Increasing Performance of the 802.11e Protocol through Access Category Shifting

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Abstract. Wireless network access has become a must in many public places as well as enterprises. It is known that in wireless networks service quality is still not optimal for all service types. The standard IEEE 802.11e aims at resolving this issue by introducing priority classes. In many situations these priority classes serve the purpose of providing better service where better service is needed. One major drawback of the protocol is that the channel may not be utilized in an optimal way. We propose a priority shifting mechanism to resolve this issue. Simulation results show that the priority class shifting can yield up to 20% improvement in the overall channel throughput for typical network situations.

1 Introduction

Wireless networks have become very popular in recent years. Network access is easily granted in public places and can be provided to selected groups by handing out the respective code. While wired networks today have a data rate that leaves few wishes unfulfilled, this is not the case in wireless networks. Unlike in wired networks, where the used hardware guarantees the specified quality of service (QoS), in wireless networks the observed service quality may strongly differ from the theoretically specified data rate of the access point, depending on the distance of the wireless station to the access point, the topology of the location, and obstacles in the environment. It is well known that in wireless networks service quality cannot be guaranteed.

Nonetheless, different transmission types, such as video, voice, and data transmission have different quality requirements. The standard IEEE 802.11e [1] aims at solving the quality of service issue in wireless local area networks (WLANs) by introducing four different priority classes as well as contention and backoff mechanisms that implement the priorities.

Many simulation studies of the standard IEEE 802.11e have demonstrated the ability of the standard to provide different service quality to the different priority classes [2], [3]. Other models and simulation studies have optimized the respective parameters for contention and backoff as to improve the overall performance of the protocol [4], [5].

The contention and backoff mechanisms in IEEE 802.11e have several known drawbacks [2], [3], [6]: one is the problem of poor channel utilization and unnecessary delays if only traffic of low priority is using the network.

In this paper we demonstrate this problem in an experimental setup as well as through simulation results using the network simulator ns-2 [7]. We propose a mechanism that can in certain situations solve the problem of poor channel utilization while being non-invasive to the protocol. The mechanism changes the traffic priorities in a suitable way. If the highest priority class is not present in a given setting all lower priority classes can be shifted up. This reduces the waiting time in the contention as well as the backoff case. As we will show in our simulation study the priority shifting yields an improvement in overall data throughput of up to 20%. In several simulation studies we investigate the potential improvements in the overall data throughput depending on the existing traffic streams with their respective priorities.

The remainder of this paper is organized as follows. Section 2 introduces the wireless standard IEEE 802.11e and its medium access mechanisms in as far as it is relevant for this work, Section 3 describes the priority shifting mechanisms and proposes the corresponding algorithm. In Section 4 we show our experimentation insights and the results obtained from our simulation studies. Section 5 concludes this paper.

2 The IEEE 802.11e protocol

For increased QoS demands by modern applications and services, an extension for the IEEE 802.11 standard [8] has been developed: 802.11e, which provides quality of service enhancements on the medium access control (MAC) layer.

2.1 Basic concepts

Similar to the original IEEE 802.11 (and also its high-speed variants a/b/g [9], [10], [11]) 802.11e provides both contention-based and contention-free channel access. It includes a new coordination function, the so-called hybrid coordination function (HCF), which provides modes of operation similar to the distributed coordination function (DCF, for contention-based access in 802.11) and the point coordination function (PCF, for contention-free access in 802.11). The HCF's contention-based channel access method is called enhanced distributed channel access (EDCA), its contention-free channel access method is called HCF controlled channel access (HCCA).

We focus on the contention-based method in this work, as it is the typical method used in today's WLAN communication. During the contention period (CP) the original 802.11 protocol ensures that no station sends while another is still busy through a so-called DCF inter frame space (DIFS). In case a collision occurs, this DIFS time is extended with a uniformly distributed random backoff interval picked out of an (in the case of subsequent collisions) exponentially increasing contention window.

The protocol IEEE 802.11e uses a similar mechanism for EDCA, the arbitrary inter frame space (AIFS), which differs in length for the four access categories (ACs, namely for voice (AC_VO), video (AC_VI), best effort (AC_BE), and background (AC_BK)) it defines. For the two lower priority access categories the AIFS is longer (table 2.1) compared to the voice and video traffic.
Also the contention window sizes vary for the different access categories (leading to significantly shorter backoff times for the higher priorities), which makes it more likely that a data frame of a higher priority access category wins the contention. Contention takes place with each new time slot[1], backoff after a collision.

2.2 Parameters

The two key parameters for IEEE 802.11e's QoS capabilities are the arbitrary inter frame space (AIFS) and the backoff time (selected out of the contention window). As already mentioned in Section 2.1, the AIFS differs between access categories, leading to a longer waiting time for packets of lower priority access categories. Table 2.1 shows the different AIFS times for the 802.11b physical layer. The AIFS times are calculated from access category-specific constants (2 for voice and video traffic, 3 for best effort, 7 for background traffic) multiplied with the slot time and added to the short inter frame space (SIFS) time, which is identical for all priority classes.

Table 2.1. AIFS times for different physical layers

	AC_VO	*AC_VI*	*AC_BE*	*AC_BK*
802.11a PHY	34μs	34μs	43μs	79μs
802.11b PHY	50μs	50μs	70μs	150μs
802.11g PHY[2]	28/50μs	28/50μs	37/70μs	73/150μs

AIFS times for voice and video access categories are equal, still there exists a difference between these two access categories regarding the backoff time, which plays also an important role in the 802.11 protocol family. The backoff time is dependent on the contention window size, which differs between the different access categories. The contention window size starts for each access category at a defined minimum (CWmin), and doubles in case of a subsequent collision (continuing this process until a defined maximum is reached, then starting again at the CWmin).

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[1] IEEE 802.11e also defines a new concept called transmission opportunity (TXOP). This provides the possibility that voice or video traffic reserves the channel for a certain time without contention.

[2] 802.11g supports two modi with different slot times

The backoff time is calculated by selecting a pseudo-random integer out of the interval [0, CW] which is multiplied with the slot time which depends on the physical layer (e.g. 20μs for 802.11b).

Table 2.2 shows the different values for the lower and upper bound of the contention window size. It can be noted here, that the values for best effort traffic and background traffic do not differ here, and are significantly larger than these for voice and video traffic, respectively.

Table 2.2. Backoff intervals (for 802.11b PHY)

	CW AC_VO	*CW AC_VI*	*CW AC_BE*	*CW AC_BK*
Minimal	[0-7]	[0-15]	[0-31]	[0-31]
Maximal	[0-15]	[0-31]	[0-1023]	[0-1023]

Regarding both parameters, AIFS and the backoff interval, it seems evident that in situations where only lower priority traffic is present, time is wasted by waiting - both between frames as well as at collision occurrences.

3 Access Category Shifting for Increased Throughput

We propose to shift the used access categories when possible, in order to increase the throughput. The assumption is that in situations where there is no voice traffic, transmission time will be lost due to unnecessary waiting.

3.1 Algorithm

In order to use the channel most efficiently, an adaptive shifting of access categories can be performed. We propose to shift the access categories of all participating stations in a way such that the highest access category (voice) is always occupied and the hierarchy among all participating stations stays intact. Every time a station enters or leaves the network, the algorithm has to check whether a shift has to be performed (and potentially all stations have to be shifted). I.e. in an environment with three wireless stations, all transmitting in best effort mode, they will all be shifted to the voice access category until another station with a higher access category joins the network (in that case, they would have to be shifted down again).

The following algorithm describes the proposed shifting of access categories in case a new station enters the network (`ac[x]` stands for the internal access category of station x, `ac_orig[x]` stands for the original access category of station x (before shifting), `max_ac` stands for the maximal unshifted access category of any station in setOfStations, `ac[]` and `ac_orig[]` are dynamically increasing arrays which contain current and original access categories of all clients):

```
enterNetwork (station_x, setOfStations)
    ac_orig[x] = ac[x];
    if (setOfStations equals emptyset)
        ac[x] = AC_VO;
    else
        if (max_ac <= ac_orig[x])
            ac[x] = AC_VO;
            foreach (station j in setOfStations)
                ac[j] = ac[j] - (ac[x] - max_ac);
        else
            ac[x] = AC_VO - (max_ac - ac_orig[x]);
```

In case a station leaves the network, the inverse procedure has to be performed:

```
leaveNetwork (station_x, setOfStations)
    if (ac[x] == AC_VO)
        soleHighestPriority = true;
        foreach (station j in setOfStations)
            if (ac[j] == AC_VO)
                soleHighestPriority = false;
        if (soleHighestPriority)
            do
                shiftAllClientsOneUp(setofClients);
            until
                setofClients contains station k with ac[k] == AC_VO);
```

This algorithm may be performed at every network entering or leave event, after a need for shifting has been determined. I.e. the algorithm needs to check whether the access category (`ac_orig[x]`) of an entering station x (or `ac_orig[y]` of a leaving station y respectively) is greater than the original access categories of all other participating stations. Additionally, the access category distance `ac_dist` between `ac_orig[x]` (or `ac_orig[y]` respectively) and the station with the highest access category among the existing (or remaining) stations has to be determined. In case a shift is necessary, all participating stations have to be shifted `ac_dist` access categories - either down (in case `ac_orig[x]` of an entering station x is higher than all others) or up (in case `ac_orig[y]` of a leaving station y was higher than all others).

In terms of complexity, one execution of the algoritm is linear in number of stations in the network. We presume a shifting time of 20 ms per station, and a network size of no more than 50 stations. A complete shift of all stations will then take no longer than one second.

3.2 Discussion

The impact of the proposed access category shifting depends on different factors. If no shifting is possible (i.e. the voice access category is already used by a station) it will make no difference (since no shifting will be done). It should be noted that today IEEE 802.11e-capable wireless stations are rare, and 802.11e-enabled access points treat normal 802.11(a,b,g) stations as stations transmitting best effort traffic, irrespective of their actual transmission type. Our approach would shift them (if no higher access categories were on the channel) to voice, and would thus increase their combined possible throughput significantly. The level of improvement is also dependent on the shifting distance and the number of stations. Obviously, a greater shifting distance leads to higher improvement. It is furthermore interesting to observe that if many stations are using high priorities, the benefit of this priority class diminishes, as more collisions occur, reducing the provided QoS (the smaller contention window of the higher access categories makes collisions within the same access category more likely). In the next section, we show the possible increase in overall throughput in typical situations.

4 Simulation and test results

We reconstructed the lower throughput performance of lower access categories both through simulation and experimentation. In this work we put the focus on simulation and show only initial experimental test results.

4.1 Experiment and Simulation

For our hardware tests, we used a Linksys WRT54GL wireless router (with original firmware) and a Samsung Q35 laptop running Ubuntu Linux. Network traffic was generated with iperf [12]. The tests took place in an office building with a distance of approximately five meters between access point and laptop. No other wireless networks were active on a possibly interfering channel.

For the simulations, we used ns-2 version 2.31 extended with the 802.11e EDCA and CFB Simulation Model [13] on a Macbook Pro laptop running OSX. All virtual stations have a five meter distance to the access point.

All experiments and simulations were based on the 802.11g physical layer with activated wireless multimedia (WMM) for the experiments and activated 802.11e for the simulations. We used constant bit-rate UDP transfer with 1472 bytes packet size.

The theoretical maximum throughput of 802.11g is specified as 54 Mbit/s. However this is only true for contention-free channel access in an ideal environment. For contention-based channel access, which we use in our experiments and simulation, approximately one third of the channel capacity is lost due to inter-frame waiting times. Thus, the maximum theoretical throughput for contention-based channel access lies at roughly 36 Mbit/s. Some models even place it lower (as e.g. [14] for 802.11a), depending on the network and error models.

4.2 The impact of the priority classes

Our first experiments and simulations targeted on demonstrating the difference between IEEE 802.11e's access categories with a single client.

Figure 4.1 shows the results of five different test runs measured with a single station using different access categories on a Linksys WRT54GL. This access point supports wireless multimedia (WMM), which is an implementation of 802.11e EDCA. In our experiments we increased the network traffic for each client over time. Depending on access category, the saturation point was reached at different points. Our measurements show that for voice and video access categories the saturation point was reached at 33 Mbit/s, for best effort traffic at 25 Mbit/s, and for background traffic at 22 Mbit/s. It can be observed that the network performance differs significantly between the different access categories, with a difference in throughput of up to 50 percent.
For comparison, we also tested the throughput without WMM (i.e. without priorization), resulting in a maximum throughput of 32 Mbit/s - marginally less than the two higher WMM priorities, but significantly more than best effort and background WMM traffic. This is a remarkable result, since WMM typically assigns the best effort access category to non-QoS stations, which may lead to significant decrease in throughput as these measurements show.

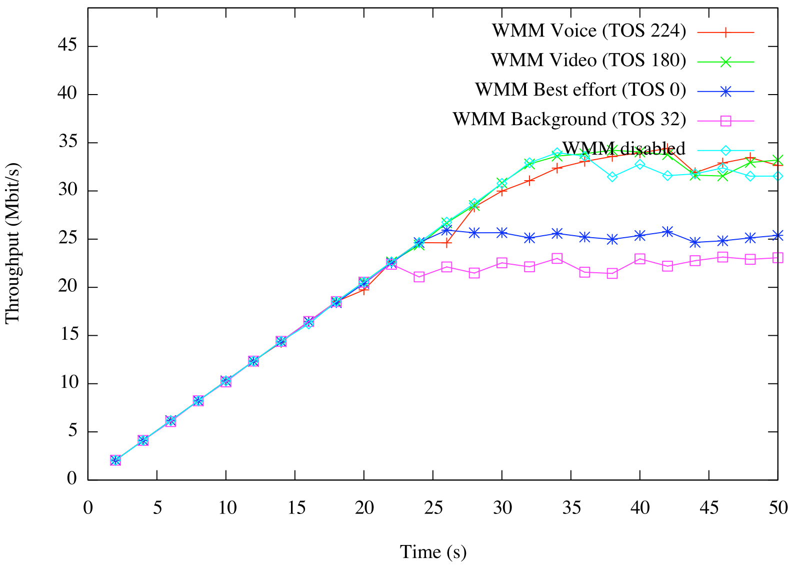

Fig. 4.1. Throughput of a single station for different access categories on Linksys

Figure 4.2 shows the simulation results for the same scenario implemented in ns-2. Here we start a constant bit rate traffic after 2 seconds at rate 58 Mbit/s (i.e. a rate which will lead to channel saturation in any case for an 802.11g access point) and stop after 14 seconds. The top line shows the result for the voice access category - 35 Mbit/s. The next line shows the result for video: 30 Mbit/s. Best effort traffic saturated at 23 Mbit/s, and background traffic at 21 Mbit/s. Again a significant difference in throughput for different access categories can be monitored, and the results roughly match the measurements in our experiments.

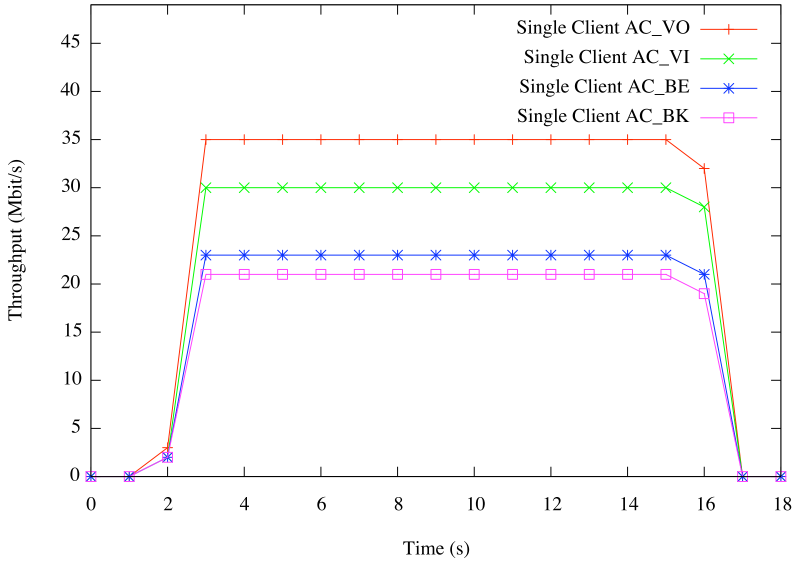

Fig. 4.2. Throughput of a single station for different access categories with ns-2

Overall, both in our experiments, as well as in the simulations we were able to monitor a clear deviation in throughput between access categories. An upshift would increase the channel throughput significantly for a single client, between 15% and 50%.

4.3 Simulations using the shifting algorithm

In [15], three to four stations per access point are stated as a typical number in a wireless network. Therefore we concentrate our simulations on different constellations for a number of three access points.

Generally, the shifting approach can be applied in three cases: (i) three access categories are used, but not voice, (ii) two access categories are used, but not voice (possible combinations are video with best effort,video with background and best effort with background), (iii) one access category is used, but not voice (this is the trivial case, already covered in section 4.2). We will analyze case 1 and two combinations of case 2 to investigate the throughput gain of the shifting approach.

Figure 4.3 shows the throughputs of three simultanously running traffic streams of video, best effort and background traffic and the sum of their combined throughput. Again, the traffic starts after two seconds and stops after 14 seconds. Video traffic reaches a throughput of 22 Mbit/s, best effort 7.6 Mbit/s and background 2 Mbit/s. The throughput sum of all traffic on the channel is 31.6 Mbit/s.

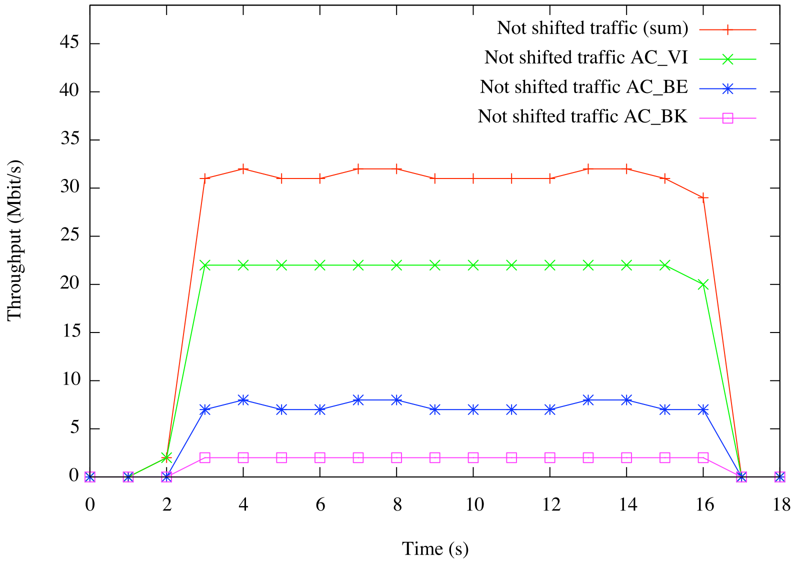

Fig. 4.3. Throughput of three stations with AC_VI, AC_BE, AC_BK

Figure 4.4 shows the situation after applying the shifting algorithm - i.e. we have now voice, video and best effort traffic. In this case the throughput of the voice traffic reaches 24.2 Mbit/s, the video traffic reaches 9.2 Mbit/s and the best effort traffic reaches 1.6 Mbit/s. The summed up throughput on the channel is 35 Mbit/s.

In the case of three stations with different access categories, we measured a difference in throughput of 10.7 percent. The overall throughput on the channel increases from 31.6 Mbit/s (without shifting) to 35 Mbit/s (after application of the shifting algorithm), which is very close to the theoretical optimum for contention-based channel access. This improvement origins from the shorter inter frame spaces of the higher access categories as well as from their shorter

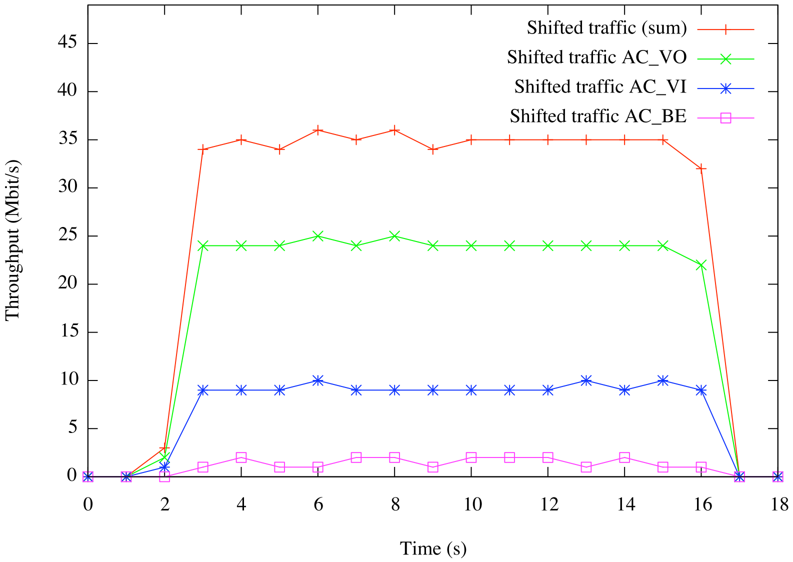

Fig. 4.4. Throughput of three stations with AC_VO, AC_VI, AC_BE

backoff intervals. It has to be noted, that only the two upper access categories benefit in throughput (2.2 Mbit/s and 1.6 Mbit/s), while the lower access category traffic decreases a little bit (0.4 Mbit/s). This results mainly from the comparatively much longer backoff interval of the best effort traffic in comparison to voice and video traffic.

We also simulated three stations using two access categories. The first simulation (figure 4.5) used one station with video traffic and two with best effort traffic. Additionally, we let the stations start at different times, to be able to monitor the throughput changes after each station entering or leave. Figure 4.5 shows the video traffic starting at time 2 and after three seconds the first station with best effort traffic enters the network. After another three seconds, the second station with best effort enters (and after 12 seconds the inverse procedure starts). The video traffic station alone reaches 30 Mbit/s throughput, after the first best effort station joins, it decreases to 24 Mbit/s. The first best effort station starts with 8.5 Mbit/s, decreasing to 6 Mbit/s after the second best effort station enters (which also uses 6 Mbit/s). The video traffic decreases to 20 Mbit/s after the second best effort station enters. The summed up throughput is 30 Mbit/s at the beginning (with only the video station), then increases to 32.5 Mbit/s after the first best effort station enters and slightly decreases to 32 Mbit/s after the second best effort station enters.

This simulation provides an overall throughput rate of 30 to 32.5 Mbit/s, which can be observed as good values in respect of the theoretical maximum.

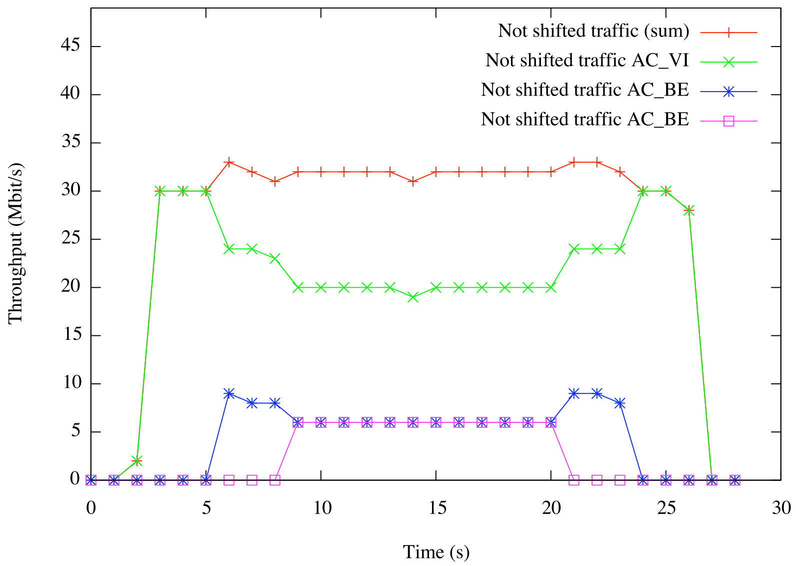

Fig. 4.5. Maximum throughput of three stations with AC_VI and AC_BE

Nevertheless, we investigated that with the shifting algorithm applied, it can still improve, as figure 4.7 and table 4.1 show.

A similar simulation also with three stations but with best effort (one station) and background traffic (two stations) (figure 4.6) shows an inferior throughput performance. The simulation starts with the best effort traffic and after three seconds the first background station enters. At time 8 the second background traffic enters and after 12 seconds the inverse procedure takes place.

The best effort traffic alone has a throughput of 23 Mbit/s, after entering of the first background traffic it decreases to 17 Mbit/s. The first background traffic has a throughput of 10 Mbit/s, decreasing to 6.5 Mbit/s after the second background traffic enters (which also has a throughput of 6.5 Mbit/s). The best effort traffic has then 14 Mbit/s. The summed up throughput is 23 Mbit/s at the beginning (when best effort traffic is alone) and increases to 27 Mbit/s when the first background traffic starts. When the second background traffic starts, the overall throughput stays at 27 Mbit/s.

To both previous cases our shifting algorithm can be applied. To compare the throughput rates, we did another simulation which shows the throughput rates after applying the algorithm. Figure 4.7 shows the results. The simulation starts with the voice traffic - at time 2 one video traffic starts, and after another three seconds the other.

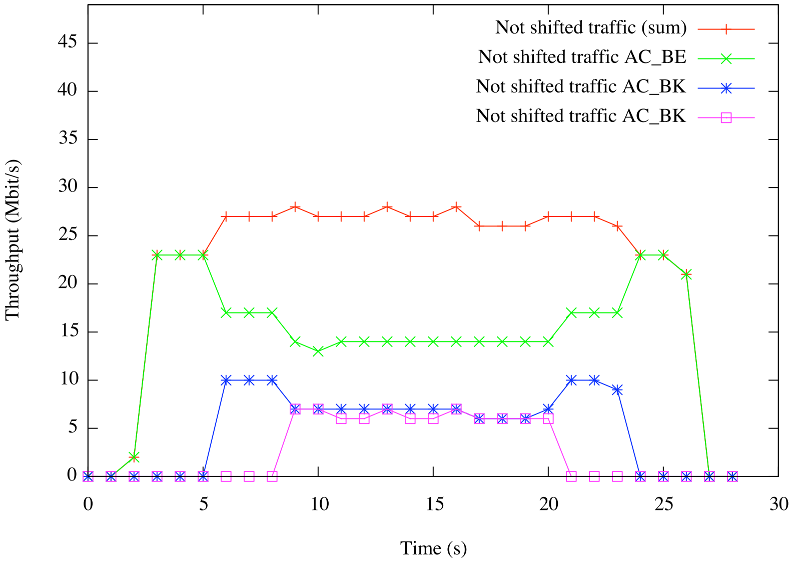

Fig. 4.6. Maximum throughput of three stations with AC_BE and AC_BK

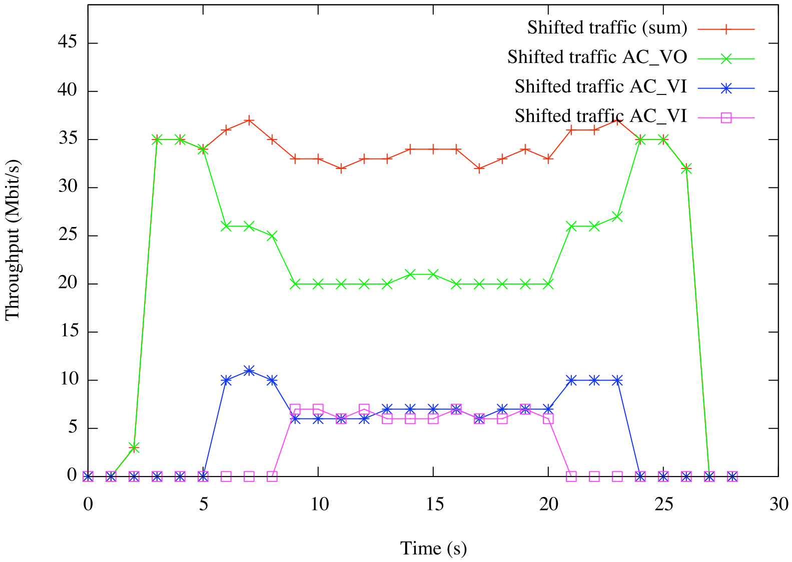

Fig. 4.7. Maximum throughput of three stations with AC_VO and AC_VI

Table 4.1. Shifting improvement for two access categories

	1 station	2 stations	3 stations
AC_VI+AC_BE	30 Mbit/s	32.5 Mbit/s	32 Mbit/s
With Shifting	35 Mbit/s	36.6 Mbit/s	33.4 Mbit/s
Improvement	16.7%	12.6%	4.4%
AC_BE+AC_BK	23 Mbit/s	27 Mbit/s	27 Mbit/s
With Shifting	35 Mbit/s	36.6 Mbit/s	33.4 Mbit/s
Improvement	52%	35.5%	23.7%
AC_VI+AC_BK	30 Mbit/s	31 Mbit/s	31 Mbit/s
With Shifting	35 Mbit/s	35.6 Mbit/s	35.2 Mbit/s
Improvement	16.6%	14.5%	13.5%

The voice traffic starts with a throughput of 35 Mbit/s and decreases to 26 Mbit/s when the first video traffic starts. The first video traffic starts with a throughput rate of 10.3 Mbit/s, decreasing to 6.6 Mbit/s when the second video traffic starts (with also 6.6 Mbit/s). The voice traffic then decreases to 20.2 Mbit/s. The summed up throughput is 35 Mbit/s for voice alone, increasing to 36.3 Mbit/s for voice and one video traffic and decreasing to 33.4 Mbit/s for three simultanous traffics (one of voice and two of video access category).

This simulation also shows another important effect, which should be explained shortly: In case many stations with high priorities communicate with one access point, the overall throughput will decrease. This effect is originated by the growing number of collisions which will more likely appear between packets of higher priority traffic (due to the significantly smaller contention window, explained in Section 2), and we reconstructed it doing additional simulatons with 5, 10 and 20 clients. Even with five clients, the voice category shows already a high collision rate, which leads to a lower throughput rate than the video category. With more than 6 clients, the best effort category shows the highest overall throughput. Thus, we recommend shifting to the highest access category only for typical situations like three to four stations. In case many stations would be shifted to the voice or video access category, the shifting should be applied considering this situation and performend only up to the best effort access category (the best effort access category has the same contention window size as the background category but a smaller AIFS waiting time, thus best effort will always show a better result than background). This adaptive shifting mechanism, regarding the current network situation will be part of our future work.

Our simulation results show that the shifting approach can lead to a significant increase of overall channel throughput, leading close to the theoretical maximum for contention-based throughput. The extent of the improvement depends both on shifting distance and number of involved stations. For typical networks situations with three stations connected to an access point, the throughput gain lies between 4.4 (for small shifts) and 23.7 percent (for longer shifts) compared to the original behaviour of IEEE 802.11e.

5 Conclusion and Outlook

In this work, we addressed the problem of poor channel utilization and unnecessary delays in IEEE 802.11e in cases where only traffic of low priority is using the network. We presented an algorithm for overall throughput enhancement through access category shifting. Our simulations show a significantly (up to 20%) higher overall throughput in typical network situations where our algorithm can be applied. With the access category shifting approach, the full throughput potential of the channel can be tapped.

Another benefit of the approach is that it is non-invasive to the protocol. It can be applied to the unmodified 802.11e protocol. We currently develop a hardware implementation, which will allow us to test the approach in experiments in our lab.

For the future, several improvements are possible. Under certain circumstances, station-specific access categories may not be sufficient for optimal QoS resource management. Therefore the algorithm can be adapted so that it is possible to apply the shifting to different traffic streams (instead of stations).

We also plan to address the starvation issue of low priority traffic by a dynamic shifting mechanism. I.e. timely before it would starve, a low priority traffic is shifted for a short time interval to a higher access category (and back again).

During our simulations we learned that too many stations with a high priority access category may lead to lower throughput due to increased collision rates. Thus we plan to parameterize the shifting approach in a way that such situations where high collision rates appear are being avoided. We plan to develop an arbitration instance on the access points, which considers the current network situation and the stations' QoS configuration and applies the shifting with respect to both.

6 Acknowledgments

This work is supported by the German Research Association (Deutsche Forschungsgemeinschaft (DFG)) under grant Wo898/1- 2.

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