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Robustness Analysis of the Wireless LAN MAC Protocols with QoS Support

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Abstract

In the past months the deployment of Wireless Local Area Network (WLAN) hot spots has vastly increased in many places world-wide and the IEEE 802.11 standard is playing a more and more important role in future mobile radio networks of the 4th Generation (4G). In order to fulfill the requirements of such 4G networks the WLAN technology has to provide mechanisms for the transport of Quality-of-Service (QoS) traffic. Therefore, service differentiation between the different types of multimedia traffic and best-effort traffic is inevitable. In this paper, we study the robustness of current and future QoS Medium Access Control (MAC) protocols in three different scenarios with overlapping cells.

Keywords

Wireless LAN, Quality-of-Service, IEEE 802.11e

Working Group 1

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Abstract

In the past months the deployment of Wireless Local Area Network (WLAN) hot spots has vastly increased in many places world-wide and the IEEE 802.11 standard is playing a more and more important role in future mobile radio networks of the 4th Generation (4G). In order to fulfill the requirements of such 4G networks the WLAN technology has to provide mechanisms for the transport of Quality-of-Service (QoS) traffic. Therefore, service differentiation between the different types of multimedia traffic and best-effort traffic is inevitable. In this paper, we study the robustness of current and future QoS Medium Access Control (MAC) protocols in three different scenarios with overlapping cells.

1 Introduction

Wireless Local Area Networks (WLAN) complying to the IEEE 802.11 standards family gained an enormous importance in recent years. So-called hot spots pop up in large numbers all around the globe at a pace that is still increasing rapidly. On the contrary, 2.5G and 3G systems with their support for higher data rates were deployed and show the general need for broadband data access anywhere, anytime. Each technology has its strengths and weaknesses in certain areas, as they were designed for different usage scenarios. This led to the discussion of future 4th Generation Mobile Networks (4G). It is expected that it will become a heterogeneous network consisting of a number of different access technologies in order to utilize the strengths of all. Nevertheless, there are still a lot of unsolved problems on the way to a complete integration.

The advantages of WLAN in the context of 4G are clearly the high data rates of currently up to 54 Mbps, the license free spectrum, and the cheap hardware. The drawbacks are a still missing support for Quality-of-Service (QoS), which is one of the major advantages of other wireless systems. To be able to support QoS in WLAN networks, the IEEE formed the IEEE 802.11e task group in 2001. The standard is still not officially finished and published, but the draft version has reached a rather stable state [1]. It basically defines two different approaches: an extended version of the existing polling scheme as well as a distributedly controlled prioritization scheme based on the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) medium access control mechanism. Both mechanisms can support QoS in single cell scenarios, i.e. cases where only a single Access Point (AP) is used.

In the context of 4G systems, this might not be sufficient. The IEEE 802.11b and IEEE 802.11g standards allow the largest coverage areas and are thus the most interesting for large-scale deployments. However, they only support three non-overlapping channels. Therefore, it is easy to see that it is not possible to cover large areas such as office buildings without the problem of an overlap in AP coverage and frequency band. As already shown in [2], these overlaps cause great problems even for best-effort traffic. It can thus be expected, that the consequences on QoS mechanisms that are based on similar mechanisms will be even worse. Therefore, we study the different QoS mechanisms in overlapping cells. Most studies about the IEEE 802.11e draft standard ignore these scenarios and focus on single-cell scenarios ([3], [4], [5]).

The paper is organized as follows. In Section 2 the different QoS MAC protocols will be explained. This includes the already standardized polling mechanism as well as the newly defined approaches. Quality assessment for voice or video transmissions can not be based on pure delay, jitter, or packet loss statistics. Therefore, Section 3 describes the methods PESQ, PSNR, and MOS that were used in our studies. Section 4 summarizes the simulation approach used in order to evaluate the QoS capabilities. The results are shown in Section 5. Finally, Section 6 concludes the paper.

2 Wireless LAN QoS MAC protocol overview

The initial Wireless LAN standard IEEE 802.11 specifies two different access mechanisms on the MAC layer. The basic mechanism *Distributed Control Function (DCF)* defines a distributed access mechanism where all the involved Stations equally share the medium. In addition, the *Point Coordination Function (PCF)* was included in the standard. It defines a polling mechanism, where a special Station, usually the Access Point, contains a list of Stations to be polled.

In DCF mode, all Stations have equal rights. Thus, no service differentiation can be reached. While the PCF provides a rudimentary form of assigning different priorities, it is still not a sufficient way to support QoS in most WLAN environments. Therefore, the IEEE 802.11e standard was initiated which defines "MAC Enhancements for Quality of Service" in WLAN. It specifies two enhancements of the basic mechanisms which are together referred to as *Hybrid Coordination Function (HCF)*. One enhancement aims at the polling mechanism while the second extends the DCF mechanism. These MAC protocols and their different capabilities to support QoS are explained in the following.

2.1 Hybrid Coordination Function (HCF)

The HCF offers a contention-based and a contention-free access method to provide QoS Stations (QSTA) with prioritized and parameterized QoS access to the wireless medium, while still supporting best-effort traffic for non-QoS STAs. The contention-based service is defined as Enhanced Distributed Channel Access (EDCA) and the contention-free based service is provided by the HCF Controlled Channel Access (HCCA).

2.1.1 Enhanced Distributed Channel Access (EDCA):

EDCA is based on differentiating User Priorities (UP), as defined in Table 1. It supports 8 different UP values from 0 to 7 as defined by the IEEE 802.1D standard. The UPs are mapped to Access Categories (AC) as shown in Fig. 1. ACs are sorted from AC0 to AC3 with AC3 having the highest priority for medium access. The service differentiation is achieved by varying the amount of time a Station senses the channel to be idle before starting the contention window (carrier sensing interval), the length of the contention window to be used and the duration a Station may transmit after it acquires the right to transmit (TXOPLimit).

Table 1: User Priority to Access Category Mapping

User Priority	802.1D Designation	Designation (Informative)	AC	CWmin	CWmax	TXOPLimit
0	Best Effort (BE)	Best Effort	0	31	1023	5.00E-05
1	Background (BK)	Best Effort				
2	-	Best Effort				
3	Excellent Effort (EE)	Video Probe	1	31	1023	3.00E-05
4	Controlled Load (CL)	Video	2	15	31	3.00E-05
5	Video (VI)	Video				
6	Voice (VO)	Voice	3	7	15	3.00E-05
7	Network Control (NC)	Voice				

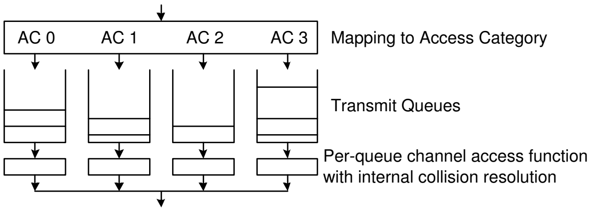

Figure 1: HCF Access Categories

For each AC an enhanced variant of the DCF called Channel Access Function (CAF) contends for the medium using a set of EDCA parameters from the EDCA Parameter Set element. Each CAF represents a virtual DCF STA with own parameters. The EDCA parameter set is defined by the Arbitration Interframe Space (AIFS), CWmin, CWmax, and TXOPLimit.

In DCF mode, a STA uses a carrier sensing interval of Distributed Interframe Space (DIFS) to decide if the medium is idle. In EDCF mode, different time intervals are used. These AIFSs are usually longer than the DIFS. Therefore, a certain prioritization can be reached. If two Stations want to transmit at the same time, the Station with the shorter IFS will get access. Therefore, lower priorities use larger IFSs in EDCA mode.

In EDCA mode, the backoff procedure of the DCF is changed. The basic mechanism defines, that a number of backoff slots is taken uniformly distributed from the interval of $[0, CW]$. Initially the CW value is set to the value CWmin. Whenever a packet loss occurs, the CW value is increased by $CW' = (CW + 1) * 2 - 1$ until the maximum value CWmax is reached.

For DCF mode, the default values are $CWmin = 31, CWmax = 1023$. EDCA uses these values to define different priorities. The final version of the standard is not finished, such that only recommended values, shown in Table 1, can be found. Here, the highest priority class is assigned a CWmin value of 7 and a CWmax value of 15 while the lowest priority class is assigned the values 31 and 1023. This will lead to different mean contention window sizes. Clearly, a STA with a lower mean contention window will get access to the medium more often. Thus, a prioritization can be reached.

2.1.2 HCF Controlled Channel Access (HCCA):

The HCCA mechanism is a polling mechanism similar to the PCF mechanism. It defines a centralized coordinator, called Hybrid Coordinator (HC), operating under QoS-aware rules with some significant differences to the point coordinator mechanism of PCF.

However, the polling mechanisms exhibit major problems in the complex cell scenarios considered in our studies. In these cases, all QoS polling mechanisms defined for Wireless LAN cannot provide any QoS to the involved STAs. The main reason is that the CFPs of overlapping cells will usually overlap in time as well, which destroys the polling mechanism in both cells. Therefore, the HCCA mechanism will not be considered in the following.

3 Voice and Video evaluation mechanisms

We want to study the QoS capabilities of various Wireless LAN MAC protocols. Therefore, QoS demanding applications such as voice and video are considered while best-effort traffic, in our case FTP up- and downloads, is used in the background. However, simple traffic statistics, such as delay, jitter, or packet loss are not sufficient to evaluate the user-experienced QoS of voice and video applications (streaming, conferencing). The ITU defined more sophisticated techniques that are explained in the following.

3.1 Perceptual Evaluation of Speech Quality (PESQ) and Mean Opinion Score (MOS)

PESQ is the most widely accepted standard for measuring voice quality of VoIP networks as defined in [6]. It is an objective method for end-to-end speech quality assessment of narrowband telephone networks and speech codecs. PESQ compares the original signal to the degraded output of the tested system.

The PESQ value is transferred from an objective quality scale to a subjective Mean Opinion Score (MOS) value as defined in [7]. The MOS provides a value between 1 and

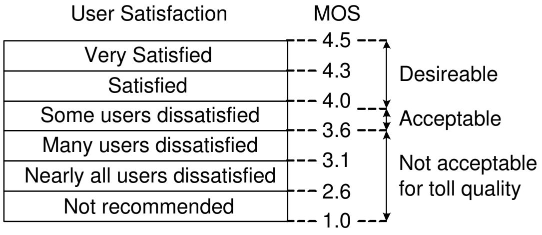

Figure 2: Mean Opinion Score (MOS)

Quality	PSNR [dB]	MOS
Excellent	37	5
Good	[31; 37)	4
Fair	[25; 31)	3
Poor	[20; 25)	2
Bad	20	1

Figure 3: PSNR to MOS mapping

4.5 as shown in Fig. 2. These MOS values can be mapped to a subjective interpretable value reaching from *desirable* to *non-acceptable* based on different speech characteristics.

3.2 Peak Signal to Noise Ratio (PSNR)

Analogous to voice sample analysis, there also exist specific statistics for evaluating the perceived quality of a video transmission. PSNR is a subjective interpretation of the quality of a transmitted video stream. It compares the maximum possible signal energy to the noise energy, which results in a higher correlation to the subjective quality perception than the conventional SNR approach.

The details of the PSNR can be found in [8] and [9]. As for the PESQ value for voice traffic, the PSNR value of a transmitted video stream can be mapped to MOS values as defined in Fig. 3.

4 Simulation Environment

In this section we introduce the simulation model that was used to retrieve the results. This includes the simulation scenarios as well as the modeled user behavior in terms of application usage.

All scenarios were simulated using the OPNET simulator with our own version of the MAC layer, which supports the IEEE 802.11e standard. We have chosen a simulator, because the QoS extension is not yet implemented in any Access Point and an analytical model will be too complex.

4.1 Simulation Scenarios

The goal of this study is to evaluate the QoS capabilities of Wireless LAN MAC protocols. In order to cover larger areas, such as whole office buildings, a number of Access Points have to be deployed to get a complete coverage. As already mentioned earlier, the WLAN standard IEEE 802.11b only allows for three non-overlapping channels. But considering the large-scale environment just explained and the restricted number of channels, it becomes obvious that there will always be some areas where AP coverage overlaps in terms of location and channel.

Nevertheless, the IEEE did not explicitly consider these scenarios in the standardization process. The QoS enabling extensions explained in Section 2 were defined to work

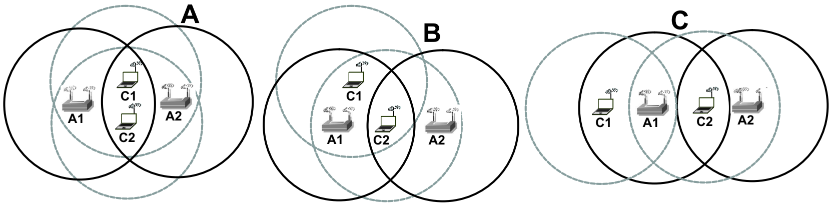

Figure 4: Overlapping Cells Simulation Scenarios

in single-cell scenarios with just limited interference from other Access Points or other technologies. Therefore, we will focus on exactly these cases to see if the QoS mechanisms can still provide their functionality in such worst-case scenarios. In the following client C1 is always associated with Access Point A1 while client C2 is solely connected to Access Point A2.

4.1.1 Overlapping Cells

In an overlapping cell scenario two Access Points are used to cover an area, but the Access Points are far enough apart to be out of the reception range of each other. This is the most important way to deploy large Wireless LAN hot spots, since such a setup will optimize the coverage area, which most operators focus on.

The three possible scenarios for overlapping cells are shown in Fig. 4. The first overlapping cells scenario is marked with an A. It shows the coverage areas of the two Access Points A1 and A2 as black solid circles around the nodes. The two Wireless LAN clients C1 and C2 are placed in the coverage area of both APs. In this scenario both clients will experience the same problems caused by the overlap. The reception range of the two clients is indicated by the dashed gray circles.

Scenario B will change the position of client C1. It is not in the reception range of the AP A2, but will still receive the packets transmitted by the other client C2. The client C2 is still in the coverage area of both Access Points. Finally, in scenario C client C1 is placed farther away from AP A2 and client C2. It is now only in the reception range of its associated AP A1. Client C2 is still located in the area covered by both APs.

4.2 Traffic Model

The users in our simulations do not move. They are located at the positions as specified in the simulation scenarios described above. They use the QoS Wireless LAN MAC protocols of the IEEE 802.11e standard and the IEEE 802.11b data rate of 11 Mbps on the physical layer. Voice applications are supplied with the highest priority. The next highest level is applied to video transmissions, while the background FTP traffic always gets the lowest priority. The way the different applications were implemented is explained in the following.

4.2.1 FTP Traffic Model:

In order to evaluate the prioritization mechanisms of the IEEE 802.11e standard, non-prioritized background traffic has to be considered as well. The most common best-effort application is the World Wide Web. However, the simulation of WWW users demands very long simulation runs in order to account for the high variability of traffic. Therefore, FTP traffic was considered as a worst-case scenario of Web traffic.

4.2.2 Voice Traffic Model:

In order to minimize the bandwidth required by a voice client, different voice compression algorithms are evaluated. The most important voice codecs are G.711 (64 Kbps), G.729 (8 Kbps), and G.723.1 (5.3 or 6.3 Kbps). Earlier studies regarding the suitability of voice codecs in Wireless LAN scenarios indicated that the inter-arrival time between consecutive voice packets has the major impact on the number of voice clients within a single Access Point due to the large overhead in Wireless LAN packets. The data rate only has a minor impact. Therefore, the G.723.1 codec with an inter-arrival time of 30 ms will be considered here. The data rate 6.3 Kbps was used, in order to increase the quality of the encoded voice stream.

4.2.3 Video Traffic Model:

As in the case of voice traffic, there are several different video codecs that can be used to compress the video. The most important standard for video streaming and video conferencing is H.263. The video streams used for the simulations are 2-minute video sequences. These sequences are encoded using the Common Intermediate Format (CIF) with 352x288 pixels. From these randomly chosen sequences, the worst-case video was chosen. The term ”worst-case” refers to the statistics of average frame size and variance.

5 Results

The results section is divided into three different parts. In the first two parts, we focus on the interaction between a user running either voice or video and a best-effort user. The third part will look at a combined solution, where all three traffic categories (Voice, Video, and Best-Effort) are performed simultaneously.

5.1 Overlapping Cells

First, we consider the overlapping cells scenario B. It is asymmetric, since only client C2 is in the overlap of both APs, while client C1 is not disturbed by the data transmission of the Access Point A2. The worst-case scenario here is that client C2 performs a QoS demanding application, while client C1 downloads files from the Access Point A1. In the following client C1 uses 1 MByte file downloads.

In the case of voice traffic and standard DCF or HCF operation, the MAC protocol can not provide an acceptable VoIP service for client C2. In the DCF mode, the mean packet loss for the voice client C2 reaches 59.97%, which maps to a MOS score of 1.0 meaning *not recommended*. In HCF mode, the average packet loss for client C2 even reaches 63.54% and again a MOS score of 1.0.

Table 2: Wireless LAN Priority Classes

Class	0	1	2	3	4	5	6
CWmin	7	15	31	63	127	255	511
CWmax	15	127	255	511	1023	2047	4095

Table 3: Scenario B: MOS values (1 MByte FTP files)

MAC Protocol	Priority Class C1	Priority Class C2	Packet Loss C2 [%]	MOS Score
DCF	default	default	59.97	1.0
HCF	default	default	63.54	1.0
HCF	4	1	7.64	< 2.6
HCF	4	2	8.29	< 2.6
HCF	5	1	0.53	3.428
HCF	5	2	0.77	3.371
HCF	6	1	0.00	3.704
HCF	6	2	0.04	> 3.6
HCF	6	3	0.03	> 3.6
HCF	6	4	0.03	> 3.6
HCF	6	5	0.39	3.535

This is clearly not acceptable. DCF cannot provide any QoS, such that the results for DCF mode are not surprising. However, HCF with standard parameters already applies a higher priority to the voice client than to the best-effort user. The problem is that with the standard parameters of $CWmin = 7, CWmax = 15$, the collision probability is very high, since a retransmission attempt is performed rather quickly. Therefore, we can conclude that such small contention window parameters are not suitable for the overlapping cells scenario B.

In order to overcome these problems, we adapt the contention window parameters as shown in Table 2. A set of priority classes is defined according to different CWmin and CWmax values. In the following, we will apply these priority settings to the two involved clients to find a better choice.

When applying these new contention window parameters to the Stations, the results are as shown in Table 3. For completeness, the results corresponding to the default DCF and HCF modes are shown as well. It can be seen that an acceptable solution for this problem can only be found when applying the priority classes (5,X) or (6,Y) with $X \in \{1,2\}$ and $Y \in \{1,2,3,4,5\}$. In case of priority class (4,1) and (4,2), the MOS lies below 2.6 and leads to a user satisfaction which is *not recommended.* For priority classes (6,1), (6,2), (6,3), and (6,4) the voice quality is still *acceptable* with just a few users dissatisfied. For priority classes (5,1), (5,2), and (6,5) the voice quality drops just below *acceptable.*

The results show that C1 must at least have priority class 5. These results are summarized in Figures 5 and 6. The 99%-quantile of the end-to-end delay of the voice

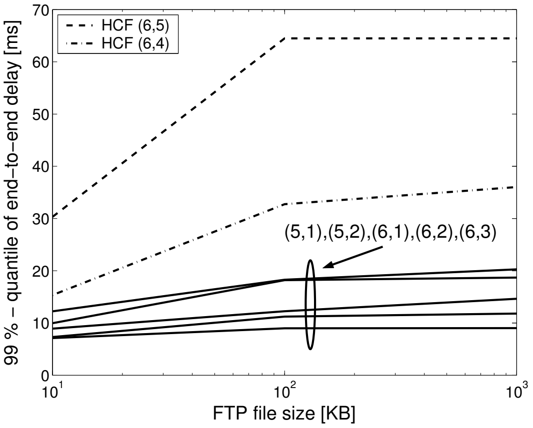

Figure 5: Scenario B: Voice Delay

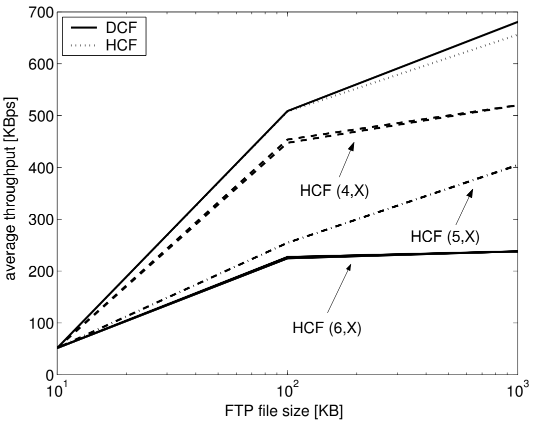

Figure 6: Scenario B: FTP Throughput (Voice)

Table 4: Scenario B: PSNR values (1 MByte FTP files)

MAC Protocol	Priority Class C1	Priority Class C2	Packet Loss C2 [%]	PSNR	MOS Score
HCF	default	default	86,19	12.66	Bad
HCF	4	1	6.84	25.45	Fair
HCF	5	1	5.67	25.69	Fair
HCF	5	2	6.01	24.60	Fair
HCF	5	3	6.34	26.55	Fair
HCF	6	1	0.07	40.67	Excellent
HCF	6	2	0.19	40.97	Excellent
HCF	6	3	0.43	46.84	Excellent
HCF	6	4	0.53	45.27	Excellent

application is shown in Fig. 5. It proves that in scenarios with varying FTP load (depending on the FTP file size), the results that were described above still hold. One drawback of lowering the priority setting of the best-effort FTP user can be seen in Fig. 6. It shows the average throughput in KBps that the FTP user will experience. Clearly, the lower the priority (larger value means lower priority), the lower the average throughput will get.

However, as it seems more important to provide QoS service than maximum throughput in the Wireless LAN scenarios considered here, choosing a priority setting of (5,X) is a good compromise. A good FTP performance can still be reached without interfering with the voice application.

In case of video traffic, the results were as shown in Table 4. It can be seen that priority classes (4,1) and (5,X) with $X \in \{1, 2, 3\}$ only provide *fair* video quality (MOS=3). If the priority set (6,Y) with $Y \in \{1, 2, 3, 4\}$ is used, the MOS value changes to 5 indicating *excellent* video quality. The PSNR is always above 37 in all simulation runs.

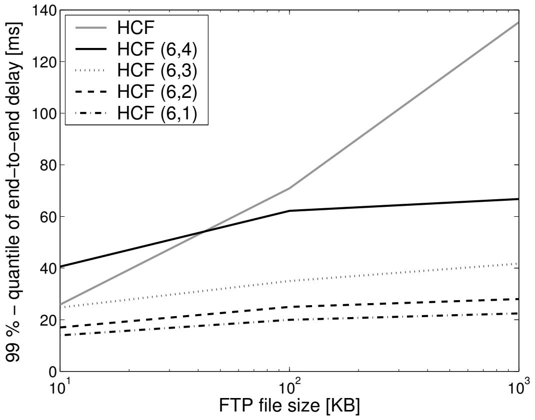

Figure 7: Scenario B: Video Delay

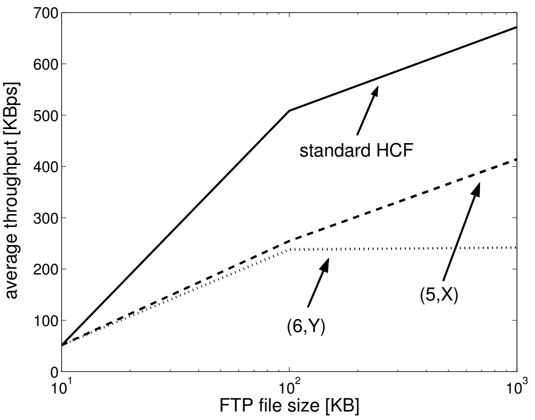

Figure 8: Scenario B: FTP Throughput (Video)

Again Fig. 7 shows the 99%-quantile of the end-to-end delay in ms for the video applications. Fig. 8 depicts the average throughput the FTP user experiences when applying different priorities.

Thus, for overlapping cells scenario B it can be concluded that when applying different priority settings to the voice, video and best-effort user, it is possible to provide QoS and still allow the FTP user to get an acceptable throughput rate. Different priority settings are possible and can be used by a wireless service provider to adapt the settings to its specific needs.

Overlapping cells scenario A is the only symmetric overlapping cells scenario. Therefore, both clients are located in the overlap and both will experience problems in the case of default HCF parameters. However, since both clients experience the same problems, the solution is even easier than in the former case with overlapping cells scenario B. Here, the priority settings of (3,1) and (4,1) are already sufficient. This means, that the priority of the FTP user can be higher here, compared to the former case. This allows the FTP client to receive an even higher share of the bandwidth than before.

Due to the symmetric nature of the overlapping cells scenario A, the FTP client will experience a much higher packet collision probability than in the overlapping cells scenario B. Therefore, packets will finally get dropped after the maximum number of retransmission on WLAN MAC layer is reached. The TCP protocol underlying the FTP application performs a packet retransmission. However, a retransmission on the TCP layer will also lead to a reduction of the data transmission rate, which leads to a lower load on the wireless medium and to a lower packet collision probability. Ultimately, the performance degradation of the FTP client allows a better quality for the voice client.

Overlapping cells scenario C on the other hand, behaves almost exactly like overlapping cells scenario B. The results for voice are shown in Figures 9 and 10, while the results for the video case can be found in Figures 11 and 12.

Again, we can conclude that there exist a number of different priority settings that can be used in order to provide QoS. The priority of the FTP client has to be set low enough in order to not disturb the QoS application. On the other hand, it should be as

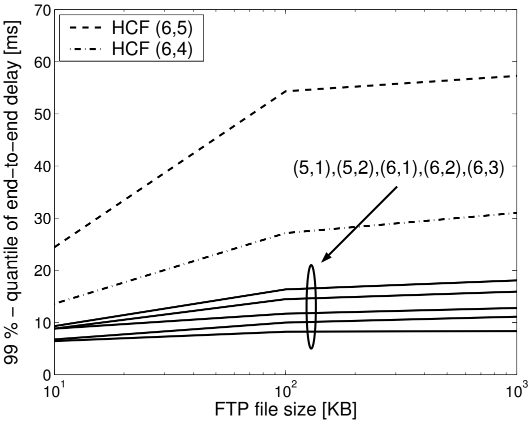

Figure 9: Scenario C: Voice Delay

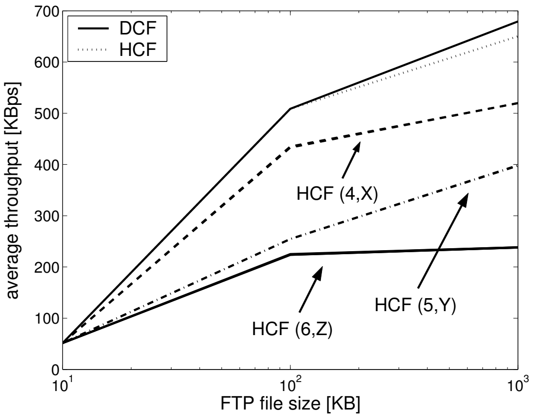

Figure 10: Scenario C: FTP Throughput (Voice)

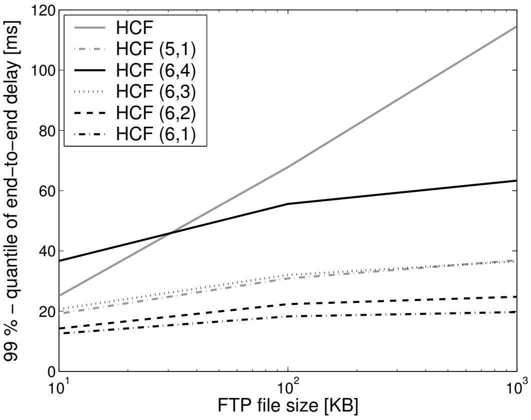

Figure 11: Scenario C: Video Delay

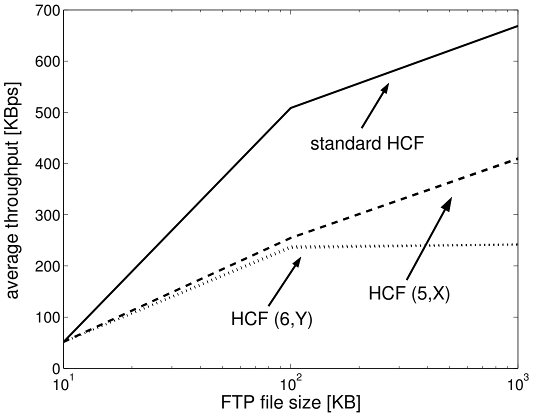

Figure 12: Scenario C: FTP Throughput (Video)

high as possible in order to allow a maximum throughput.

5.2 Combined Solution

The goal of the QoS enabled MAC protocols is to provide QoS for voice and video applications at the same time. In order to evaluate our priority settings for such a case, we simulated the worst case scenario (overlapping cells scenario B) with client C2 using voice and video at the same time. Client C1 performs FTP downloads. The priority setting chosen was (6,2,1), meaning that the voice application uses priority class 1, the video application was configured to use priority class 2, while the best-effort FTP traffic was handled with priority class 6. The results are shown in Table 5.

It can be seen that HCF with priority class (6,2,1) can provide adequate QoS even if both multimedia applications are used in a single STA. The same simulation with HCF default parameters results in packet loss for both voice and video applications above 80 % and this certainly provides bad voice and video quality. The best-effort FTP user

Table 5: Combined solution (1 MB files), Voice and Video

Traffic Type	Priority Class	Packet Loss [%]	End-to-End Delay 99%-quantile [ms]	End-to-End Delay Maximum	Jitter [ms] Score	MOS
Voice	1	0.03	10.77	22.12	5.68	>3.6
Video	2	0.27	34.94	59.53	75.04	5

suffers a performance degradation in terms of average throughput of about 50% to 60%. Considering the immense potential in providing QoS in large-scale Wireless LANs surely compensates for this.

6 Conclusion and Outlook

Wireless LAN based on the IEEE 802.11 standards family gains more and more importance in Wireless Networks. The upcoming discussion about an integration of WLAN in future heterogeneous mobile networks of the 4th Generation even helps to further strengthen its importance.

However, this development necessitates the support of QoS demanding applications. The basic Medium Access Control protocol CSMA/CA defined for Wireless LAN is simple and allows a distributed access with equal medium share only. The simple polling mechanism of the PCF mode on the other hand is not sufficient for large-scale deployments. Therefore, more advanced mechanisms have to be considered. The IEEE 802.11e standard defines such an extension. It is supposed to overcome the former deficiencies.

In our studies we focused on the newly standardized MAC protocol known as *Hybrid Coordination Function*. It defines ways to assign different priorities to the involved Stations. Large-scale deployments of Wireless LAN have the additional problem of overlapping cells in terms of coverage and channel. Therefore, we performed simulation studies that evaluate the QoS capabilities of HCF in case of overlapping cells.

These simulation studies clearly showed, that the proposed prioritization parameters are not sufficient in overlapping cells. They can prioritize certain Stations, but they lead to high levels of packet loss, and thus to large quality degradation in case of voice and video applications. Our studies show that different sets of prioritization parameters can be applied that will provide the required level of prioritization while still allowing a high medium utilization. Our studies prove that QoS support in Wireless LAN environments is definitely possible.

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