Impact of the Transmission Scheme on the Performance in Wireless LANs

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Abstract. In wireless LANs, different multi-user access methods such as TDMA, OFDMA and SDMA are available which can be used with or without channel knowledge at the transmitter and a single antenna (MISO) or multiple antennas (MIMO) at the receiver. A cross-layer scheduler is considered which can be configured with these different PHY methods as well as with knowledge about application requirements and channel conditions at the MAC layer. The scheduler computes priorities on the MAC layer that are handed over to the physical layer in order to keep quality-of-service constraints such as throughput and delay. In this paper, it is demonstrated that controlling the priorities by a QoS aware resource allocation method allows to meet the requirements by the applications under various channel conditions. MISO-SDMA has a relatively small performance penalty in comparison to MIMO-SDMA which gives the best result. For MIMO-TDMA and -OFDMA, channel knowledge at the PHY layer does not result in essential performance enhancement.

Keywords: Wireless LAN, cross-layer, MIMO.

1 Introduction

Wireless LANs have to meet increasing requirements nowadays and in the future: high data rates for each user, high spectral efficiency in the sense of a high total capacity and meeting several types of QoS requirements for different applications.

Up to now, most protocol stacks are designed according to the OSI model which defines seven layers from the physical layer up to the application layer, with an increasing degree of abstraction from the physical hardware. In legacy protocol stacks, these different protocol layers have been optimised independently of each other. This separation is in particular problematic for the design of the two lowest layers, which are the MAC and the PHY layer, because there are close mutual dependencies between these two layers. The QoS requirements have already to be considered by selecting the physical transmission method. Moreover, the actual channel conditions and the effects of these conditions for

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a QoS aware transmission have to be known when selecting a particular packet for the transmission.

To cope with these requirements, in the framework of the xLAYER project funded by the German Research Foundation (DFG), a cross-layer transmission system for wireless LANs is developed which is located inside the access point resp. base station and has full control of the channel access. The introduced transmission system extends the proposal of the IEEE 802.11n standards draft, where centralised channel access with assignment of user priorities is specified as Hybrid Coordinated Channel Access (HCCA). By means of this transmission system, a comparison of the scheduler performance in case of TDMA, OFDMA and SDMA was given in [6] where a statistical channel model [5] specified by the IEEE 802.11n Task Group was used. With the aim of a more precise modeling of the channel in case of indoor scenarios, a raytracing approach shall now be considered which allows a more realistic simulation of the signal propagation between the base station and the users. The model was investigated along with various physical transmission schemes in [1]. In this paper, the interaction between the newly introduced physical model and the higher-layer scheduler is highlighted. The QoS properties for different users are compared for different MAC scheduling methods along with the different approaches on the PHY layer. In this way, information also can be obtained on how much complexity on the PHY layer such as the requirement of channel knowledge and the number of antennas at the receiver side is required.

2 Cross-Layer Scheduler

The cross-layer scheduler deployed in the simulation includes two stages as shown in Fig. 1: the hardware-independent stage which is located in the MAC layer selects packets based on a certain scheduling strategy. For each user, a separate data flow with an own queue is maintained. The packets for each data flow are assigned a priority value according to the selected scheduling strategy. After the packets have been classified in this way, a list is handed over to the hardware-dependent stage inside the PHY layer. According to different transmission strategies, time slots, OFDM subcarriers or spatial transmission paths are assigned to the users according to the given priorities. For each user, the channel matrix is available for each OFDM subcarrier at regular sampling intervals. From the channel matrices and the user priorities, the allocation of the users to the channel resources and the resulting capacities are calculated. To do so, the physical layer scheduler maximises the weighted sum rate according to the priorities given by the MAC layer scheduler.

In each turn of the scheduler, at first, one packet is taken from each user provided that data is ready for transmission in the respective queue. For the user with the longest transmission time which results from the packet length and the available capacity, one packet is selected. The other users with shorter transmission times fill in the gap with further packets as far as possible. If finally the remaining gap is too small to transmit a complete packet, then only a part

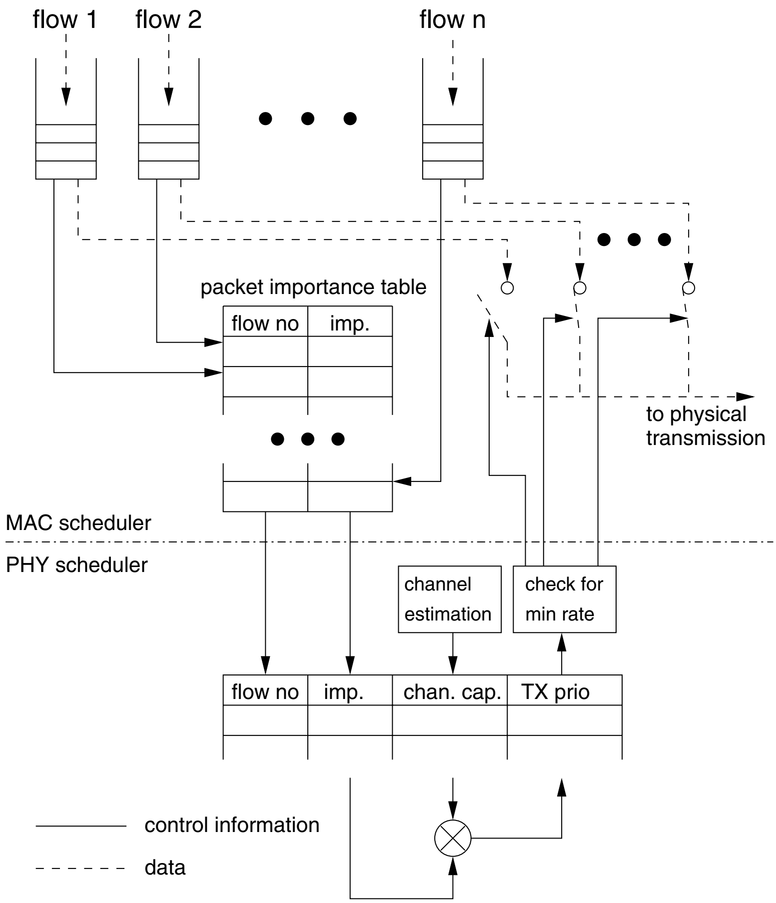

Fig. 1. Design of the parallelised cross-layer scheduler

of the packet is sent which fits into the gap and the remaining data is added to the next packet which is waiting in the queue. In this way, the available airtime is used whenever possible.

Two scheduling strategies are considered: in case of the modified Round Robin (RR) strategy, the MAC scheduler is unaware of queue states. In each turn of the scheduler, it assigns priorities in a linearly decreasing way as shown in table 1.

The quality-of-service (QoS) scheduler sketched in Fig. 2 compares the achieved throughput and the packet age against target values, where the target value $S_{u,\mathrm{tar}}$ for the throughput is the amount of data transmitted by user u within a sliding time window; in order to control the delay, the packet expiry time $t_{u,\mathrm{tar}}$ for the next packet that is at the top of the queue for user u is used. With $S_{u,\mathrm{cur}}$ being the current throughput of a user and t_{cur} being the current system model time, The differences $S_{u,\mathrm{tar}} - S_{u,\mathrm{cur}}$ and $t_{u,\mathrm{tar}} - t_{\mathrm{cur}}$ are adaptively weighted and converted into a priority w_u for each user u as described in detail in [7].

Table 1. Priority assignment for modified Round Robin scheduling

	time slot					
	1	2	3	...	8	9 ...
user 1	7	6	5	...	0	7 ...
user 2	6	5	4	...	2	1 ...
...				...		
user 8	0	7	6	...	4	3 ...

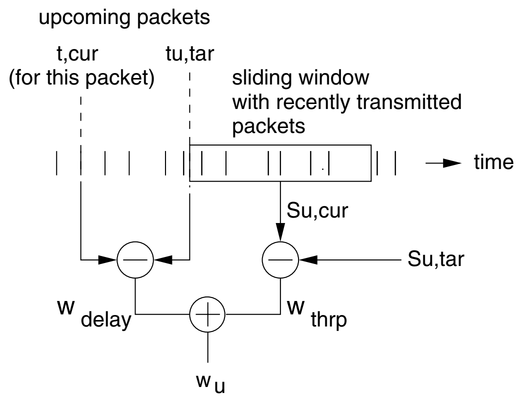

Fig. 2. Principle of the QoS aware scheduler

In this paper, only the downlink from the access point to the mobile stations is considered for the transmission of user data; in the uplink direction, only acknowledgement packets are transmitted.

3 Physical Transmission Methods

SISO (Single Input Single Output): In this case, the different locations of the users have little effect because both the access point and the mobile terminals only have one antenna. In this paper, this case is not furthermore considered.

MISO (Multiple Input Single Output): In the case of MISO, the access point exploits the different spatial locations between the users, however the mobile terminals do not. Users located at different positions however can be separated by the access point so that the sum rate over all users can be increased. The per-user rate is expected to remain unchanged.

If TDMA or OFDMA is used together with a MISO transmission, further cases can be distinguished regarding the usage of spatial diversity. *Space-Time Block Codes* (STBC) [8] improve the reliability of the transmission because they allow to combine the signals received at different antennas. In this way, it is likely that at least at one antenna a good signal is available. *Beamforming* (BF) [10] allows to focus the transmitted signal onto particular users during the transmission of a packet which uses the transmit power more efficiently. When combining MISO with SDMA, Dirty Paper Coding (DPC) can be deployed where users with higher priority are separated by "pre-subtracting" interference caused by signals for users with lower priority. For a sufficient number of users, the number of receive antennas becomes irrelevant [4] so that DPC then also can be deployed by using a single antenna at the user. In section 5 these anticipated effects of the different transmission methods are evaluated more closely by simulations.

MIMO (Multiple Input Multiple Output): In this case, both the access point and the mobile stations have more than one antenna. When combining with TDMA or OFDMA, successive interference cancellation (SIC) [3] is used if no channel knowledge is available at the AP or Singular Value Decomposition (SVD) in case that channel knowledge is perfect. In case of SDMA, the method to separate the users is DPC as already described in the section about MISO.

Considering an access point with N_{T} transmit antennas and mobile stations with N_{R} receive antennas each, the channel matrix $\mathbf{H}_u[m]$ of subcarrier m for user u has the size $N_{\mathrm{R}} \times N_{\mathrm{T}}$. The transmitter is described by a covariance matrix $\mathbf{\Phi}_{\mathbf{x}_u}[m]$ for each subcarrier m. Furthermore, the model considers an effective noise vector $\tilde{\mathbf{n}}_u[m]$ with the covariance matrix $\mathbf{\Phi}_{\tilde{\mathbf{n}}_u}[m]$ including additive white Gaussian noise and interference. The data rate $R_{\mathrm{u}[m]}$ for user u and subcarrier m can then be calculated as [9]

$$R_{\mathrm{u}}[m] = \log_2 \det(\mathbf{I} + \mathbf{\Phi}_{\tilde{\mathbf{n}}_u}^{-1}[m]\mathbf{H}_u[m]\mathbf{\Phi}_{\mathbf{x}_u}[m]\mathbf{H}_u^{\mathrm{H}}[m]). \tag{1}$$

4 Simulation Setup

An indoor scenario is considered where $N_{\mathrm{U}} = 8$ users are located in a room with the size $8\,\mathrm{m} \times 6\,\mathrm{m} \times 3\,\mathrm{m}$ as shown in Fig. 4, where each of them is equipped with a mobile station which remains at a fixed place. Slight movements of the users are simulated by clusters of scatterers which slowly orbit around a center in front of the mobile stations. An access point with N_{T} transmit antennas is mounted at the ceiling. The access point keeps a separate queue for each user resp. data flow with a length of 50 packets. Each of the mobile stations has $N_{\mathrm{R}} = 1$ receive antenna in case of MISO and $N_{\mathrm{R}} = 4$ antennas in case of MIMO. An OFDM transmission system is used with $N_{\mathrm{M}} = 32$ subcarriers working at a carrier frequency f_{C} of 5.2 GHz with a channel bandwidth of 40 MHz. Reflections on the walls and on the scatterers are simulated by a simplified raytracing model as specified in [2] which considers reflections up to second order. The signal-to-noise-ratio at the receiver averaged over all users, subcarriers and time samples is set to 20 dB.

An example for the channel characteristics is given in Fig. 3 which shows the absolute value of the channel matrices $\mathbf{H}$ as a function of the sample k and the subcarrier m for a particular user.

The channel coefficients which are the basis for the calculations of the physical-layer scheduler are updated every 4 ms.

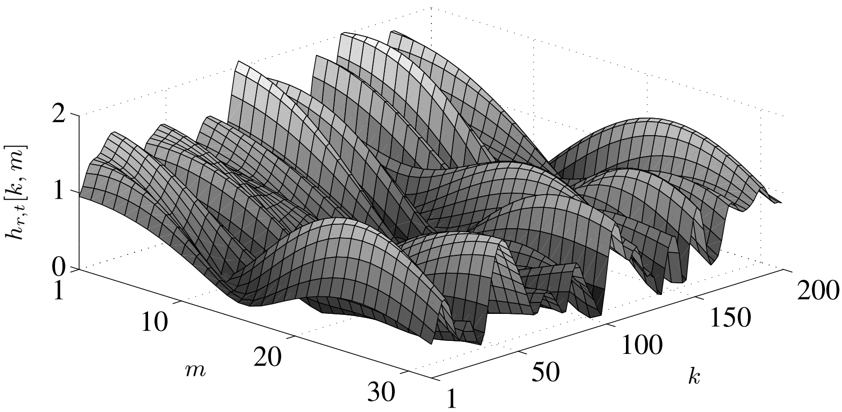

Fig. 3. Example for the characteristics of the channel model with m subcarriers for $k = 200$ time slots

The users 1, 2 and 3 have time-critical flows with delay constraints of 15 ms each; the other users have best-effort flows with a given data rate. The packet size is set to 40000 bytes for all users. The loads for the non-time-critical flows are set to values above the available channel capacities so that the system is always in saturation to allow a comparison between the different transmission schemes. The simulated model time is 10 seconds.

The simulator used for the investigations discussed in this paper is called WARP2; it implements the IEEE 802.11 protocol stack and has been extended with the two-stage MAC/PHY scheduler as described above.

5 Simulation Results

Fig. 5 shows the total throughput as well as the per-route throughputs which are achieved for the different transmission schemes where "dumb" resp. "smart" means that the transmission scheme works without resp. with channel knowledge. As expected, SDMA achieves the best performance, followed by MIMO-OFDMA and MIMO-TDMA. A notable fact is that the presence or absence of channel knowledge does not enhance the total throughput significantly in all cases.

The QoS scheduler keeps the requirements of the time-critical flows except for dumb MISO-TDMA and dumb MISO-OFDMA where a channel with a small total capacity has to be shared which results in failure of serving even the time-critical users. In this case, a call admission control would be needed to disconnect users whose requirements cannot be met, which will be future work. The remaining airtime is distributed among the non-time-critical flows. In most cases, the users are served in a fair manner in the sense that they get an amount of channel capacity which is proportional to their offered load. In certain situations, however, channel conditions prevent a fair distribution as it can for example be seen

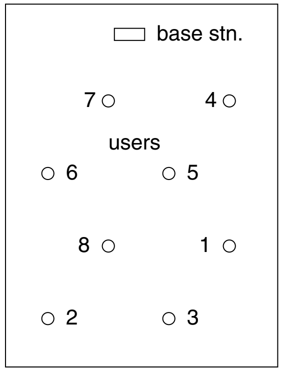

Fig. 4. Arrangement of the users inside the scenario

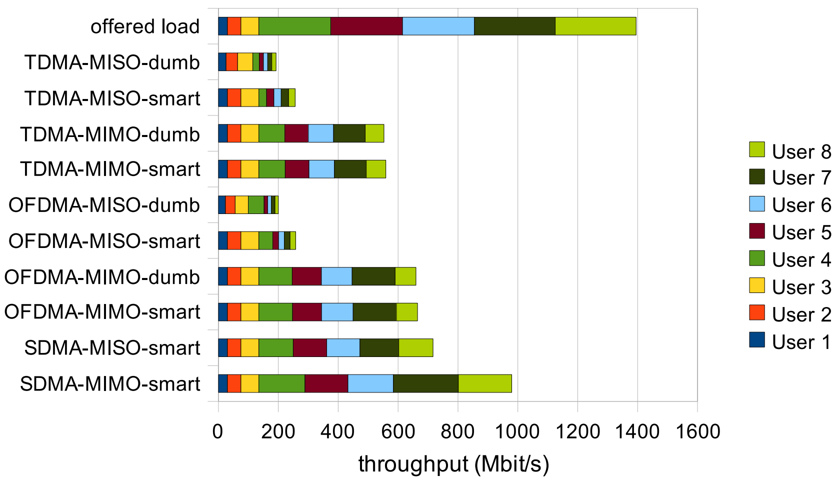

Fig. 5. Throughput for the different transmission methods, QoS scheduler

for user 8 who is served less than the other non-time-critical users in the TDMA or OFDMA case. With SDMA, channel resources are sufficient so that the user can be correctly served as well.

Except for the MIMO-SDMA scenarios, the achieved throughput for the non-time-critical flows is significantly smaller than the offered traffic load. This means that the system is in saturation; the respective queues are filled up to the maximum limit. Any packets which exceed the queueing capacity are dropped.

For MIMO-TDMA and MIMO-OFDMA the results for dumb and smart transmission are almost the same whereas there is a notable increase for MISO-TDMA/-OFDMA. The reason is that in case of MIMO, the user gets a better average channel with less variation due to the antenna diversity which then

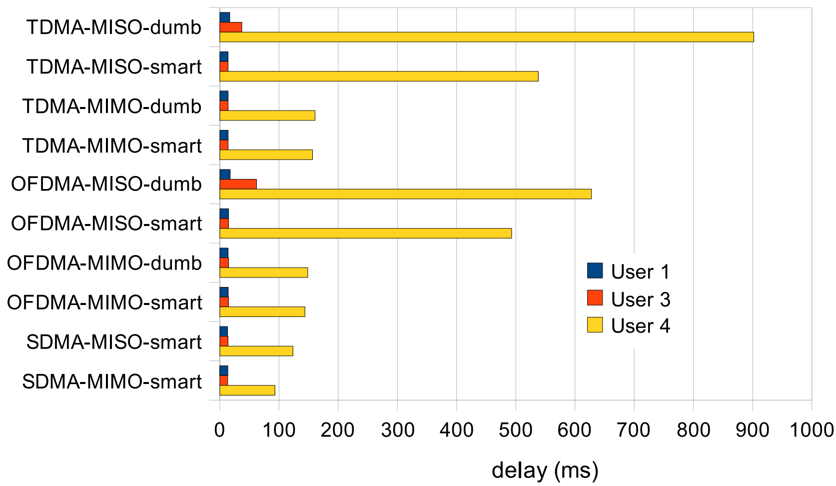

Fig. 6. Delay for the different transmission methods, QoS scheduler

cannot be enhanced much more by channel knowledge. Therefore, MIMO-TDMA/OFDMA is attractive for system designs because without the requirement for channel knowledge less feedback in the uplink from the receiver to the sender is needed. For maximum performance requirements, MIMO-SDMA is the method of choice, however also MISO-SDMA gives good results which are still higher than for MIMO-TDMA or -OFDMA which makes it attractive for small devices without space for multiple antennas.

The delays achieved by the above scenario are illustrated in Fig. 6. For overview reasons, the delay is shown only for three out of the eight users, two users with a time-critical flow and one user with a non-time-critical flow. The QoS requirements for the time-critical users are kept independent of the total capacity of the transmission system, except for dumb MISO-TDMA or -OFDMA where the total channel capacity is insufficient so that the users cannot be correctly served. The delays for the non-time-critical flows are high because the queues run full in this case. With increasing total capacity, the delays are reduced because due to the higher service rate, the dwell time of the packets inside the queue decreases.

An example for the behaviour of the queues during the time progress is given in Fig. 7 for the QoS scheduler in case of dumb MIMO-OFDMA. where the queue lengths are shown for three users for the first second of model time. User 1 and 3 get real-time service so that the queue lengths are kept at a maximum of 3 in order to avoid exceeding the maximum delay due to queueing. User 4 has a higher load and is a best-effort user, so that the offered load cannot be fully served and the queue are filled quickly up to the maximum length. The limited queue size also limits the delay of the queued packets, however packet loss will occur.

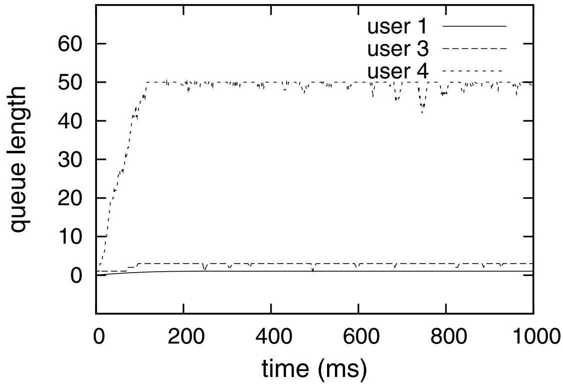

Fig. 7. Queue lengths for three users, QoS scheduler

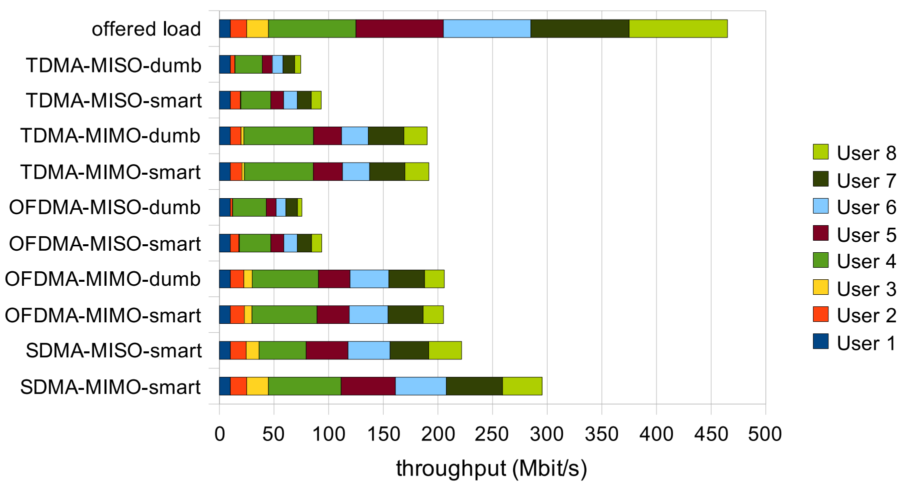

Fig. 8. Throughput for the different transmission methods, RR scheduler

For comparison, the same simulation setup has been run with RR as the MAC scheduling strategy. Fig. 8 shows the results for the achieved throughput. The total capacities in case of the different transmission schemes are similar to those achieved in the case of the QoS scheduler, however the allocation of troughput to individual users is largely different. The QoS requirements for the time-critical users cannot be kept except in the cases that the total available throughput is high. Despite of the regular assignment of priorities, even users with equal offered traffic load achieve significantly different throughputs due to different channel conditions: a user who is located at a distant position from the access point in average experiences a reduced channel quality in comparison to a user who is closer. User 4 is always assigned a disproportionately high capacity,

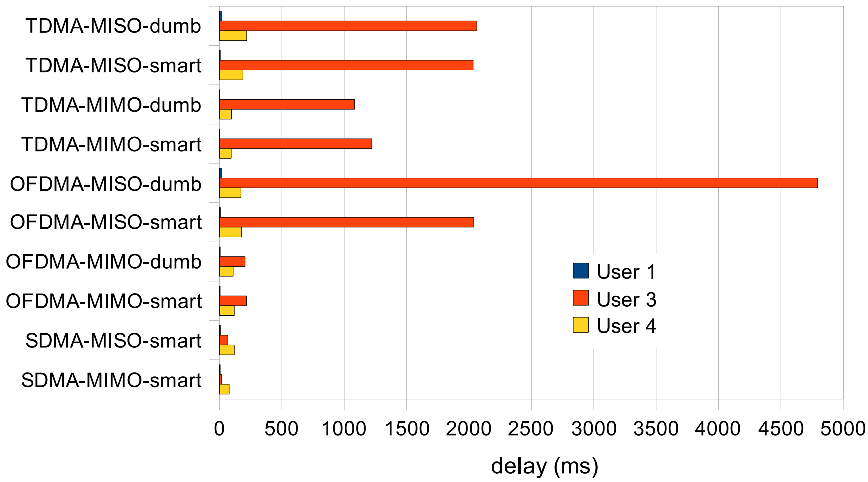

Fig. 9. Delay for the different transmission methods, RR scheduler

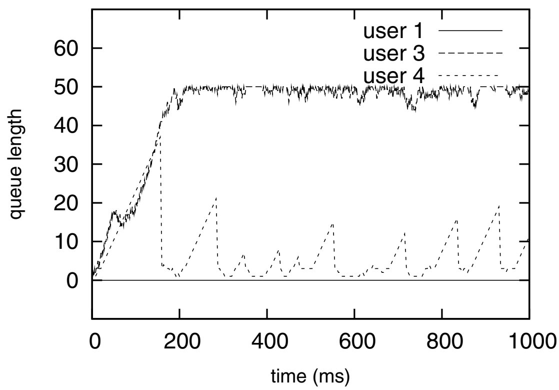

Fig. 10. Queue lengths for three users, RR scheduler

whereas the QoS scheduler discussed before reduces the service of user 4 to some extent in order to provide more capacity to other users. The delay results in Fig. 9 correspond to the throughput measurements. The QoS requirements for the time-critical users are are only met if the total capacity of the system is sufficiently high so that the system works in a best-effort manner.

Fig. 10 shows the temporal queueing behaviour of the users 1, 3 and 4. User 1 has a relatively small load so that the RR scheduler serves him frequently enough to keep the queue at zero size, i. e. no packet is backlogged, each packet is immediately prepared for transmission. User 3 has a load which is higher than the service rate, the queue is quickly growing. Since the user is time-critical, the packets expire so that the queue is flushed and the packets discarded in certain time intervals. User 4 has a higher load, but is not time-critical so that the packets are not subject to ageing. The queue rapidly grows to the maximum; any extra packets beyond the queue length are dropped.

6 Conclusion and Outlook

The performance of the cross-layer scheduler has been tested along with different MAC scheduling methods including and without knowledge about user requirements and queue states; different transmission methods with and without channel knowledge were investigated as well as transmission with single or multiple antennas at the receiver. With the QoS scheduler on the MAC layer, performance requirements can be kept for time-critical flows under a wide range of total system capacities. The remaining capacity is allocated to non-time-critical flows in a fair manner in the sense that each flow approximately gets the same portion of the available resources. The comparison with the RR scheduler shows that users with the same offered traffic load achieve different throughputs due to different long-term channel conditions; by the help of QoS scheduling, this problem can be balanced by assigning the priorities in a suitable way. MIMO-TDMA or MIMO-OFDMA transmissions show a relatively small speed penalty when transmissions with or without channel knowledge are compared so that effort of providing and processing channel state information can be saved. The speed penalty of MISO-SDMA vs. MIMO-SDMA is relatively small so that the scheme is suitable for small devices without space for multiple antennas.

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