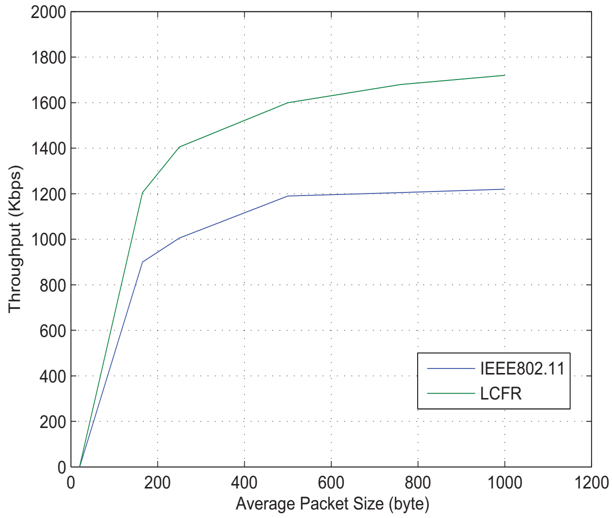

Fig. 3. Throughput, 50 network nodes

V. CONCLUSION

WLANs are nowadays very popular wireless networks that are widely used in indoor networking. WLANs are important components of next generation wireless networks because of their ability to support very high data rates. Next generation wireless networks must support reliable communications and high data rates under various scenarios. A way of solving these tasks is the application of adaptive methods where system characteristics change according to variations of the environment and network structure.

The throughput is a key performance metric of the wireless network. In this work, we created the simulation model that allows analyzing the throughput under various adaptive policies. The simulation model is based on IEEE 802.11 standard and was created on C++. It evaluates the throughput performance at the MAC layer in a multi-user environment, and it can be also used to assess other important characteristics of the wireless network such as the delay and probability of collisions.

The model is flexible and suitable for different network configurations including ad hoc scenarios. In this work, the created model was used for the estimation and comparison of the network throughputs and delays under different MAC protocols. The first protocol tested is the IEEE 802. 11, and the other method is a less collision fast resolution protocol proposed in [13]. The simulation model was tested by using the parameters given in [13], and our simulation results showed

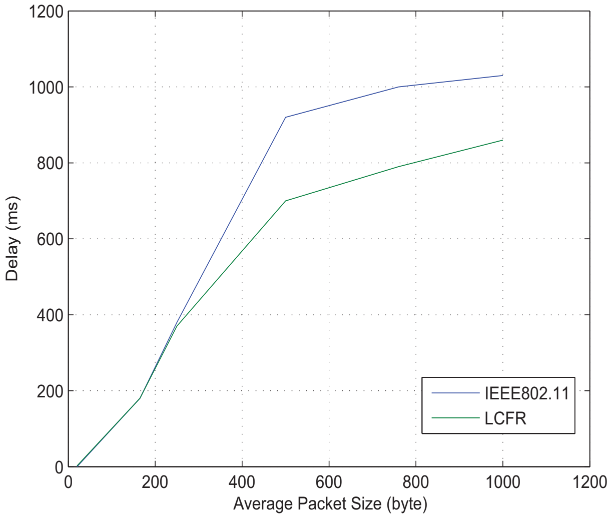

Fig. 4. Delay, 10 network nodes

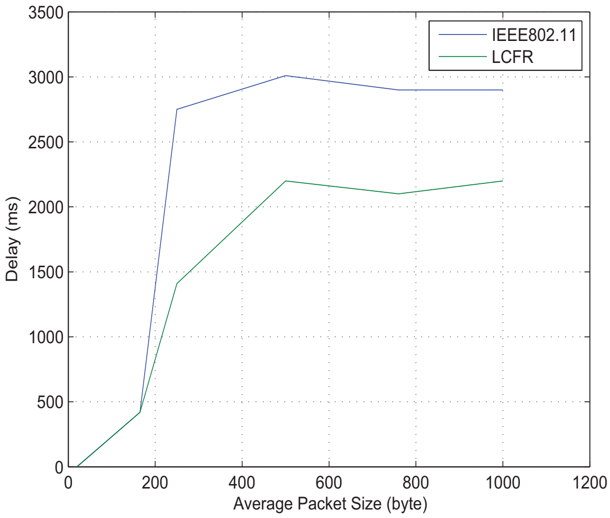

Fig. 5. Delay, 20 network nodes

a good match with the results in [13]. This fact proves the reliability of the created model, and the future work assumes analyzing other algorithms aiming at the improvement of the wireless network throughput.

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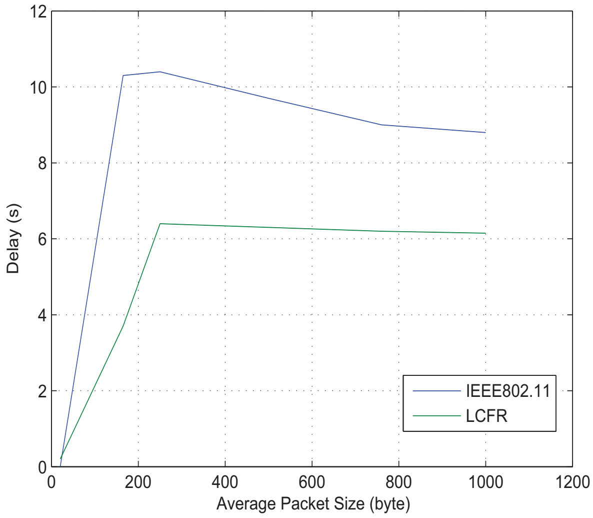

Fig. 6. Delay, 50 network nodes

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