Wireless LAN Performance in Overlapping Cells

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***Abstract*— In this paper we study the effect of overlapping cells on the performance of Wireless LAN hot spots. Our results show that the MAC protocol defined in the IEEE 802.11 standard can not guarantee spatial coexistence of multiple hot spots. We identify the reasons for the observed problems and propose a prioritization algorithm that can provide fairness in terms of average throughput and alternating medium access to all involved clients. Finally, we summarize the problems of implementing this approach in hot spots based on the 802.11b standard.**

I. Introduction

Wireless LAN has recently gained attraction in the public. So-called hot spots are installed in many cities world-wide and the IEEE 802.11 standard is expected to evolve to an important access technology for future 4th generation (4G) mobile networks. The bandwidth of up to 54 Mbps in hot spot environments encourages ISPs to provide high-speed Internet access to wireless users, while multi-mode devices are being developed. However, as more Wireless LAN cells are installed, the restrictions of the technology become more obvious. The 802.11b standard operating in the 2.4 GHz band provides only 3 non-overlapping channels. This might cause serious problems in highly populated areas especially if multiple providers are co-located and users are setting up a Wireless LAN as a replacement of a wired local area network in their private homes. On the other hand, the hardware is cheap compared to other wireless access technologies, the frequency band is free of any license fees, while the data rate is high. These factors make Wireless LAN an interesting alternative to other wireless access technologies such as UMTS.

Various performance studies of the Wireless LAN Medium Access Control (MAC) protocol can be found in the literature, such as [1], [2], or [3]. These publications, however, focus on MAC protocol performance issues within single cell scenarios. This is not sufficient for the evaluation of Wireless LAN as a future access technology in 4G networks. Therefore, we investigate the impact of *overlapping* and *co-located cells* on the performance of a best-effort Wireless LAN hot spot in this paper. We evaluate how the CSMA/CA MAC protocol of users in different cells interact and what the consequences are on the performance. We identify situations where the communication of single clients is completely blocked due to high collision probabilities and the unfairness in distributed environments.

However, we present a solution that overcomes such problems. We show that our approach assures an adequate level of fairness for all involved clients. Nevertheless, our results proof that the IEEE 802.11b standard is not sufficient to implement this solution, but the extensions defined in the IEEE 802.11e standard are necessary in large-scale implementations of Wireless LAN hot spots.

This paper is organized as follows. In Section II the simulation model will be explained. This consists of the Wireless LAN MAC protocol, as well as the simulation scenarios and the involved user behavior. The results will be presented and discussed in Section III. In Section IV the conclusions are drawn and an outlook for future research is given.

II. Simulation model

This Section will describe the different parts necessary for our simulations. First we briefly summarize the Wireless LAN Medium Access Control protocol and some of its extensions. Then we describe the user behavior assumed in our simulations. Finally the different simulation scenarios are explained in detail.

A. Wireless LAN Medium Access Control Protocol

We implemented a simulation of the best-effort part of the Wireless LAN MAC protocol, known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), complying to the IEEE 802.11 standard as defined in [4] and the IEEE 802.11b extensions for the 2.4 GHz band specified in [5].

Stations deliver data packets of arbitrary length (up to 2304 bytes) after sensing the medium idle for at least a minimum duration of DCF Interframe Space (DIFS). If two or more stations find the channel idle at the same time, a collision occurs. In order to reduce the probability of such collisions, a Collision Avoidance (CA) mechanism is implemented. It states that a station has to perform a backoff procedure before starting a transmission. The duration of this backoff is determined by the Contention Window (CW) value. Initially set to a certain $CWmin$ value (by default 31), the CW value is used to randomly choose the number of backoff slots in the range of $[0, CW]$. A single slot is $10\mu s$ in IEEE 802.11b. In case of a collision, the CW value is increased by the term $CW := (CW+1)*2-1$, with a maximum value of $CWmax$ (by default 1023). This will guarantee that in the case of a collision, the probability of another collision at the time of the next transmission attempt is further decreased.

One problem that is specific in the wireless domain is the Hidden Node problem. It emerges if two clients that are not within the reception range of each other have an identical destination node. While one of them is transmitting, the other node still finds the medium idle and starts its own transmission, which will lead to an immediate collision at the destination node. Thus, hidden nodes will decrease the system performance. Therefore, the IEEE 802.11 standard specifies a Request-to-Send/Clear-to-Send (RTS/CTS) mechanism. Stations will issue a short RTS frame before starting the data transmission. The destination node will answer the transmission request by issuing a CTS frame. Upon successful reception of the CTS frame, the source node can start the actual data transmission. A special value within the RTS and CTS packets specifies the amount of time necessary for the whole data transmission (data packet transmission plus ACK packet reception). All other stations receiving an RTS the CTS frame will read this value and set their Network Allocation Vector (NAV) timer. This timer tells the station to defer its transmission attempts until the timer is elapsed. Therefore, the RTS/CTS mechanism will assure that hidden nodes do not cause an increased collision probability, especially if large data packets are used. However, in [3] it was shown that the increased overhead introduced by this mechanism exceeds the gain that can be achieved in many cases. The RTS/CTS mechanism was shown to be better turned off in single cell scenarios. In this paper we will evaluate whether the RTS/CTS mechanism is of any help in multiple cell scenarios.

The data rate within the cells was set to 11 Mbps and we assumed that the signals can be received without any bit errors at distances of up to 100 meters. At farther distances the signal can not be received any more and it does not cause interference at stations not within this reception range.

B. Simulated User Behavior

The goal of our studies was to show the behavior of the Wireless LAN MAC protocol in the case of overlapping and co-located cells, when the medium is highly loaded. Therefore, the users were assumed to perform FTP downloads of files with varying file sizes. The underlying transport protocol was TCP Reno with a Receive Buffer of 64 KBytes.

When small file sizes are used, such as files of 10 KBytes, the TCP connection setup time will be large compared to the download time of a single file. Since each single file is being downloaded in a new TCP connection and the TCP slow start mechanisms is performed for each new download, the medium is not fully utilized in these cases. Therefore, we also accounted for large file sizes of up to 10 MBytes, where the medium is fully utilized by a single client. As soon as a single download is finished, the next download will be started.

C. Simulation Scenarios

In order to account for all the different possibilities on how to set up overlapping and co-located cells, only two Wireless LAN Access Points (AP) with one associated station at each of the APs were considered. This allows seven different simulation scenarios, which will be introduced in the following.

In all of these scenarios, the APs act as the FTP servers in order to focus on the effects of such a setup on the performance of the wireless medium. Effects caused by the wired part of the connection from the APs to the FTP server are ignored. Since we want to perform our studies on a worst-case scenario, the two APs use the same Wireless LAN channel.

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 larger Wireless LAN hot spots, since such a setup will optimize the coverage area, which most operators focus on. The three different scenarios that can be found for the case of overlapping cells, are shown in Figure 1. The first overlapping cells scenario is

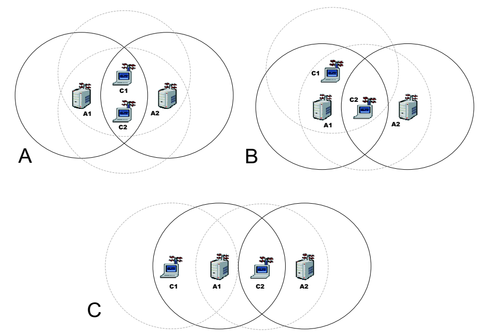

Fig. 1. Simulation Scenarios: overlapping cells

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 the client C1 is placed farther away from the AP A2 and the client C2. It is now only in the reception range of its associated AP A1. The client C2 is still located in the area covered by both APs.

2) Co-located Cells: The different scenarios that can be found for co-located cells are shown in Figure 2. In all these cases, the APs are in the reception range of each other. An appropriate planning process should try to avoid these situations, but as more wireless operators start their service while private users set up their own private hot spots, these scenarios are definitely possible in practice. The Wireless LAN MAC protocol should still be able to serve the users in a fair manner. The scenario marked as A shows the case where all the involved stations are placed in close vicinity. Each node receives the transmission of all the others. This case should not be too different from the case where two clients are located in the vicinity of a single access point, in terms of the bandwidth they can receive. Scenario B, on the other hand, shows the case where the two clients C1 and C2 are located in the reception range of their own but not of the other AP. The clients' transmissions will not be disturbed by the access points. However, the access points will disturb each other's

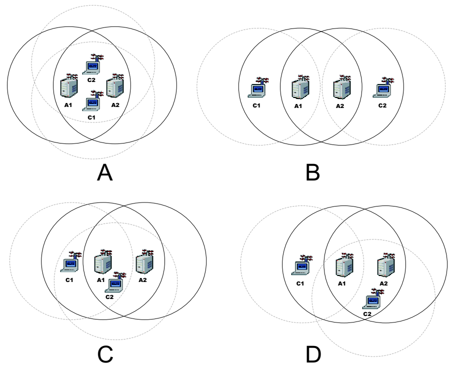

Fig. 2. Simulation Scenarios: co-located cells

transmissions. In Scenario C, the client C1 is located outside the reception range of AP A2, while client C2 can receive the signals from all the involved nodes. Scenario D is a slight modification of Scenario C. Here, the client C2 is moved away from the client C1, such that it is outside its reception range. However, it is still in the area covered by both APs.

3) Reference Scenarios: In order to evaluate the effect of the overlapping and co-located cells, reference cases are needed. In our studies we defined three different reference scenarios that allow us to study the influence of the various client and access point positions on the performance of the Wireless LAN cells. These scenarios are shown in Figure 3. Scenario A consists simply of one Access Point and a single

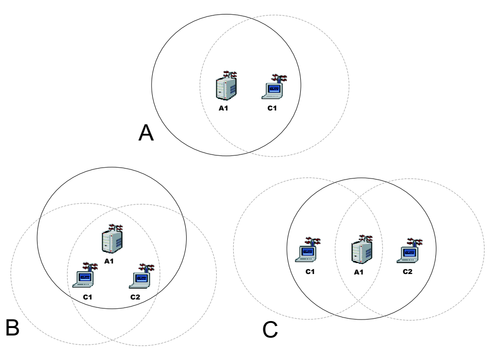

Fig. 3. Simulation Scenarios: reference scenarios

client. It is used to derive the maximum performance of the Wireless LAN MAC protocol in the absence of multiple clients and access points. Scenario B involves a second client. All stations are located in the reception range of each other. This will help to evaluate the performance of a two clients scenario without the influence of multiple cells. Finally, in Scenario C the clients are located farther apart from each other. This helps to include the influence of hidden nodes, a common case in multiple cell scenarios.

III. Results

A. Reference Scenarios

The results for the reference scenarios are summarized in Table I. It shows the average throughput in KBps experienced by the two Wireless LAN clients. The reference scenarios are all symmetric, such that both clients receive the same average throughput. Therefore, just one value is given for each case.

TABLE I

Reference scenarios: average throughput in KBps

Scenario	**RTS**	10 KB	100 KB	1 MB	10 MB
A	-	80	520	714	751
	256	80	520	597	616
B		80	260	354	374
	256	80	260	312	303
C		79	258	347	358
	256	77	256	289	297

Table I shows that the throughput increases as the size of the requested file is increased from 10 KB to 10 MB. The results for scenario A show the maximum achievable throughput at about 750 KBps, because no other client is involved, such that the number of collisions is minimal. In addition it shows the overhead induced by the RTS mechanism (an RTS threshold of 256 Bytes was chosen). It reaches a maximum of about 20 percent in the case of 10 MB file downloads.

The results for scenario B show the average throughput if two clients are simultaneously active in a single cell. In the case of small file sizes, the medium is under low load, such that both clients can be served like in the case with just one client (80 KBps). As the file size and thus the load is increased, the clients still share the throughput equally. Under high load, the RTS mechanism causes an overhead of about 20 percent.

The last two rows of the Table show the impact of the two clients being hidden from one another. As long as the load is low, the throughput can be kept at the same level, but as the load increases, the throughput declines by around 5 percent in the case without RTS and by 2 percent with RTS.

However, an equal share of the average throughput for both clients is not the only important factor of fairness. As we will see later, there are cases where the average throughput is shared equally over a longer period of time, but the clients do not alternate their access on the medium as we might expect. The following figures show different ways the two clients get access on the medium. The bar shows a representative time period of 10 seconds. A gray line from top to bottom show a successful packet reception at client C2 while the black lines represent the packet reception at client C1. Figure 4 shows a

Fig. 4. Fairness indicator: fair alternating access

fair sharing of the medium. Over the whole 10 second period the two clients alternatively receive packets. This result was found using the reference scenario B. Conversely, Figure 5 shows the unfair counterpart. The alternating gray and black blocks show that the clients block each other for longer periods of time. For the first 5 seconds one client exclusively utilizes the medium indicated by the black blocks and then the situation changes and only the other client receives data packets for the remaining time shown by the gray block. Such an unfair behavior is not desired. Therefore, in all our

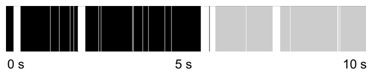

Fig. 5. Fairness indicator: unfair sharing

studies we have to account not only for fairness in terms of average throughput, but also in terms of alternating access to the medium.

B. Overlapping Cells

Let us first consider the simple case of the overlapping cells scenario A, where both clients are located in the overlap of the two access points. This is a symmetric case, such that the results are the same for both involved clients. Figure 6 shows the average throughput received by either of the two clients. By comparing the results to the reference scenarios, we can figure out that the achievable throughput is decreased by just a few percent, even though the number of collisions in this case is considerably higher.

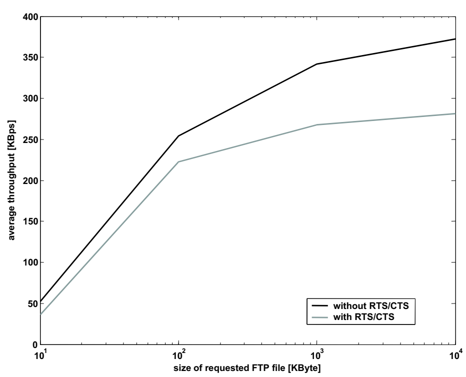

Fig. 6. Overlapping Cells A: average throughput

Fig. 7. Fairness in the overlapping cells scenario A

However, Figure 7 indicates that the MAC protocol does not guarantee fairness. While there is only short periods of time when both clients alternatively receive data packets, there is a period of 8 seconds where one of the clients almost exclusively utilizes the medium, which is not a desirable behavior.

This unfairness is by far intensified once we consider the overlapping cells scenario B. In this asymmetric case, only client C2 is in the overlap of the two access point, while client C1 is not disturbed by the data transmissions of the access point A2. Figure 8 shows that for an increasing load on the medium, the client C1 can take all the bandwidth it needs, while client C2 is only able to utilize the remaining bandwidth. For large file sizes this means that client C2 is not able to receive any more data. Figure 8 also shows that using RTS/CTS does not change the situation. The client C2 can still only utilize the remaining bandwidth.

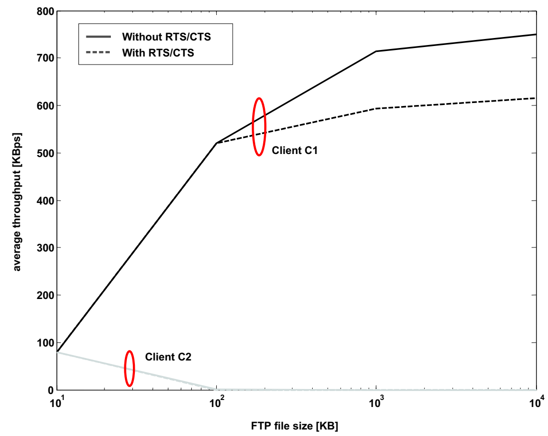

Fig. 8. Overlapping Cells B with standard parameters

As a solution to this problem, the chances of a successful transmission of client C2 have to be increased. This can be achieved by adjusting the contention window parameters appropriately. We introduce a set of different priority classes as shown in Table II. The higher the priority class, the larger

TABLE II

WIRELESS LAN PRIORITY CLASSES

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

the contention window and thus, the lower the probability of getting access to the medium.

TABLE III

OVERLAPPING CELLS SCENARIO B WITH PRIORITIZATION (1 MB FILES)

Priority Class C1	**Priority Class C2**	**RTS/CTS**	**throughput C1**	**throughput C2**
4	1	-	556 KBps	0 KBps
5	1	-	417 KBps	2 KBps
5	2	-	417 KBps	2 KBps
6	**1**	**-**	**264 KBps**	**157 KBps**
4	2	256	459 KBps	2 KBps
5	2	256	364 KBps	13 KBps
5	3	256	233 KBps	10 KBps
6	**3**	**256**	**204 KBps**	**163 KBps**
6	**4**	**256**	**224 KBps**	**108 KBps**
6	**5**	**256**	**237 KBps**	**70 KBps**

Table III shows the results that can be found when applying different priorities to the two clients. However, the results for the cases without RTS/CTS indicate that the only way to achieve a solution to be problem is to use the priority classes 6 at client C1 and 1 at client C2, in the following (6,1). Even small changes to these settings, e.g. using priority classes (5,1) will result in complete unfairness again.

On the other hand, it can be seen that when using RTS/CTS, a number of different priority settings becomes possible. The priority classes (6,3), (6,4), and (6,5) lead to acceptable results. This means that the robustness of the MAC protocol is by far increased if RTS/CTS is used. In addition, such a prioritization leaves some higher priority classes unused, such that there is still potential for higher priority classes, for example in the case of high priority traffic. Therefore, we will set our focus to these parameters in the following.

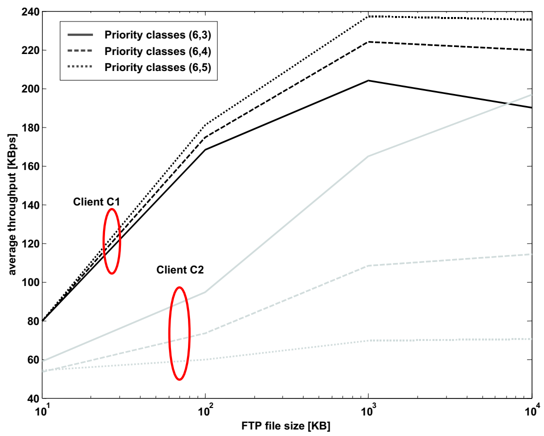

Fig. 9. Overlapping Cells B with prioritization

Figure 9 presents the results for the different priority classes. It can be seen that there is the option to use different priority settings to perform a fine-grained prioritization. While priorities (6,5) privilege client C1 in terms of throughput, a setting of (6,3) will lead to more equal shares regarding the throughput rates. The fairness plot in Figure 10 shows that fairness is given at the access level and the clients receive packets alternatingly.

Fig. 10. Fairness in the overlapping cells scenario B

Applying these priority settings to overlapping cells scenario C leads to the results shown in Figure 11. In this case, the priorities (6,4) will already give higher throughput to client C2. The settings (6,3) would intensify this effect. Fairness is still given as shown in Figure 12.

Summarizing the results for overlapping cells, we can conclude that a client in the overlap of two cells should increase its own priority to either class 4 or 5. In addition it has to inform its associated AP to also change its contention window settings. Clients that can only receive a single AP use the priority class 6.

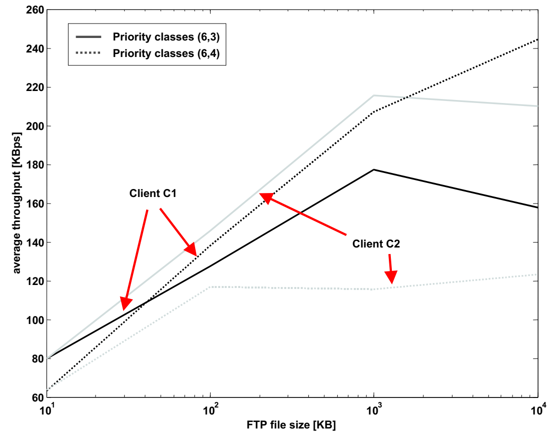

Fig. 11. Overlapping Cells C with prioritization

Fig. 12. Fairness in the overlapping cells scenario C

C. Co-located Cells

The symmetric co-located cells scenarios A and B do not cause any fairness problems. The simulations with the default contention window settings yield throughput rates that are comparable to the reference scenario as shown in Table IV.

TABLE IV
RESULTS FOR CO-LOCATED CELLS A AND B

Scenario	**RTS**	10 KB	100 KB	1 MB	10 MB
A	-	80	263	418	428
	256	51	256	312	319
B	-	78	260	325	378
	256	51	256	312	319

However, in the co-located cells scenario C, the situation changes dramatically. Figure 13 shows that on of the clients is experiencing an extreme unfairness. It can not receive any more data packets when the load of the cell reaches a certain level. RTS/CTS alone does not ease the problem. In contrast to the overlapping cells, here the client C1 is disadvantaged. This means that in the co-located cells not the client in the overlap but the client in the reception range of a single AP has to be privileged. Applying the priority classes as found for overlapping cells but in reversed order leads to the results shown in Figure 14. Again, the problem is solved and both clients share the throughput adequately. Also fairness is given as shown in Figure 15. Similar results can be found for the co-located cells scenario D as summarized in Table V.

Considering the results for co-located cells it can be concluded that a client in the coverage area of a single cell should be served with a higher priority in order to achieve fairness in terms of average throughput and alternating medium access, while clients in the overlap should use priority class 6.

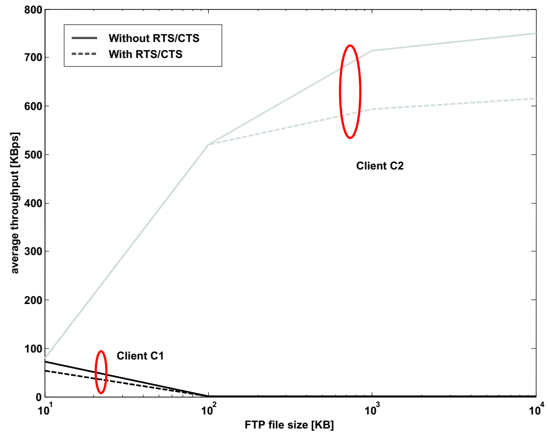

Fig. 13. Co-located Cells C with standard parameters

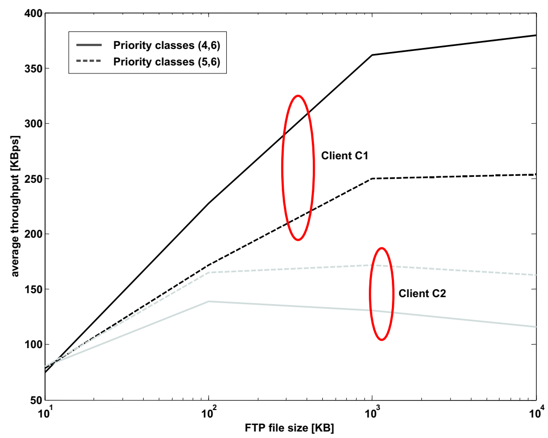

Fig. 14. Co-located cells C with prioritization

D. Combined Solution

Combining the results for both, the overlapping cells and the co-located cells, the following mechanism for achieving fairness can be proposed. For increased robustness of the proposed solution, the RTS/CTS mechanism is turned on. The clients inform their associated APs whether they are in the coverage area of one or more APs. The APs on the other hand scan their channel for other APs in their reception range. If the AP finds itself in an overlapping cell, it tells all its clients that are in an overlap to increase the priority. All other clients will be told to set their priority level to 6. In the case that the AP is placed in a co-located cell this process is inverted. Clients in the overlap are told to use the low priority class 4, while all the others should use priority class 6. This will ensure that all clients will experience fairness in terms of throughput and alternating channel access.

Implementing this solution will improve the fairness in

Fig. 15. Fairness in co-located cells scenario C with prioritization

TABLE V

RESULTS FOR CO-LOCATED CELLS SCENARIO C (FILE SIZE: 1 MB)

Priority Class C1	**Priority Class C2**	**RTS/CTS**	**throughput C1**	**throughput C2**
5	6	256	297 KBps	134 KBps
4	6	256	415 KBps	78 KBps

overlapping and co-located cells, both in terms of the average throughput and alternating access to the medium. On the downside, the proposed prioritization scheme will cause a performance degradation compared to the standard contention window settings of about 20 to 30 percent. Considering the big advantage of the fairness improvement, such a trade-off is definitely acceptable.

Unfortunately, this approach can not be implemented in the case of a IEEE 802.11b network. The reason is that all clients associated to a single access point will be treated alike. The AP can not distinguish the different clients. Therefore, the problems will remain until the introduction of the IEEE 802.11e standard with its enhanced prioritization mechanisms.

IV. CONCLUSIONS AND OUTLOOK

The rapid increase in the number of Wireless LAN hot spots will soon result in situations where the spatial coexistence of overlapping and co-located WLAN cells is mandatory. The limited number of non-overlapping channels necessitates an implicit cooperation of the MAC protocol of WLAN cells.

In this article we presented situations where fairness is not given, but certain clients suffer dramatic deteriorations of their achievable throughput. In less problematic cases we can still find a level of unfairness in terms of alternating medium access that is certainly not acceptable. We identified the reasons for the unfairness and introduced a prioritization scheme and adaptation algorithm that is able to solve the problems. We showed that different scenarios necessitate different solutions, but a combined solution is feasible.

Finally, we explained why the basic 802.11a and IEEE 802.11b standards do not allow to implement such a solution, but the QoS enabled extension 802.11e is necessary.

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