# Analysis of User Plane in IEEE 802.11b/g QoS Networks

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*Abstract* — **In this paper we present the performances evaluation of infrastructure 802.11b/g QoS networks, in both HCF (Hybrid Coordination Function) operating modes: EDCA (Enhanced Distributed Channel Access) and HCCA (HCF Controlled Channel Access). Besides comparing these two modes in terms of total network throughput (between themselves as well as against the theoretical limit), in this paper we introduce further analyses: impact of modulation scheme on the total throughput, determination of throughput for different traffic categories and average packet delivery delay.**

*Keywords* — **EDCA, HCCA, HCF, MAC layer, QoS, WLAN.**

## I. INTRODUCTION

GROWING popularity of multimedia applications such as Internet telephony, audio and video streaming, interactive games etc. resulted in the need to provide user access to multimedia services through WLAN (Wireless Local Area Network) connections. Multimedia applications require a certain level of quality of service - QoS in order to provide a guaranteed network throughput, controlling the percentage of lost packets, limited delay and jitter, etc.

According to earlier versions of IEEE 802.11 standard which define medium access control - MAC and physical - PHY layers of WLAN networks, the principle of Best Effort does not support any classification of user traffic either by priority or by the parameters of transmission. According to this architecture, data packets of different services are treated in the same way. Waiting in queues can cause too long delay or even loss of packets what is unacceptable for sensitive multimedia services.

Therefore, the latest version of the standard [1] introduced IEEE 802.11e amendment that defines a set of Quality of Service enhancements in WLAN networks by modifications of MAC layer. The basic MAC mechanism is DCF (Distributed Coordination Function), distributed wireless medium access method that employs CSMA/CA (Carrier Sense Medium Access with Collision avoidance) multiple access method. The other two mechanisms, which represent the upgrade of DCF method are PCF (Point Coordination Function) and HCF (Hybrid Coordination Function), defined in the IEEE 802.11e, also. Further, HCF includes two new access methods: EDCA (Enhanced Distributed Channel Access) and HCCA (HCF Controlled Channel Access).

The aim of the study was to assess the performances of infrastructure 802.11e network, in the EDCA and HCCA modes. For this purpose, a specific program that simulates the operation of the network was developed in the C programming language. The mutual comparison of EDCA and HCCA methods, but also in relation to the theoretically obtained values, was performed from the standpoint of the throughput of user data. In addition, the analysis of the impact of applied modulation schemes on the total throughput, as well as determining throughputs for different traffic categories and average packet delivery delays were carried out.

## II. QOS LIMITATIONS OF 802.11 MAC

The most important functions which MAC layer of a wireless network should support are: the channel access control, providing quality of service to the applications of higher layers and providing security in the network. As for the other functions, ensuring service quality is a much more complex task in wireless than in wireline networks. Wireless links have specific characteristics: a relatively high percentage of lost packets, loss of packet sequences, receiving packets out of order, a long delay and jitter. Throughputs in the wireless channel are much smaller, while the probability of error at the physical layer is higher up to three orders of magnitude in WLAN with respect to the LAN networks. Also, the consequence of frequent collisions and retransmissions is unpredictable packet delivery delays, which degrade the quality of real-time video and voice services.

## III. HCF CHANNEL ACCESS MECHANISMS

### *A. EDCA (Enhanced Distributed Channel Access)*

EDCA defines four access categories (AC) for different types of user traffic: Voice(AC_VO), Video (AC_VI), Best Effort (AC_BE) and Background (AC_BK). Service differentiation is introduced in such a way that in the competition for the medium, each AC uses a set of associated parameters. Traffic is assigned to AC on the basis of traffic priority (UP-User Priority), as defined in IEEE 802.1p standard. There are eight UPs. An appropriate UP value is assigned to the packet depending on the type of application, i.e. according to traffic to which it belongs [1].

QoS station maintains four queues for packet delivery (for each AC) and four independent EDCA functions for

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each queue. EDCAF (EDCA function) uses an enhanced version of DCF and competes for the medium on the principles of CSMA/CA and backoff algorithm (as well as DCF), but additionally taking into account parameters specific to that traffic category. EDCAFs of all stations compete for TXOP (Transmission Opportunity). TXOP is a limited time interval during which the stations in a waiting queue for the appropriate category can send data, but only if the time required to send a frame does not exceed the length of TXOP (when this is not the case, fragmentation is performed before sending).

A set of parameters is associated to each EDCAF:

- AIFS (Arbitration Inter Frame Space) - the period during which the medium is free before a packet delivery or backoff procedure starts; AIFS is equal to the integer multiple AIFSN (AIFS Number) and the time slot duration;
- $CW_{min}$ and $CW_{max}$ - contention window sizes used for the backoff;
- TXOP limit - the maximum duration of delivery after accessing to media.

The values of EDCA parameters vary depending on the AC category. A higher priority AC has a smaller AIFSN value, i.e. packets wait a short time before an attempt to access the channel is made, while in the opposite case packets of lower priority AC wait longer. Also, the sizes of $CW_{min}$ and $CW_{max}$ are small for higher-priority AC. TXOP Limit is set in such a way that a higher priority AC gets a transmission possibility over a long period of time. Therefore, a higher priority of AC means a shorter waiting period (AIFS), a small contention window and a longer transmission time limited to the TXOP Limit.

As the EDCA parameters are associated to individual AC, the standard uses the following labels: AIFS [AC], $CW_{min}$ [AC], $CW_{max}$ [AC] and TXOP Limit [AC]. In comparison with DCF, EDCA uses different parameters specific for each AC category, contrary to DCF where the parameters are the same for all traffic classes. Table 1 gives the standard preset values of EDCA parameters.

TABLE 1: STANDARD VALUE OF EDCA PARAMETERS.

| *AC* | *$CW_{min}$* | *$CW_{max}$* | *AIFSN* | *TXOP limit* |
|---|---|---|---|---|
| AC_VO | 7 | 15 | 2 | 1.504 ms |
| AC_VI | 15 | 31 | 2 | 3.008 ms |
| AC_BE | 31 | 1023 | 3 | 0 |
| AC_BK | 31 | 1023 | 7 | 0 |

EDCAFs in the station operate as a virtual station. Each function tries independently of the other to get its own TXOP. There are two levels of competition. On the internal level, there is competition between multiple EDCAFs of one station, and on the external level, between EDCAFs of different stations. Internal (term “virtual” is also used) collision occurs in a situation where, after the backoff time, two or more virtual stations, according to EDCAFs of one QoS station, try to access the media at the same time. In this case, access to the media is guaranteed to the highest priority EDCAF of all EDCAFs involved in the collision. Remaining stations are behaving as in the case of external collisions, i.e. contention windows will be doubled and backoff procedure will start.

### *B. HCCA (HCF Controlled Channel Access)*

In HCCA methods, TXOP are also used, but now a central element of the network - HC (Hybrid Coordinator) controls the access to wireless medium. HC defines a polling schedule for stations and performs classification of data flows in the queues. On the basis of specific collaboration with stations at the session layer, the quality of service can be configured with great precision. It should be noted that although HC is the central coordinator, it is different from the PC (Point Coordinator) from the PCF method. The most important difference is that in the case of HC an undisturbed exchange of data frames between stations in the network can be carried out both during the contention free period - CFP as well as during the contention period - CP. Another important difference is that HC assigns TXOP to stations (TXOP length is specified in the polling frame). A station can perform transmission in accordance with the limited duration of the TXOP. This method assures admission control of the traffic flows, preserving the quality of service of existing flows. There are two types of admission control: Contention-based admission control (based on the traffic differentiation by priority) and Controlled-access (the strict parameters of the transfer are agreed in advance: minimum throughput, maximum delivery delay and jitter, etc.).

## IV. SIMULATION RESULTS

A simulator of 802.11e network is implemented in the C programming language environment. Simulations were performed for different scenarios in order to compare the mechanisms of access to the wireless medium, but also to determine the maximum total throughputs, average packet delivery delays and throughputs that characterize different EDCAF functions. Network topology is based on the infrastructure model. It consists of one Basic Service Set - BSS and a variable number of wireless stations that connect to the central Access Point (AP). To determine the maximum throughput, error-free transmission is assumed. However, in order to analyze the network behavior that is closer to real situations, a certain percentage of lost packets is introduced. Usual causes of failure in a wireless network are: interference in the range of network, insufficient level of receiving signal, multipath fading, and fading due to the movement of the station.

Within the stations HCF function was implemented. All stations in the network (including the AP) are QoS station. Two scenarios are considered. In the first one the stations use the medium access mechanism based on the traffic priority (EDCA), while in the other scenario the access is based on the use of transmission parameters (HCCA). For the purpose of comparison of these mechanisms, in the HCCA mode it was adopted that all communications are carried out by polling the stations, but not by free access during CP interval. Also, a simple algorithm of admission control of traffic flows (Controlled-access) is applied.

Two transmission techniques were implemented at the physical layer: DSSS/CCK (DSSS/Complementary Code Keying) (802.11b networks) and DSSS-OFDM (802.11g networks). In the case of CCK modulation two frame formats were used: Long (long PLCP preamble and DBPSK modulated PLCP header) and Short (short PLCP preamble and DQPSK modulated PLCP header). It was assumed that all stations in the network use the same technique. Therefore, in the case of DSSS-OFDM time slot duration was set to 9 µs, i.e. 20 µs for DSSS/CCK. All traffic categories were generated on a CBR (Constant Bit Rate) principle which means that the packets were generated at constant time intervals. During simulations, all stations within the same AC generated packets of the same size. Packets older than time MSDULifeTime (MAC Service Data Unit Life Time was 500 time units, where the time unit duration was 1024 µs) were discarded. The duration of a simulation was 100 s.

### *A. EDCA access method*

All four EDCA functions were implemented in the simulator. AC_BK and AC_BE had the same EDCA parameters in terms of minimum and maximum sizes of the contention window used for backoff, but also with respect to the rights to send only one packet after the access to the medium is granted. The difference between these two traffic categories is only in the period during which the media must be free before packet delivery or backoff procedure starts. For the sake of clarity of the results obtained by simulations, but also because of a reasonable assumption that stations will not generate traffic of all categories at the same time, only three categories were used in simulations: AC_VO, AC_VI and AC_BK.

ACK (Acknowledgement) frames were not used for confirmation of voice and video packets because it would result in additional delays (especially in the cases of erroneous reception). Instead of that, the loss of the packet is just recorded. Obviously, background packets must be confirmed by ACK frames. This is why, in the case of unsuccessful reception, retransmission procedure was carried out. The maximum values of retransmission counter were adopted to be equal to standard recommended values (7 for long frames and 4 for short). Further, for background traffic category, the value of TXOP Limit was equal to 0. It means that during one TXOP, only one packet is permitted to be sent. Other TXOP values are given in Table 1. Table 2 provides an overview of EDCAF parameters used in simulations.

TABLE 2: EDCAF PARAMETERS USED IN SIMULATIONS.

| *AC* | *AC_VO* | *AC_VI* | *AC_BK* |
|---|---|---|---|
| Packet size (*Byte*) | 160 | 1280 | 1600 |
| Packet interval (*ms*) | 20 | 16 | 12.5 |
| Generated throughput (*KByte/s*) | 8 | 80 | 128 |

Fig. 1 shows the average throughputs for different EDCAFs in the case of DSSS/CCK transmission techniques and long frame format. The throughputs are calculated taking into account packets that are sent by all stations. Two cases are considered. First, when there are no errors in transmission (marked with “0%” in Fig. 1) and second, when 10% of packets are lost (marked with “10%” in Fig. 1). It is interesting to note that the throughput of voice packets is almost constant. Increasing the number of stations in the network does not affect significantly the throughput of this category. On the other side, the throughput of video packets is nearly constant for a small number of stations in the network, and begins to decline when the number of stations exceeds 10. A more dramatic case corresponds to the throughput of background packets. Note that the throughput decreases already with 4 stations in the network (the throughput is about 35% smaller than in the case with two stations), and with 10 stations in the network practically diminishes. The reason for this lies in the inability of AC_BK (of any station) to obtain a TXOP, because it is more likely that some of the voice or video EDCAF won the right to access. Also, after each collision (internal or external), the contention window doubles, and AC_BK has to wait longer than other EDCAFs.

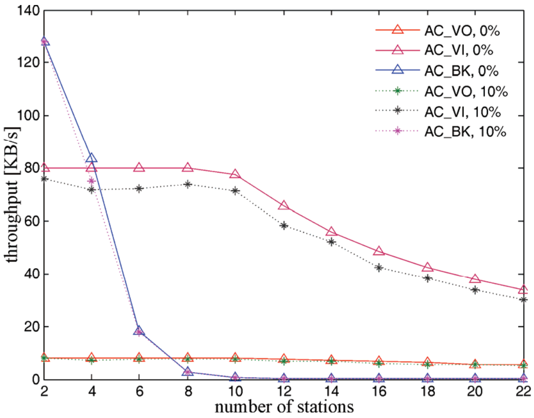

Fig. 1. Throughputs for different AC - DSSS/CCK (*Long* format).

In the case of the DSSS/CCK transmission technique and a short frame format, the average throughputs for different EDCAFs (for the cases where no errors in transmission occur and where 10% of packets are lost) are shown in Fig. 2. As in the previous case (long format frames), background traffic is affected the most by increasing the number of stations, but assuming the same number of stations throughputs are higher. Also, the stream of voice packets is almost constant, while the throughput of video packets decreases as the number of stations increases.

As expected, the situation in terms of traffic flows is much better in 802.11g than 802.11b network (Fig. 3). Throughputs of voice and video traffic categories do not fall by increasing the number of stations (flow rates practically correspond to those given in Table 2). On the other side, background traffic keeps the high values up to the inclusion of 14 stations in the network. The reason for this behavior lies in the fact that packets are transmitted much faster now. Consequently, the time of medium occupancy is considerably shorter, and after the packet delivery the medium is released completely so that the other stations (or other EDCAFs) can re-access the radio channel and send its packets.

Average delivery delays for different categories in the case of DSSS/CCK transmission technique and long frame format are given in Fig. 4. For multimedia packets, transmission delivery delay (for voice and video packets the values of the delay should not exceed 20 ms and 100 ms, respectively) and jitter are important parameters. Fig. 4 shows that these values are not reached except in the cases of error-free transmissions and a small number of stations in the network (up to 8). For a larger number of stations, the significant increase in the delays is a consequence of the waiting of packets in the queues to be sent. After an unsuccessful transmission, the stations will start the retransmission procedure, and consequently, wait for a longer time (EIFS - Extended Inter Frame Space). Therefore, the delays of some packets remain relatively short (of the order of tens of ms), while the others become approximately equal to the packet lifetime. It should be stressed that the shown values are obtained by averaging.

In the case of DSSS/CCK transmission technique and a short frame format, the average delivery delays for appropriate categories are similar to those in the case of a long format (Fig. 5).

Average delivery delays for different categories for the DSSS-OFDM transmission technique that uses a short PLCP preamble are shown in Fig. 6. For error-free transmissions, the delays are within the permissible limits; otherwise, the oscillation of average delivery delay occurs as a result of losses and rejections of the packets.

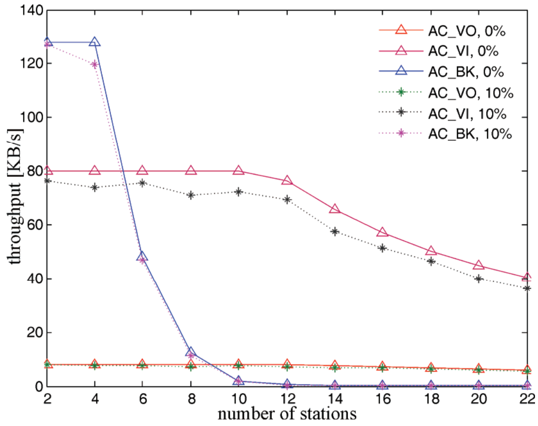

Fig. 2. Throughputs for different AC - DSSS/CCK (*Short* format).

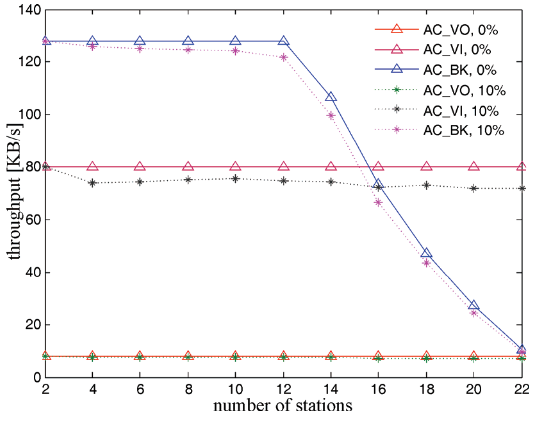

Fig. 3. Throughputs for different AC - DSSS-OFDM.

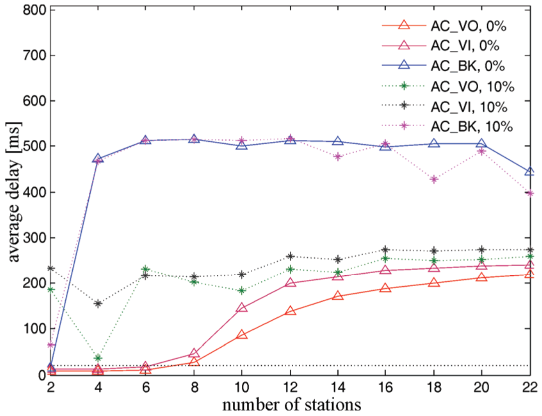

Fig. 4. Average delivery delay for different AC - DSSS/CCK (*Long* format).

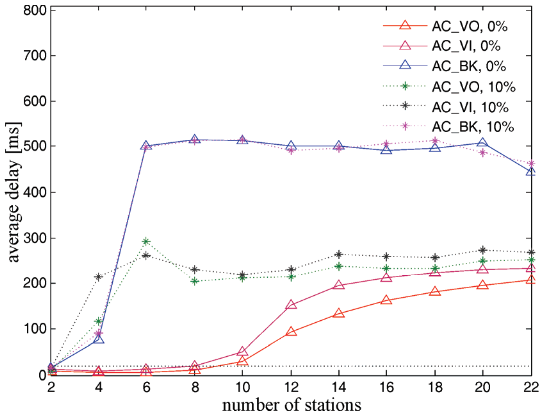

Fig. 5. Average delivery delay for different AC - DSSS/CCK (*Short* format).

Considering the cases of error-free transmissions and transmissions with 10% of lost packets separately, total channel throughputs for all three analysed transmission techniques are given in Fig. 7. Based on the obtained results, it was found that the maximum throughputs, assuming error-free transmission, for EDCA method amount to 7.6 Mb/s (long format) and 8.7 Mb/s (short format) for DSSS/CCK, and 22.8 Mb/s for DSSS-OFDM. Considering transmission with losses (10%), throughputs go down to 7.1 Mb/s and 8.1 Mb/s for DSSS/CCK, and 21.3 Mb/s for DSSS-OFDM.

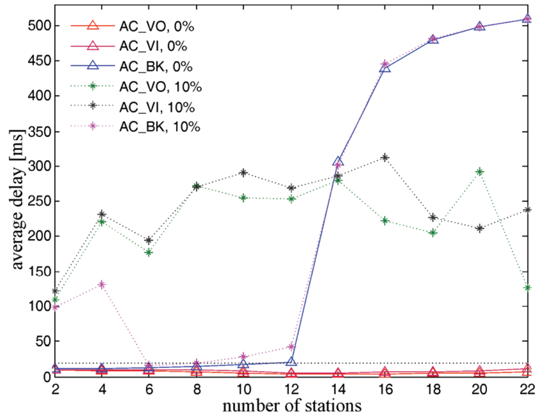

Fig. 6. Average delivery delay for different AC - DSSS-OFDM.

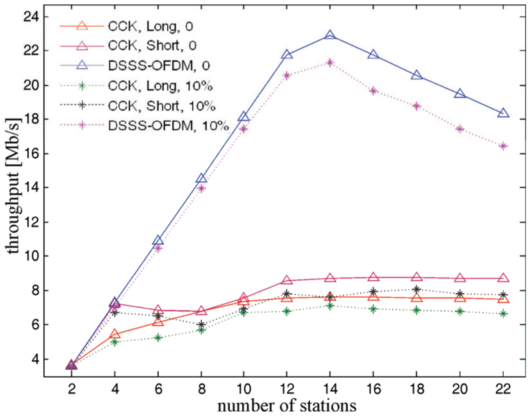

Fig. 7. EDCA: total throughputs for DSSS/CCK Long/Short format and DSSS-OFDM.

### B. *HCCA access method*

The goal was to determine the channel throughput of the network in HCCA mode. It was implied that all communication in the network is performed by "polling" the stations. According to this technique, AP sends QoS CF-Poll frames to the stations. In that way, the next station in the table gets the opportunity to use TXOP. Frames are confirmed by BlockAck mechanism at the end of TXOP, for each station.

In order to compare the obtained throughputs, traffic with the same attributes as in the case of EDCA method was generated (Table 2). Three traffic streams (TS), which correspond to voice, video and background traffic categories in EDCA mode, were generated. Clearly, background traffic does not require strict transfer conditions in terms of throughput, delivery delay, etc. Because of this, in order to compare EDCA and HCCA methods, it was taken that background traffic is a flow with the same parameters as in Table 2. For these traffic streams, the throughputs are constant and packets are of equal sizes. Practically, the values of these parameters correspond to HCCA parameters: the average throughput and medium size of MSDU frame.

Further, the length of beacon interval ($T_b$) is 100 ms. The service interval ($T_{SI}$) must have a value that is a divider of $T_b$, but not longer than the interval in which TS packets are generated. It was taken that $T_{SI}$ = 12.5 ms.

In all simulations, on the basis of the set parameters, the maximum number of stations that can be served is determined by controlled-access method.

Error-free transmission was taken into consideration, only.

In both cases, using either long or short format frame of DSSS/CCK access methods, packets are of relatively long duration, and it was determined, by access control algorithm, that 4 stations at most can be served at the same time. Nevertheless, the conditions of constant and relatively small packet delays, which are influenced by service period and the time required for the packet transmission, are satisfied. The total throughputs are close to those obtained in EDCA mode (Table 3).

TABLE 3: HCCA AND EDCA THROUGHPUTS .

| ***Number of stations*** | ***Throughput [Mb/s]*** | | | |
|---|---|---|---|---|
| | ***HCCA (Short PPDU)*** | ***HCCA (Long PPDU)*** | ***EDCA (Short PPDU)*** | ***EDCA (Long PPDU)*** |
| 2 | 3.63 | 3.68 | 3.61 | 3.66 |
| 4 | 7.27 | 7.37 | 7.22 | 5.43 |

In the case of DSSS-OFDM transmission technique the maximum number of served stations is 12. The achieved maximum throughputs (together with EDCA throughputs) are shown in Fig. 8. It is obvious that the maximum throughputs of HCCA and EDCA methods are approximately equal in 802.11g networks. Precisely, maximum throughputs of HCCA are slightly higher (on the order of 0.5%). However, the packet delivery delays in HCCA mode are smaller and limited to the duration of the service interval (SI duration was chosen to be 12.5 ms).

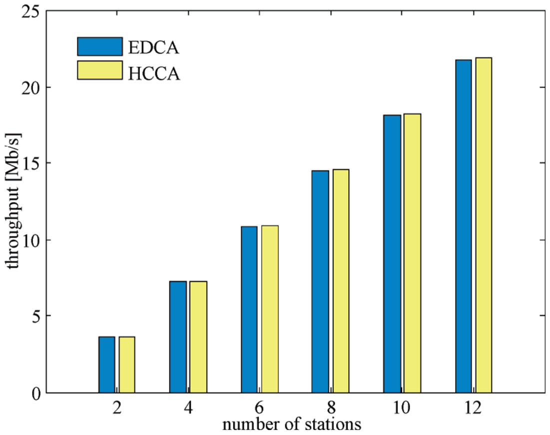

Fig. 8. Throughputs for HCCA and EDCA; DSSS-OFDM error-free transmission.

## V. CONCLUSION

On the basis of the presented results it can be concluded that the obtained throughputs differ significantly from the values declared by standard (11 Mb/s in 802.11b and 54 Mb/s in 802.11g networks). User data, i.e. data arriving from the higher layers to the MAC layer, use only a part of the total channel throughput. This is due to the fact that MAC and physical layer add their own information, which is not relevant to users, but is necessary for the proper functioning of layers. In order to increase usable throughputs, it is neccessary to reduce the amount of redundant information and/or implement more efficient modulations, for example, by using a short frame format. However, this results in weaker protection of frame on the occurrence of errors in transmission. On the other side, a part of the throughput is used for sending management and control information necessary for the proper operation of the network. The obtained maximum throughputs for EDCA method amount to 7.6 Mb/s (long format) and 8.7 Mb/s (short format) for DSSS/CCK, and 22.8 Mb/s for DSSS-OFDM, assuming error-free transmission. Having in mind transmission with losses (10%), throughputs go down to 7.1 Mb/s and 8.1 Mb/s for DSSS/CCK, and accordingly 21.3Mb/s for DSSS-OFDM.

EDCA parameters suggested by the standard are favourable for traffic of higher categories, but at the same time prevent access to categories of a lower priority. Practically, this means that in 802.11b networks, with increasing the number of stations, low-priority traffic flows become seriously "affected" by higher priority traffic. Although for scenarios with more stations involved, slightly higher channel throughputs are observed, delivered traffic consists mainly of higher priority packets (voice and video).

EDCA method is applicable in those situations where a simple prioritization of traffic is satisfactory (for example, for applications that aren't time consuming), but it is not applicable when it is necessary to support strict transfer conditions. An example of this are packet delays at the MAC layer. When there is a packet loss in transmission (a real case), before retransmission, the station must wait for a relatively long period of time to re-access the radio channel, and consequently, packets are accumulating in the queue. This leads to large delays in packet transfer causing rejection of the packets due to the too long waiting period in the buffer.

On the other hand, HCCA method takes care of the service requirements of all incoming flows. As is known, for applications which generate video and voice packets, a constant stream of packets is requred, defined by a maximum packet delay and without jitter. This type of applications is served by setting an appropriate value for the service interval in such a way as to be smaller than the specified maximum service interval of all flows.

Based on the parameters of traffic flows defined in simulations, HC served a smaller number of stations with respect to EDCA. Numerically, the maximum number of stations served by HC was 4 and 12 for 802.11b and 802.11g networks, respectively. However, by analyzing the achieved throughtputs of EDCA traffic categories (Fig. 1, 2 and 3), it is clear that the maximum number of stations calculated by HCCA admission control method corresponds to threshold values of the number of stations that can be served assuming EDCA (the threshold value is indicated by the steep decrease of background traffic throughput). It is interesting to note that in this case the total throughputs are approximately equal. In the case of HCCA mode, the maximum throughputs are 22.9 Mb/s (42% utilization) for DSSS-OFDM and 7.4 Mb/s (67%) for DSSS/CCK.

Finally, HCF introduces significant improvements in terms of service quality allowing access to multimedia services in 802.11 networks. Further improvements of HCF could include optimal settings of EDCA parameters or a more efficient „polling“ algorithm.

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