MAC Level Performance Evaluation of Downlink Resource Allocation Strategies for an OFDMA System based on IEEE 802.16

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***Abstract*— In this paper, different downlink resource allocation strategies for an OFDMA are analyzed in detail. The performance of a centrally controlled system based on IEEE 802.16 is investigated by means of stochastic event-driven simulations. The focus is on the tradeoff between system capacity maximization due to the exploitation of multi user diversity and fairness in terms of packet delay. Since QoS (Quality of Service) provision is a critical design issue in the development of future broadband radio systems, the presented results can be considered as a contribution to the design process of such systems.**

***Index Terms*— OFDMA, IEEE 802.16, resource scheduling, QoS, medium access control**

I. Introduction

The OFDMA transmission scheme (*Orthogonal Frequency Division Multiple Access*) is of great prominence in the design of future broadband radio systems. Several research projects in the area focus on that technique [1][2]. Especially in combination with adaptive modulation and dynamic power allocation the use of OFDMA has been proved to be quite beneficial [3]. Apparently, the major key component in the design of an OFDMA system is the resource allocation or scheduling scheme. The transmission resources are in general defined by orthogonal narrowband subcarriers which are grouped into subchannels. Furthermore, these subchannels are subdivided into time slots. The problem is to assign these two-dimensional resources to different data connections dynamically in a way that generally contrary QoS requirements like delay and capacity are met at the same time in a certain extent. The use of an OFDMA transmission scheme with appropriate settings of subcarrier and subchannel bandwidth it is possible to exploit the diversity of a frequency-selective fading channel. That exploitation can significantly increase the system capacity in multi user scenarios [4]. However, a problem in the exploitation of multi user diversity is that it might result in unfairness between the different data connections since connections with good channel conditions are always preferred compared to connections with bad channel conditions.

In this paper we analyze the performance of three different OFDMA resource scheduling strategies in terms of system capacity and fairness. For the assessment of fairness the packet transmission delay of different data connections has been evaluated. The scheduling strategies provide different degrees of fairness and system capacity.

In contrast to most works in the OFDMA research field this paper is not just focused on the PHY (*Physical Layer*). The characteristics of both PHY and MAC (*Medium Access Control*) are incorporated. This means that packet data transmissions comprising ARQ (*Automatic Repeat Request*) and segmentation processes are analyzed, and not just bit streams. The MAC protocol of the investigated system is thereby based on a centrally controlled scheme like IEEE 802.16 [6]. The performance evaluation of downlink data transmissions has been conducted by the means of stochastic event-driven simulations. For that approach a comprehensive simulation environment based on NS-2 has been developed.

The paper is organized as follows. Section II describes the different OFDMA resource scheduling strategies. The focus is on the tradeoff between capacity and fairness. The analyzed OFDMA system, comprising PHY and MAC, is presented in Section III. The results of the performance evaluation and the interpretation are given in Section IV. Finally, the paper ends with a conclusion.

II. OFDMA Resource Scheduling

The transmission resources in an OFDMA system in general consist of orthogonal subchannels in the frequency domain. These subchannels are formed by subcarrier sets. The latter can either be distributed or adjacent in the frequency channel [7]. The first approach offers the possibility to exploit the diversity of the frequency channel, and the second scheme results in an averaging effect concerning both fading and interference. Low quality subcarriers of a subchannel can be compensated by high quality subcarriers with the use of a channel coding scheme with a long constraint length [8]. Detailed performance comparisons of both schemes with a basic OFDMA scheduling algorithm are given in [9] and [10]. In these works only a Round Robin approach was used for the scheduling.

The resource scheduling scheme with different strategies, which is evaluated in this paper, is an extension of the algorithm used in the previous works. The general resource allocation procedure is the same for all strategies. Since we investigate the downlink a centrally controlled system like IEEE 802.16, the resource scheduling is conducted in the BS (*Base Station*). It is done periodically at the beginning of a MAC frame, whose structure is described in detail in the next section. The resources within the following MAC frame are assigned to downlink connections to MTs (*Mobile Terminals*) by a process which incorporates a general loop. The basic steps of that loop are described in the following.

At first, a queue is selected from the set of active connections. A connection is considered active if there is at least one data packet to be transmitted. The according connection then gets the resource with the best quality regarding the fading from the set of not assigned resources within the MAC frame. Finally, the transmission power and an appropriate modulation and coding scheme are selected, and the data packets that fit into the allocated resource element are removed from the queue. This procedure continues until either all active connections have been able to transmit all data packets or all resources within the MAC frame are allocated. This resource scheduling scheme can in general be used for both up- and downlink, but in this paper only the downlink is considered. A uniform transmission power allocation is used. This means that the same fraction of the overall transmission power is assigned to all parallel transmission of a station in a time slot. When there are for example 4 parallel downlink transmissions in a slot and the overall transmission power is 30 dBm, each transmission gets 24 dBm. The PHY mode (combination of modulation and coding scheme) is selected due to the SINR estimation based on pathloss, fading and assigned power. We assume perfect channel knowledge at the BS. The investigated OFDMA resource allocation strategies only differ in the connection or queue selection scheme. Following three strategies have been implemented.

- Max Capacity:	Queue that can achieve the highest capacity in the next resource allocation
- Max Delay:	Queue that has currently the maximum waiting time
- Round Robin:	Next queue in the sense of Round Robin [5]

The investigated scheduling strategies provide different degrees of the tradeoff between exploitation of multi user diversity and therefore system capacity and fairness. The *Max Capacity* scheme provides the maximum system capacity of the considered schemes since in every resource allocation step the queue with the highest achievable capacity is selected. In general this scheduling scheme can be considered as a heurist algorithm for the search of the global capacity maximum. Maximum fairness between all connections is achieved with *Max Delay*. In every step that queue is selected which has largest waiting time. The waiting time is here the time that the first packet in the queue has been waiting for transmission. *Round Robin* queue selection forms a tradeoff between system capacity and fairness. The fairness is an inherent trait of that scheme. As long as there is more than one active connection with data to transmit no single connection can block all other connections. In the mean every connection gets the same amount of resources. This scheme is expected to achieve a higher system capacity than the *Max Delay* approach. The *Round Robin* selection is conducted for resource allocation and not for single packet transmissions. This means that, depending on the quality of a resource, different numbers of packets can be transmitted. Consider following downlink transmission scenario. There is an MT which has a position close to the BS and one which is far away, e.g. at the cell border. Although the amount of resources assigned to each station is the same due to the *Round Robin* selection, the MT close to the base station can always receive more packets than the other MT because of the better channel quality.

III. System Description

The system operates on a 10 MHz channel at 5 GHz which is subdivided into 128 orthogonal subcarriers. The latter are grouped into 4 subchannels each with 32 adjacent subcarriers. This results in an effective subchannel bandwidth of 2.5 MHz. An OFDMA symbol has a total duration of 13.6 µs comprising a cyclic prefix of 0.8 µs. This is a rather basic OFDMA system, but for the performance evaluation of the different resource scheduling strategies this is sufficient. QPSK¾, 16QAM¾, and 64QAM¾ are used as modulation and coding schemes for data transmission.

The MAC scheme is based in IEEE 802.16a [6]. This means that the access to the medium is centrally controlled by the BS. The frequency channel is subdivided into fixed length MAC frame and the assignment of resource within these frames is conducted periodically at the beginning of each frame. These resource allocations, both up and downlink, are broadcasted by the BS to all associated MTs. The MAC frame structure, which used in this paper, is shown in Fig. 1. It consists of 9 time slots each with a length of 108.8 µs, which accords to 8 OFDMA symbols. This results in an overall MAC frame length of 979.2 µs.

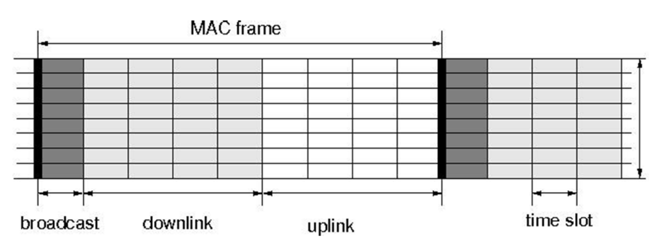

Fig. 1. MAC frame structure

The first time slot is reserved for broadcast transmissions like downlink and uplink resource allocation announcements. For both the downlink and the uplink 4 slots are reserved for data transmissions. In this paper, only downlink transmissions are investigated. In general, the length of the broadcast transmission phase depends on the number of possible resource allocation combinations comprising the number of connections, resources and PHY modes [11]. However, the signaling overhead can be significantly decreased when the resource allocations of consecutive MAC frames are correlated [12]. In this paper we assume a fixed broadcast overhead (~11.11%) since we focus on the OFDMA scheduling and not on the signaling.

Table 1 contains the number of 40 byte MPDUs (*MAC Protocol Data Units*) that can be transmitted in a resource element, comprising one time slot and one subchannel, and the resulting capacity depending on the PHY mode. Due to the use of fixed length MPDUs a segmentation and reassembly process is required on top of the MAC layer. An SR-ARQ scheme (*Selective Repeat ARQ*) is used to handle transmission errors. We consider a connection oriented data transmission in this paper. It is assumed that all connections have already been established.

TABLE 1 : SUBCHANNEL CAPACITY

PHY mode	*MPDUs per resource*	*capacity per resource*
QPSK ¾	1	326.8 kbit/s
16QAM ¾	2	653.6 kbit/s
64QAM ¾	3	980.4 kbit/s

IV. PERFORMANCE EVALUATION

A. Simulation Environment

A comprehensive OFDMA and MAC extension has been developed for the NS-2 simulator [12] to conduct event-driven simulations. The simulator comprises the implementation of a centrally controlled MAC scheme like IEEE 802.16 and an OFDMA transmission model. Furthermore, an SR-ARQ and segmentation scheme has been implemented. The OFDMA subchannel fading is modeled by the Jakes fading generator for the generation of time correlated fading [14]. The fading processes of adjacent subchannels are assumed to be uncorrelated. BER and PER are calculated via the expressions for AWGN channels [15]. A constant coding gain of 2 dB is assumed for the channel coding. The according link adaptation curve for the used PHY modes is given in Fig. 2.

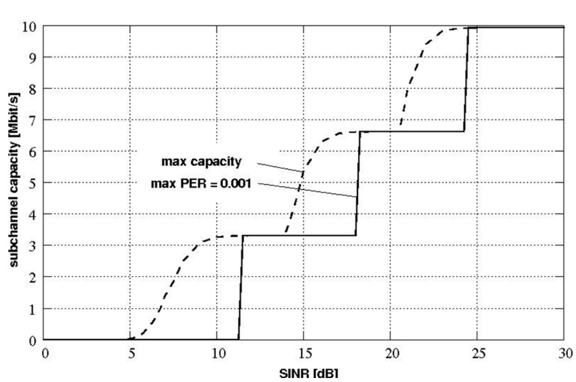

Fig. 2. Link adaptation curve

It shows the mapping for capacity maximization without a PER constraint and with a maximum PER constraint of 0.001. The second mapping is used in this work since the first scheme results in higher packet delays due to possible retransmissions. In general the coding gain depends on the SINR level. This would affect the steepness of the maximum capacity curve. Since we conduct the link adaptation with the constraint of a maximum PER (solid curve), our assumption of a constant coding gain can be applied. The system never operates in a state of high PER.

B. Simulation Scenario

The simulation consists of a singe BS and 12 MTs at fixed positions. 4 MTs are placed at a distance of 250m to the BS, and 8 MTs are placed at 100m distance in a circle around the BS. Each MT has one downlink connection. The offered traffic load is modeled by a Poisson source which generates 100 byte sized packets. Hence, due to segmentation process, 3 MPDUs are required for the transmission of a single data packet. In every simulation each connections has the same traffic load. In the following, the downlink connections to MTs at 100m are denoted *inner connections*. Connections to the MTs at 250m are named *outer connections*. A Doppler shift of 100 Hz has been used for the generation of the OFDMA subchannel fading and the pathloss exponent is 2.5. The total downlink transmission power, which has to be shared between all parallel downlink transmissions, has a level of 30 dBm. The maximum accepted PER is 0.001. Although there is no interference in the simulated scenario the term SINR will be used in the following discussion of performance results.

C. Simulation Results

Fig. 3 shows the cumulative distribution functions of the SINR level during downlink burst receptions depending on the distance between BS and MT and the traffic load. The OFDMA resource scheduling scheme in this case is *Max Capacity*.

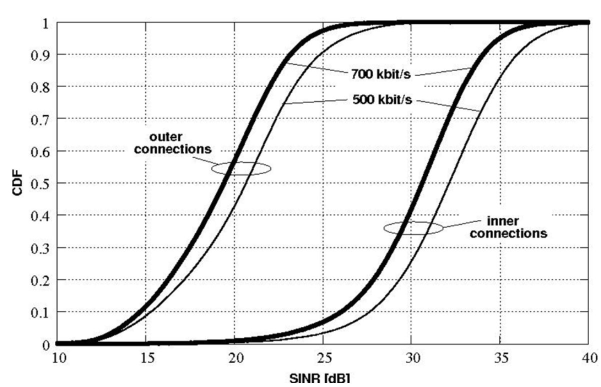

Fig. 3. SINR CDFs

These measurement results reveal in comparison with Fig. 2 that the outer connections have a very large probability of using 64QAM¾, which provides the highest capacity of the available PHY modes. The inner connections have a very low probability of using that PHY mode. The reduction of the SINR with increased traffic loads is based on the effect that the overall downlink transmission power has to be shared between more data transmissions in parallel. Doubling the number of parallel transmissions results in an SINR reduction of 3 dB. The mean overall resource utilization in a MAC frame depending on the traffic load per downlink connection is shown in Fig. 4. It is obvious that the *Max Capacity* scheme achieves the maximum system capacity which corresponds to the most efficient resource utilization. The most inefficient resource utilization is observed with the *Max Delay* strategy. The performance of *Round Robin* lies between the two other schemes.

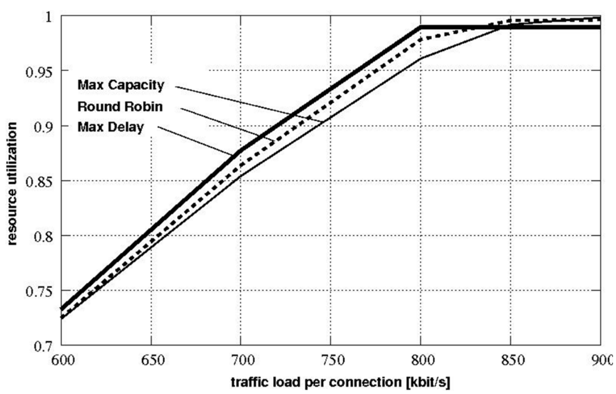

Fig. 4. Mean resource utilization

The reason for the different amounts of resources, which are used for data transmissions, depending on the used OFDMA resource scheduling approach is revealed in Fig. 5. It shows the overall PHY mode usage at 700 kbit/s traffic load. In comparison with the according SINR evaluation in Fig. 3 it has to be kept in mind that the overall PHY mode usage comprises both inner and outer connections. The results show that the *Max Capacity* scheme provides the largest system capacity due to the most efficient PHY mode usage. It has the largest probability of using 64QAM¾ and the smallest probability of using QPSK¾ compared to the other scheduling strategies. In accordance to the resource utilization results *Max Delay* has the least efficient PHY mode usage.

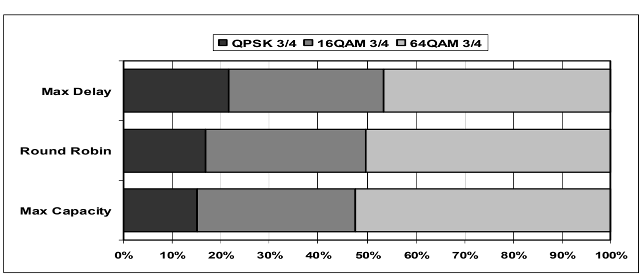

Fig. 5. PHY mode usage

Fig. 6 shows the mean number of MPDUs that are transmitted within a MAC frame depending on scheduling strategy and traffic load per connection. Corresponding to the previous resource utilization results it can be seen that the *Max Capacity* scheme provides the highest system capacity. The most interesting effect, which is revealed by these results, is that the overall number of MPDUs per MAC frame does grow in a stepwise linear manner with the traffic load per connection. In the first linear section of the curve (from 200 kbit/s to approx. 800 kbit/s), all connections, both inner and outer, can be served. No transmission queue is in an overload situation. The length and the gradient of the second linear section depend on the applied scheduling strategy. Actually, the *Max Delay* curve has no second linear section at all. The last linear section in each curve, which is a constant, represents the saturation of the system. In comparison with the resource utilization in Fig. 4 it can be seen that in the range of the second linear section the resource utilization is already at 100%. However, the system capacity can still be increased. The reason is that the resources allocations to the connections are reorganized when the traffic load is further increased. The higher the traffic load, the higher is the degree of unfairness in the system. The connections with good channel conditions are preferred in comparison with other connections. The extent of that unfairness due to resource reorganization depends on the OFDMA scheduling strategy.

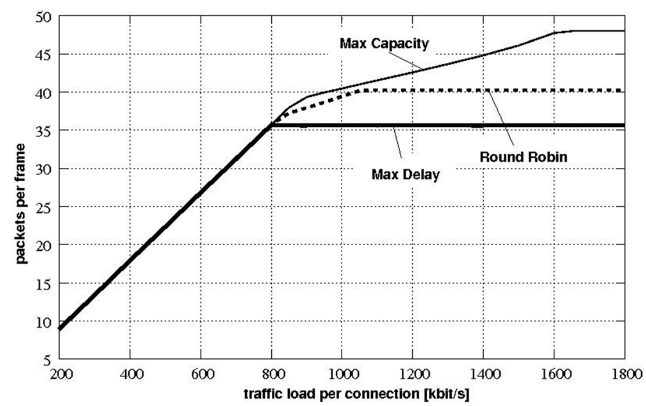

Fig. 6. MPDUs per MAC frame

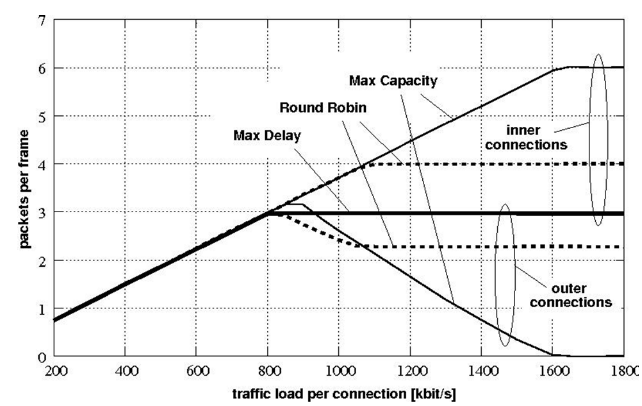

Fig. 7. MPDUs per connection per MAC frame

In the following, the effect of that resource reorganization and the resulting unfairness will be shown. The mean number of MPDUs for each connection within a MAC frame is given in Fig. 7. The connections are divided inner and outer connections. These results clearly demonstrate the resource sharing between inner and outer connections depending on the scheduling strategy. With *Max Capacity* the inner connections get more resources than the inner connection when the traffic load is high since they are preferred during the resource allocation due to the higher expected SINR compared to the outer connections. In the extreme case, when the mean overall number of MPDUs per MAC frame is in saturation, the outer connections get no resources at all. It can be seen that the *Max Delay* approach provides the highest degree of fairness between inner and outer connections. Both connection types have exactly the same capacity, but as shown in Fig. 6, the system capacity with that strategy is clearly reduced compared to *Max Capacity*. The performance of *Round Robin* is between the other two schemes, both concerning fairness and system capacity.

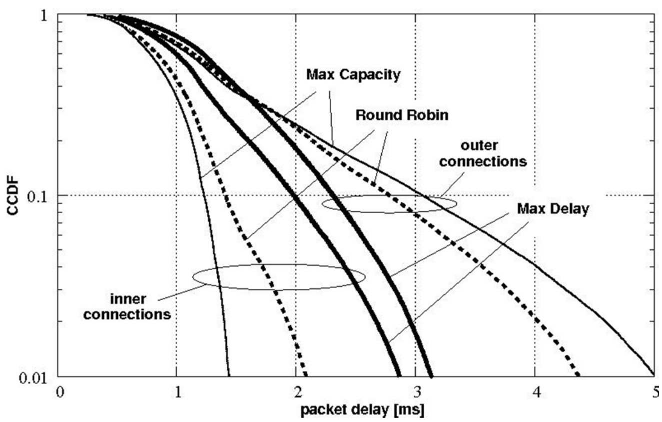

Fig. 8. Packet delay CCDF (700 kbit/s)

The complementary distribution function of the packet delay at 700 kbit/s traffic load per connection is given in Fig. 8. This delay is measured after the reassembling of data packets on top of the MAC layer. Hence, possible retransmissions of MPDUs due to transmission errors are included.

It shows how the delay of the outer connections can be decreased by increasing the delay of the inner connections. The extent of that tradeoff depends on the resource allocation strategy. Concerning the packet delay *Max Capacity* shows the largest degree of unfairness and *Max Delay* provides maximum fairness. This corresponds to the previous results. But it is important to see that there is already unfairness concerning the packet delay even when the mean number of MPDUs per frame is exactly the same for all connections and all scheduling strategies.

V. Conclusion

In this paper, the performance of different OFDMA resource scheduling strategies has been evaluated for a centrally controlled MAC scheme based on IEEE 802.16. The focus was on downlink transmissions. This evaluation has been conduced by means of stochastic event-driven simulations with a comprehensive simulation environment. The simulated OFDMA system comprised both PHY and MAC layer. Furthermore, the focus was on packet data transmission and not on bit streams. It has been shown that the tradeoff between system capacity and packet delay strongly depends on the applied scheduling strategy. Three different strategies, *Max Capacity*, *Round Robin* and *Max Delay*, have been simulated in a reference scenario and the detailed performance analysis comprised resource utilization, PHY mode usage and packet delay measurements.

This work is considered as an important basis for further research activities concerning the development of broadband OFDMA systems. The next step is the performance analysis of priority scheduling of data connections with different QoS requirements. Additionally, further enhanced scheduling strategies like *Proportional Fair* will be analyzed.

Acknowledgements

This work is partly being funded by the German Federal Ministry of Education and Research (BMBF) under the project WIGWAM (*Wireless Gigabit with Advanced Multimedia Support*). Further, the authors would like to thank the colleagues at Siemens AG and ComNets for the fruitful discussions.

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