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Abstract

Wireless LAN, based on the IEEE 802.11 standards, has been extensively studied since its release. The topic of several of these research papers was the discrepancy of delays and buffer overflow probabilities experienced by the Access Point on one hand and the stations on the other hand. This is widely referred to as the unfair channel access phenomenon. A related issue that has not yet been investigated is another kind of unfairness resulting from different collision probabilities. Interestingly, the latter unfairness favors the Access Point, contrary to the former. In this paper, we present an extensive simulation study of this problem and validate the results by means of analytical models. Here, mainly bi-directional voice traffic and TCP traffic flows are considered. The results reveal how pronounced this unfairness is and how the recent introduction of the Quality-of-Service extension exacerbates the unfair channel access phenomenon.

1 Introduction

The continuous standardization of *Wireless Local Area Networks* (Wireless LANs) is a success story. Since the first release of the IEEE 802.11 Wireless LAN standard in 1997 [1], it gradually improved its performance and evolved into a very flexible and well-understood technology. Today, this wireless technology is a standard equipment in laptops and other portable and mobile devices. These provide convenient wireless access to the Internet for users at home, in public facilities, and in more and more areas of our everyday life.

The standard defines two access mechanisms, the *Distributed Coordination Function* (DCF) and the Point Coordination Function, whereas only the DCF has actually been implemented. This method is based on *Carrier Sense with Collision Avoidance* (CSMA/CA). The collision avoidance in the DCF is realized by a truncated binary exponential backoff algorithm. Thus, collisions can only occur if similar backoff windows are chosen. All stations within a cell use the same parameter set for the contention resolution. This should assure a fair medium share between the stations. Berger-Sabbatel et al. [2] underlines this statement for ad-hoc networks with similar traffic loads at the stations. In contrast, several papers [3, 4, 5] have been published showing that the mechanism is unfair in an infrastructure network, where all traffic has to be routed over an *Access Point* (AP), even if the stations reside within the same area. All papers have different "fairness" considerations, either the short-term throughput at the MAC layer, the delay, or the throughput at the TCP layer. They agree however, that uplink flows (stations to AP) are favored in comparison to downlink flows (AP to stations). The extensive queuing delays and buffer overflows at the Access Point are identified as the reason for this.

Because these works analyze the system on flow level exclusively, the collision probabilities are neglected. When focusing on the stations themselves without regarding queuing effects, the fairness between the Access Point and the station inverts. In such a scenario, the Access Point is preferred compared to the stations in terms of packet loss. This new perspective on the unfair channel access is shown in this paper with analytical models and simulation. One of the conclusions we draw is that the current status of the network cannot be observed at the Access Point alone. Therefore, if load or admission control is to be applied, all aspects, the contention delay, the packet loss, and queuing effects have to be considered at each station.

The remainder of this work is organized as follows. In Section 2 the work related to the unfairness problem is shown. Section 3 introduces the unfair channel access phenomenon. In Section 4 simulation results are presented showing the unfairness between the Access Point and stations for different traffic models. The simulation results from OPNET and MATLAB are validated by analytical models. Section 5 shows how the unfair channel access phenomenon is even intensified in IEEE 802.11e networks with the introduction of transmission bursts. Finally, a short conclusion and a brief outlook is given in Section 6.

2 Related work

A large amount of papers have been published on the Wireless LAN channel access. In this section however, just the papers addressing any kind of unfairness in Wireless LAN are presented. The first part covers general unfairness papers and the second part focuses on TCP unfairness over Wireless LAN.

Gilles Berger-Sabbatel [2] analyzes the short-term fairness in Wireless LAN and its impact on the delay. To evaluate the fairness in Wireless LAN saturated sources without any hidden oder exposed stations are used. Using the *Jain fairness index*, it is shown by an analytical model, simulations, and measurements, that the DCF is short-term fair. Furthermore, it is claimed that many papers [6, 7] consider the IEEE 802.11 standard as short-term unfair because these papers use the Wavelan CSMA/CA access method [8] for their simulations without noticing that the access method differs from the DCF.

In [9] and [3], the authors observe a significant unfairness between downlink and uplink flows when the DCF or the *Enhanced Distributed Channel Access* (EDCA) from the IEEE 802.11e [10] standard is employed in a Wireless LAN with an Access Point. It is claimed that the DCF allows equal utilization of the medium and thus, if the downlink has much more offered load than the uplink, the downlink becomes the bottleneck. Grilo et al. [9] use three traffic models, a voice model, a video model, and an HTTP traffic model. The results show that as soon as the utilization increases, the Access Point becomes the bottleneck both with the DCF and the EDCA. To solve the problem, the Access Point should use a polling based access mechanism. In contrast, [3] proposes a mechanism where the Access Point uses a shorter interframe space duration compared to the stations before accessing the shared medium.

The TCP unfairness between uplink and downlink connections in Wireless LANs is presented in [11, 12, 13]. It is shown for different traffic models that the downlink flows tend to starve. The first paper claims that the starvation is caused by both the TCP-induced and the MAC-induced unfairness. Pilosof et al. [12] claim that the problem can be solved by increasing the buffer size at the Access Point to avoid packet loss due to buffer overflow. Similar to this paper, [13] identifies the equal access probabilities of the Access Point and the stations as the problem for the TCP unfairness. However, they show that an increased buffer size does not solve this misfortune and propose an adaptive EDCA parameter set.

Another paper about TCP unfairness is presented by Blefari-Melazzi et al. [5]. They claim that downstream TCP connections suffer because of the arising congestion and corresponding packet losses happening in the download buffer at the Access Point. Furthermore, for upstream TCP connections, the Access Point has to transmit the TCP Acknowledgments which are delayed and lost, because the Access Point cannot access the medium with a priority higher than other stations. [14] also looks at the TCP fairness for upstream flows. They have shown that the TCP acknowledgment will be delayed using the standard DCF access mechanism. However, they propose a scheme of how to prioritize the Access Point by using a different parameter set for the medium access according to the IEEE 802.11e standard. The proposed mechanisms were tested in an experimental scenario and the results can be found in [15].

In this paper, we present the fairness in terms of collision probabilities which is completely different to the papers described above. Therefore, we first introduce our fairness considerations with a small simulation scenario and afterwards, we will present the results of complex simulation studies using UDP voice traffic and TCP traffic flows. These results are validated by analytical models.

3 Introduction to the Unfair Channel Access Phenomenon

Since the contention access parameters for both the AP and the stations are identical, see Table 1, it could be expected that the channel access among stations and the AP is fair in terms of collision probability. To underline this assumption, a simulation is configured using the OPNET Modeler [16] simulation environment with the IEEE 802.11g Wireless LAN model. 23 stations are communicating with the Access Point using a bi-directional voice stream. Each voice stream is characterized by the interarrival time of the packets, the packet size, and the beginning of the voice conversation, the phase. In the simulation, the phase is chosen uniformly distributed within an interval of 10 ms. The ITU-T G.711 [17] voice codec is used with an interarrival time of 10 ms and a data rate of 64 kbps. Fig. 1 depicts the average collision probability of the scenario during the steady-state phase.

Surprisingly, the simulation exhibits that the channel access is severely unfair between the AP and the stations. The average collision probability measured at the AP is just below 5 % and the lowest in the network. The average collision probability of the stations

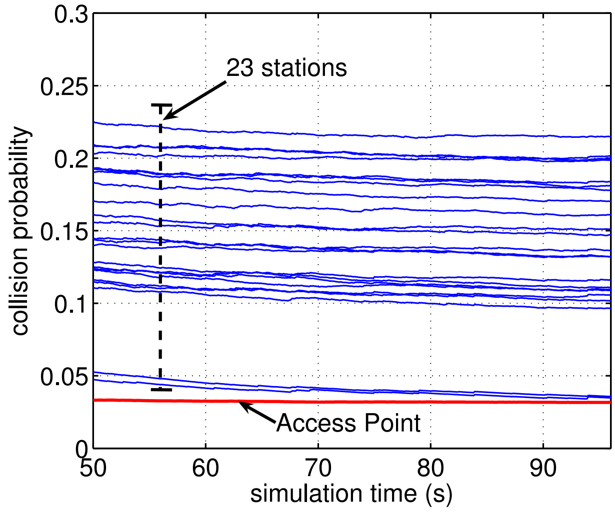

Figure 1: Unfairness between Access Point and stations

ranges from around 5 % up to over 20 %. The cause of the different collision probabilities of the stations lies in the phase patterns. Further simulations have shown the same behavior, i.e. that the collision probability of the Access Point is always the lowest. We should remark that only one packet is transmitted during one transmission opportunity, meaning that no frame bursting (TXOPLimits) from the IEEE 802.11e standard is used. The effect of frame bursting is shown in Section 5.

The difference in the collision probabilities can be traced back to the unfair channel access between the AP and the stations. This can be explained as follows. Each station competes against 22 stations and the Access Point for the channel access. On the other hand, the Access Point competes against 23 stations. It seems that every network entity has to compete against 23 others. However, the Access Point has to access the channel as often as all 23 stations together. During one 10 ms interval each station has to transmit one voice packet, whereas the Access Point has to access the channel 23 times. In other words, the probability of a frame collision upon a channel access of a station is significantly higher compared to the collision probability of the Access Point. This explains the different collision probabilities of a single station and the AP from Fig. 1.

4 Unfairness of the DCF

The simple simulation scenario has shown the unfairness between voice stations and the Access Point in terms of collision probability. In this section, an analytical model is set up for the voice traffic scenario. The results are compared with a simple MATLAB simulation and a detailed OPNET simulation. The second subsection deals with the unfair channel access for downlink TCP flows. There, the unfairness is even more obvious.

4.1 Unfair Channel Access Using Voice Traffic

As in the previous scenario, an infrastructure basic service set is configured with N stations and one Access Point. The stations and the Access Point are communicating symmetrically using the ITU-T G.711 voice codec [17] with a packet interarrival time of $A = 10\,ms$. Further, let M be the number of slots between two packet arrivals. These slots can either be used for packet transmissions, interframe spaces, or contention.

Assume that all stations and the AP are able to transmit their packets within the interval A. This means that every station is able to transmit one packet during this interval and the AP is able to transmit N packets. So, during the interval A, $2 \cdot N$ packets are transmitted. X slots are needed to transmit one packet, including the ACK, the *Short Interframe Space* (SIFS), the *Distributed Interframe Space* (DIFS), and the packet transmission itself. This means that during the interval A, the remaining $M - 2 \cdot N \cdot X$ slots are available for contention.

Now the access probability and collision probability can be calculated using an iteration process. The iteration starts by calculating the access probabilities assuming that no collision occurs on the channel. This results in the probability

$$p'_s = \frac{1}{M - (2N-1)X} \tag{1}$$

that a station accesses a given slot and the probability

$$p'_{AP} = \frac{N}{M - (2N-1)X} \tag{2}$$

that the Access Point accesses the medium. The numerator shows the number of packets that have to be transmitted and the denominator describes the number of available slots. One transmission is subtracted because the station or Access Point whose access probability is calculated has not yet transmitted its packet. Having defined the initial access probabilities of the iteration process, the independent collision probabilities can be calculated:

$$q_s = 1 - (1 - p'_{AP})(1 - p'_s)^{N-1} \tag{3}$$

$$q_{AP} = 1 - (1 - p'_s)^N, \tag{4}$$

with q_s being the collision probability of the stations and q_{AP} being the collision probability of the Access Point. Before redefining the access probabilities, the mean number of collisions have to be estimated. The mean number of transmissions needed for a successful packet reception leads to $X_s = E(Geo(q_s)) = \frac{q_s}{1-q_s}$ for the stations and $X_{AP} = E(Geo(q_{AP})) = \frac{q_{AP}}{1-q_{AP}}$ for the Access Point. The transmission of N packets results in an N-fold geometric distribution or in $Y_s = E(NegBin(q_s, N)) = \frac{N \cdot q_s}{1-q_s}$ for all stations together and $Y_{AP} = E(NegBin(q_{AP})) = \frac{N \cdot q_{AP}}{1-q_{AP}}$ for the Access Point. Assuming that two or more packets collide, the mean number of collision K can be defined as

$$K \leq \left\lceil \frac{\frac{N \cdot q_s}{1-q_s} + \frac{N \cdot q_{AP}}{1-q_{AP}}}{2} \right\rceil \tag{5}$$

Knowing the average number of collisions, the remaining number of slots for contention is $M-(2N-1+K)X$ and the new probability that a station accesses a slot is

$$p'_s = \frac{\frac{q_s}{1-q_s}+1}{M-(2N-1+K)X} \tag{6}$$

$$p'_{AP} = \frac{N\frac{q_{AP}}{1-q_{AP}}+N}{M-(2N-1+K)X} \tag{7}$$

Finally, we can iterate between q and p', using (1) and (2) as the initial access probabilities.

In order to compare the results from the analytical model, we have performed simulations using MATLAB and OPNET. The MATLAB simulation includes the CSMA/CA mechanism without regarding extensions like immediate transmission from the Distributed Coordination Function or influences from other layers. In contrast, the OPNET simulation includes the complete DCF with all its extensions and simulates all layers of the ISO/OSI Stack. The parameters used for the simulation and the analytical model are shown in Table 1.

Table 1: Parameters for the simulations

Parameter	**Value**
Voice frame duration	10 ms
Wireless LAN standard	IEEE 802.11g
Data rate	54 Mbps
Control data rate	24 Mbps
Slot length	9 μs
DIFS time	28 μs
SIFS time	10 μs
CWmin	15
CWmax	1023
Packet length	960 bits+header
ACK length	112 bits+header
Signal extension	6 μs
AP buffer size	4,096,000 bits

The results from both the analytical model and the MATLAB simulation are illustrated in Fig. 2. It shows the average collision probabilities for 2 to 24 voice stations. Two observations can be made from this experiment. First, it reveals that the analytical model and the simulation fit well. The second observation is that both the analytical model and the simulation reveal the unfairness between the Access Point and the stations. For 24 stations, the collision probability of the Access Point is around 5.5 % and for the stations around 10.5 %.

The results show however only the unfairness in terms of collision probability for the CSMA/CA channel access protocol. The DCF of the IEEE 802.11 standard has some

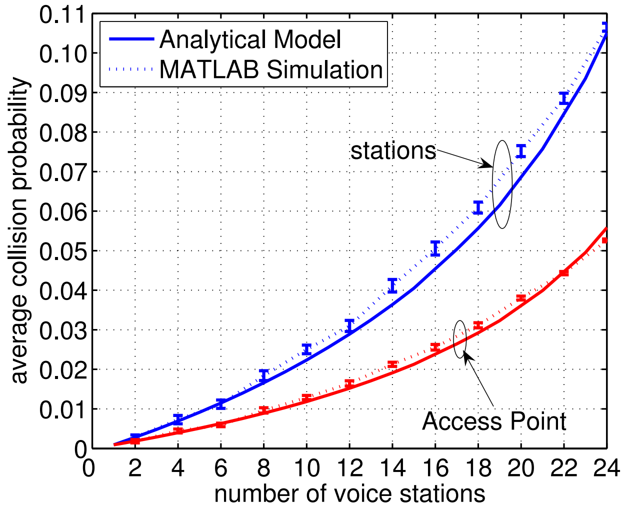

Figure 2: Unfairness between AP and stations; comparison between a MATLAB simulation and analytical results

extensions to the CSMA/CA protocol like immediate transmissions and post backoffs. Therefore, a detailed simulation was set up using the OPNET Modeler 12.0. The simulation accounts for the complete DCF and the full ISO/OSI stack. In Fig. 3, the OPNET simulation results are demonstrated together with the results from the analytical model. The figure reveals that the collision probability of the analytical model is higher than that of the simulation, especially when the network is not at its capacity limits. This effect results from immediate transmissions. If a station in idle mode senses the medium idle for at least a *Distributed Interframe Space* (DIFS) it is allowed to directly transmit the packet without waiting for a backoff interval to expire. In highly loaded networks, the number of immediate transmissions decrease. This is the reason why the collision probabilities of the analytical model and simulation match well under high load. However, the figure also shows the unfairness between the Access Point and the stations. For 27 stations, the collision probability of the Access Point is 8.23 % and for the stations 15.68 %.

4.2 Unfair Channel Access for TCP Traffic Flows

All results, the OPNET simulation, the MATLAB simulation, and the analytical model show the unfairness in Wireless LAN for bi-directional voice traffic. In this chapter however, it is evaluated whether the unfairness between stations and the Access Point also occurs for TCP traffic. Therefore, saturated downstream TCP traffic is considered which means that every second TCP downlink packet is acknowledged by the station. The packet size for the downlink packets is set to 1500 Bytes. With all headers, the MAC Acknowledgment frame, and the interframe spaces, 37 slots are needed to completely transmit one TCP packet using the IEEE 802.11g standard. In contrast, the TCP

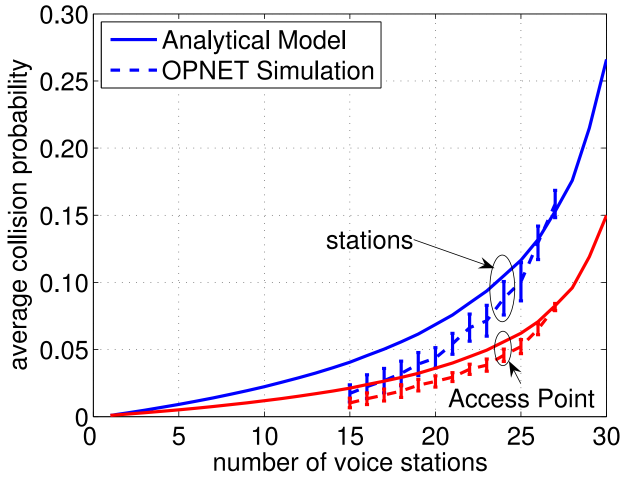

Figure 3: Comparison of OPNET simulation results with the complete DCF and analytical results

Acknowledgment only needs 13 slots for transmission. Further parameters for the TCP simulations are shown in Table 2.

Table 2: Parameters for the TCP simulations

Parameter	**Value**
Application	saturated TCP
Packet size	1500 Bytes
TCP receive buffer	65535 Bytes
Fast Retransmit	enabled (TCP Reno)
MTU	WLAN (2304 Bytes)
WLAN AP buffer	1024e4 bits
WLAN station buffer	1024e3 bits
CWmin	15
CWmax	1023

The simulations have been performed using both the OPNET Modeler and MATLAB. Thereby, similar to the voice scenarios, the OPNET simulations account for the complete stack with a detailed TCP model and the MATLAB simulation only considers the Wireless LAN MAC layer and a TCP emulation. An analytical model for the unfairness phenomenon using TCP traffic is rather complex. The analytical voice traffic model cannot be used directly, because the packets do not arrive in fixed intervals and especially the TCP Acknowledgments from the stations depend on the transmitted packets on the downlink. Therefore, only an approximation is made also using an iteration process. To start with the iteration, the access probabilities are calculated using the following equations:

$$p'_s = \frac{1}{2 \cdot N \cdot CW} \quad (8)$$

$$p'_{AP} = \frac{1}{CW}. \quad (9)$$

As you can see from these first equations, we assume that the backoff is calculated between 0 and the *contention window* (CW) in every backoff interval. This results in an access probability of $\frac{1}{CW}$ for the Access Point; because the Access Point tries to transmit a packet in every contention phase. In contrast, a station only tries to access every second frame. N is again the number of stations in the system. From this starting point of the iteration process, the collision probability is calculated similar to the analytical voice model:

$$q_s = 1 - (1 - p'_{AP})(1 - p'_s)^{N-1} \quad (10)$$

$$q_{AP} = 1 - (1 - p'_s)^N. \quad (11)$$

Now, the access probabilities for the stations can be redefined

$$p'_s = \frac{\frac{q_s}{1-q_s} + 1}{\frac{4}{3} \cdot N \cdot CW} \quad (12)$$

and the Access Point

$$p'_{AP} = \frac{\frac{q_{AP}}{1-q_{AP}} + 1}{\frac{3}{4} \cdot CW}. \quad (13)$$

The factor $\frac{3}{4}$ and $\frac{4}{3}$ result from simulation studies and depend on the number of packets which are transmitted before the Access Point or the station can access the wireless medium. The collision probabilities from the simulations and analytical model are shown in Fig. 4. On the x-axis, the number of TCP stations is increased from 1 up to 16. The figure reveals that the collision probability of the Access Point is not influenced by the number of clients. In contrast, the collision probability of the stations increase with an increasing number of stations until a constant level of around 14.4 % is reached. If we compare the collision probabilities of the bi-directional voice scenario and this TCP scenario, the unfairness between Access Point and the stations becomes even more obvious. The collision probabilities of the station is 2.6 times higher than the collision probabilities of the Access Point.

In real-world scenarios, this unfairness is even worse. With the introduction of the TXOPLimit in the IEEE 802.11e [10], the Access Point is allowed to transmit several packets in a row only separated by short interframe spaces. In the following section, we will show the unfairness in IEEE 802.11e networks in terms of collision probability, contention delay, and delay variation.

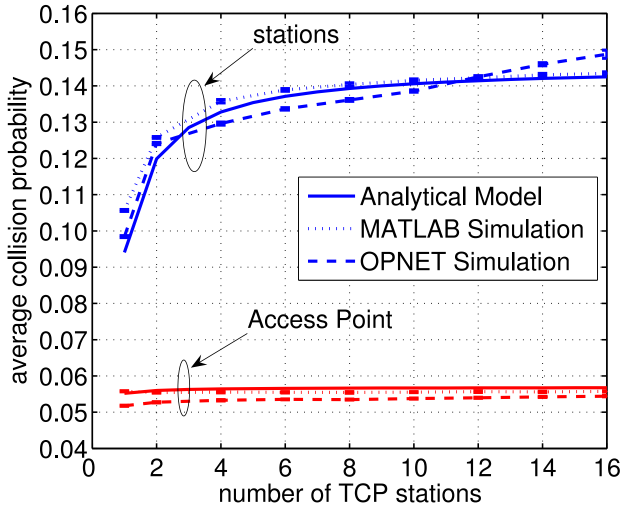

Figure 4: Unfairness between AP and stations using saturated TCP traffic on the downlink

5 Unfairness of the EDCA

With the introduction of the IEEE 802.11e standard and the TXOPLimit, the unfairness between stations operating at different loads changed. The TXOPLimit defines the time a station is allowed to transmit packets in a row after it gained access to the medium. The packets are only separated by the Acknowledgment frame and a short interframe space. For our scenario, this means that the Access Point can transmit more than one packet, up to all N packets for the N stations, after it gained access. When considering the detailed analytical model this means that the access probability and collision probability of the Access Point decrease. The effect is that more stations can be supported because the wireless medium is better utilized. However, the unfairness between stations and Access Point increases.

5.1 Influence of the TXOPLimit on Voice Traffic

The influence of the TXOPLimit parameter can also be shown with some small modifications of the analytical model from Section 4. q_c and q_{AP} remain the same and only p'_s and p'_{AP} have to be changed. For the stations, the nominator remains the same and the denominator has to take the number of packets within a burst into account. This depends on the number of stations in the system. The more voice stations are active in the system, the more average number of packets are transmitted per burst from the AP. Thus, the Access Point just has to content for medium access $S = \lfloor \frac{N}{4} \rfloor$ times instead of N times. However, the number of slots needed to transmit a burst is enlarged to $X + (\frac{N}{S} - 1) \cdot Y$ where Y is the time it takes to transmit each ongoing packet

(SIFS+Data). This results in the access probability of the stations:

$$p'_s = \frac{\frac{q_s}{1-q_s} + 1}{M - (N-1+K)X - S(X + (\frac{N}{S} - 1)Y)} \tag{14}$$

and the Access Point:

$$p'_{AP} = \frac{S \cdot \frac{q_{AP}}{1-q_{AP}} + S}{M - (N+K)X - (S-1)(X + (\frac{N}{S} - 1)Y)}. \tag{15}$$

Finally, the average number of collisions decreases which results in:

$$K \leq E\left[\left\lceil \frac{NegBin(q_{AP}, S) + NegBin(q_s, N)}{2} \right\rceil\right]. \tag{16}$$

The results of the analytical model and the OPNET simulations are shown in Fig. 5. For the simulation, the parameter settings have been set to the values specified in Table 1 and the TXOPLimit for the voice queue is set to 1504 μs. With these settings, a maximum number of 32 voice stations can be supported. The figure reveals two things. On the one hand, the collision probability in both directions decreases compared to the results from Fig. 3 but on the other hand, the unfairness between Access Point and stations has increased. While the average collision probability stays almost constant at around 0.8% with an increasing number of stations, the collision probability of the stations increases from 1.5% for 20 stations up to 11.8% for 32 stations.

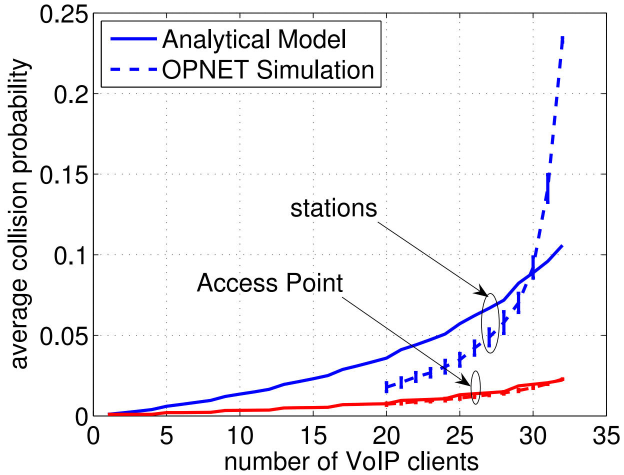

Figure 5: Unfairness between AP and stations with a TXOPLimit of 1504 μs

5.2 Influence of the TXOPLimit on TCP Traffic

Finally, the influence of the TXOPLimit parameter is evaluated for TCP traffic flows. The TCP traffic model from Section 4.2 is used for the simulations. Fig. 6 exhibits the average collision probabilities for three different settings of the TXOPLimit, one data packet, 1504 μs, and 3008 μs. With a TXOPLimit of 1504 μs up to 4 TCP packets can be transmitted in a row after the Access Point has gained access to the wireless medium. Since no Block-Acknowledgements are used, the Access Point recognizes a collision right after the first packet of a transmission burst is transmitted and will stop the transmission of the following burst packets.

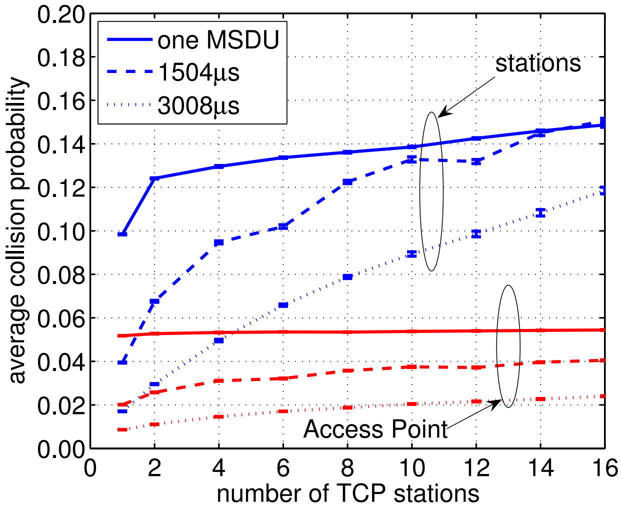

Figure 6: Impact of transmission bursts on the collision probabilities

The figure reveals that an increasing TXOPLimit decreases the collision probability for both the Access Point and the stations because the access probability of the Access Point decreases. However, the unfairness between the stations and the Access Point remains the same. Therefore, we can conclude that the IEEE 802.11e standard does not dispose of this unfairness phenomenon neither for voice UDP flows nor for TCP flows.

6 Conclusion

In this paper, we revealed an unfairness phenomenon on the channel access in Wireless LAN. In contrast to other publications in this area, which focus mostly on the fairness of TCP streams in Wireless LANs, we have taken a look at the fairness in terms of collision probability and contention delay on the wireless link. We have seen that highly loaded stations, normally the Access Point, are prefered compared to low loaded stations. Analytical models and simulations have shown that the collision probabilities differ by a factor of 2. The knowledge of this unfairness is a prerequisite for load and admission control mechanisms. If these mechanisms are based on measurements at the Access Point only, the gathered data does not reflect the current situation appropriately.

Acknowledgments

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