Performance Evaluation of a basic OFDMA Scheduling Algorithm for Packet Data Transmissions

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Abstract

Currently, the OFDMA transmission scheme seems to be a promising candidate for future broadband radio systems. The crucial part which determines the performance is thereby the combination of dynamic subcarrier allocation, transmission power allotment, and adaptive modulation. In this paper, the general effects of OFDMA scheduling concerning QoS for packet based data transmissions are described. Based on that information a basic scheduling algorithm which provides both fairness and exploitation of multi-user diversity is proposed for the deployment in centrally controlled systems like IEEE 802.16. Furthermore, a detailed performance evaluation of the algorithm is given for an exemplary scenario. The results show the impacts of multi-user diversity regarding packet delay and capacity.

1. Introduction

Due to its substantial advantages, the Orthogonal Frequency Division Multiple Access (OFDMA) transmission technique has become a promising candidate for B3G (beyond third generation) broadband radio systems. Currently, that transmission scheme is for example deployed in the well known standard IEEE 802.16a [1]. Especially in combination with adaptive modulation and power allocation OFDMA has shown to be quite beneficial [2]. An important feature of the OFDMA transmission scheme is the possibility to exploit multi-user diversity. That means that different terminals experience different fading levels on different subchannels at the same time. When a scheduler for multi-channel schemes like OFDMA is able to exploit that diversity, the system capacity can be significantly increased as performance evaluations have shown [3]. In this paper, a basic OFDMA scheduling algorithm for the downlink transmission of data packets is proposed. This algorithm exploits the diversity in the frequency domain, and at the same time it provides fairness between all data connections based on an embedded round-robin scheme. Since the transmissions of data packets and not bit-streams are investigated, also a segmentation process is applied, which can be considered as an adaptation of the packets to the resources of the OFDMA transmission scheme.

The paper is organized as follows. In the next section, the general effects of OFDMA scheduling schemes are explained. Further, it is recapitulated how the structure of OFMDA subchannels influences the scheduling scheme. Section 3 describes the investigated OFDMA system. This section comprises the Physical Layer, the Medium Access Control, and the proposed basic OFDMA scheduling algorithm. In Section 4, a detailed performance evaluation of the OFDMA system is given. The performance of the proposed scheduling algorithm is thereby analysed for two different OFDMA schemes by the means of stochastic simulations. Finally, the paper ends with some concluding remarks

2. OFDMA Scheduling

The scheduling of data packets in OFDMA systems is a challenging task. It is required that the scheduler is able to exploit the multi user diversity and provide fairness at the same time. Within the scheduling process time-subchannel elements are allocated for the transmission of a data packet. A subchannel comprises a set of subcarriers. How these subcarrier set are mapped onto the frequency spectrum has direct influence on the OFDMA scheduling scheme. In this paper, two different approaches are compared.

In the first scheme, a subchannel consists of subcarriers that are distributed in a pseudo-random manner over the frequency spectrum. This technique can be considered as an averaging approach, it is for example used in IEEE 802.16a [4]. Concerning the scheduling on MAC level this technique has the effect that all subchannels show in average the same characteristics regarding interference and fading.

The second approach is based on OFDMA subchannels whose subcarriers are adjacent in the frequency spectrum. Therefore the fading is assumed to be correlated on the subcarriers that form a subchannel. The advantage of this mapping approach compared to the averaging is that there is diversity between the subchannels. Since the fading for different terminals on different subchannels can be considered uncorrelated, optimal allocation patterns can be applied which maximize the system capacity. The problem is to find the optimum terminal-subchannel pairs. Nevertheless, these allocation schemes normally have two problems. They imply a rather high computational complexity, and further the capacity maximization may be achieved by the cost of unfairness since resources are only assigned to terminals with good channel conditions. That may therefore lead to unacceptable high delays for the other terminals.

A general problem in multi-channel transmission schemes is also the transmission power allocation. A fixed overall transmission power has to be allotted to different subchannels, in our case OFDMA subchannels. From the information theoretic point of view the water-filling solution provides the maximum capacity [5]. But in real OFDMA systems the power allocation has to be performed in combination with an adaptive modulation and channel coding scheme. Such a combination of modulation and coding scheme will be denoted PHY mode in the rest of this paper.

Another critical issue is that the application of an OFDMA scheduling algorithm, which exploits the multi-user diversity, requires accurate channel state information (CSI) of all scheduled terminals. This normally implies an increased signaling overhead compared to an averaging approach like the technique applied in IEEE 802.16a. Most of the works concerning the performance evaluation of OFDM or OFDMA transmission schemes focus on the achievable capacity. In contrast to that, this paper also provides a QoS evaluation by the means of delay evaluations for packet transmissions.

3. System Description

3.1. OFDMA Transmission Scheme

The considered OFDMA system operates with a channel bandwidth of 80 MHz at 5 GHz. The frequency channel is subdivided into 1024 subcarriers with a spacing of 78.125 kHz. The symbols have a length of 13.6 μs, including a guard interval of 0.8 μs to mitigate inter symbol interference in multi-path environments. An OFDMA subchannels consists of 30 data subcarriers and 2 subcarriers for the transmission of pilot symbols. Both described schemes for mapping of OFDMA subchannels onto subcarriers are compared.

In Figure 1, the cumulative distribution function of the effective subchannel fading for the two different approaches, namely pseudo-randomly distributed and adjacent, is shown. In the channel model used in this work the subchannel fading process of the first mapping scheme is the mean of 32 independent Rayleigh fading processes.

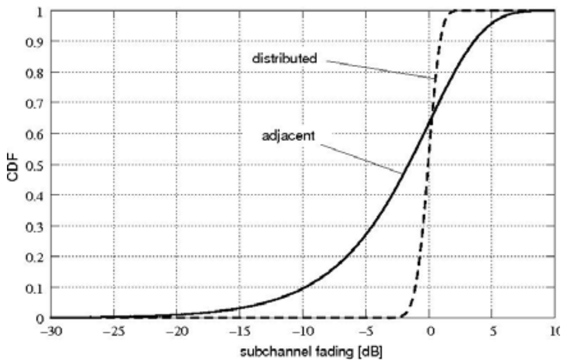

Figure 1 : Subchannel fading for different mappings of OFDMA subchannels onto subcarriers

For the second approach, a single independent Rayleigh fading process is assumed for each OFDMA subchannel. This is a basic fading model, but anyway the general effects of different resource allocation schemes can be shown. It also reveals that the averaging scheme implies a distinct reduction of the variance of the subchannel fading.

Three different PHY modes are used for the performance evaluation, namely QPSK¾, 16QAM¾, and 64QAM¾. For this work, a rather simple model for the channel coding is used. Only the reduced capacity due to the redundancy is considered whereby the coding gain is neglected. However, this simplification has no effects on the general conclusions drawn from the simulation results. The bit error rates and packet error rates for the different modulation schemes are calculated on the assumptions of an AWGN channel [6]. The according link adaptation curve for the PHY mode selection is shown in Figure 2. The dotted line therein represents the curve on which the maximum capacity can be achieved according to a known SNR, the bold line shows the achievable capacity under the constraint of a maximum tolerated PER of 0.01 for all PHY modes except the most robust one, i.e. QPSK½.

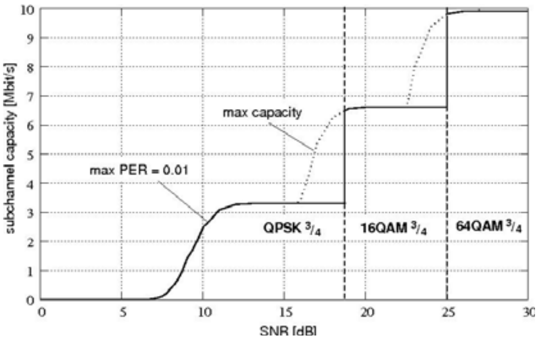

Figure 2 : Link adaptation curve

3.2. Medium Access Control

The MAC structure of the investigated system is based on a centrally controlled scheme like IEEE 802.16. A periodic MAC frame structure is mapped onto the frequency channel. In general, these frames consist of control and data phases. In the control phase, the messages of a resource request/grant scheme are transmitted [7]. Since only the downlink is considered in this paper, resource or bandwidth requests from the mobile terminals are not required. The resource or bandwidth grant message can be considered as a resource allocation table. This is required in an OFDMA system because each mobile terminal that is associated to a base station has to be informed prior to the transmission of user data which subcarriers or subchannels it may receive or transmit on in the data phase [8]. The latter in general consists of uplink- and downlink data transmissions.

The signalling overhead is not considered in this paper. Therefore, a simplified MAC frame model is applied. The according structure is shown in Figure 3. The frame consists of 5 time slots. The first slot is thereby reserved for the transmission of control data packets.

A single MAC frame comprises several scheduling intervals. Within such an interval, time-frequency elements are allotted to connections based on an OFDMA scheduling algorithm. These elements are denoted resource elements in the following. A scheduling interval matches a single time slot. The latter has a length of 108.8 µs which is corresponds to 8 symbols. Therefore, the MAC frame has a cumulative length of 5 x 108.8 µs = 544 µs. Due to the short frames a constant fading level is assumed during a MAC frame.

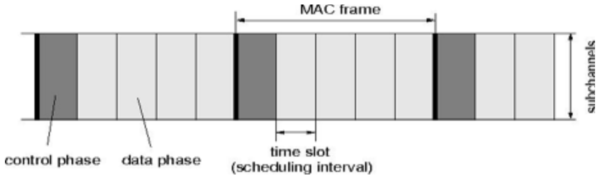

Figure 3 : MAC frame structure

Since the transmission of data packets and not of bit streams is considered, a mapping of packets onto resource elements is needed. This task is accomplished by a segmentation process. In that process, Network Layer Protocol Data Units (NPDUs) are segmented into MAC Protocol Data Units (MPDUs). The MPDUs have a fixed size of 45 bytes, whereby 5 bytes (11.11 %) are considered as overhead (i.e. sequence number, connection ID, etc.). That packet size has the advantage that the packets can be mapped onto the resource elements without a waste of capacity due to clipping. That mapping is shown in Figure 4 for the PHY modes used in this work.

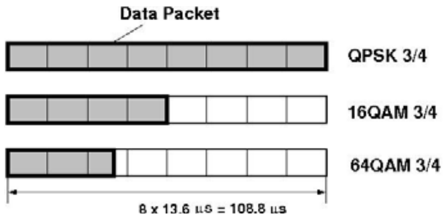

Figure 4 : Mapping of packets onto resource elements

The according MAC capacity per subchannel after the reduction of control and segmentation overhead depending on the PHY mode is shown in Table 1.

Table 1 : Capacity depending on modulation and coding schemes

mode	*bits per symbol*	*packets per element*	*net capacity*
QPSK ¾	60	1	2.35 Mbit/s
16QAM ¾	120	2	4.70 Mbit/s
64QAM ¾	180	3	7.06 Mibt/s

A standard Selective Repeat Automatic Repeat Request (SR-ARQ) scheme is used on top of the MAC layer to provide reliable data connections due to packet retransmissions in the case of errors

3.3. OFDMA Scheduling Algorithm

The proposed basic OFDMA scheduling algorithm employs a combination of dynamic subchannel selection, PHY mode selection and power allocation. To each allocated subchannel within the same scheduling interval (i.e. a time slot) is thereby assigned the same fraction of the total transmission power. This power allocation scheme does not take into account current channel characteristics. After the power allocation, reasonable PHY modes are assigned to all allocated subchannels based on preceding SNR estimations.

The basic scheduling algorithm consists of a loop where each cycle comprises five steps:

1. *connection selection*
2. *subchannel selection*
3. *power adaptation*
4. *mode adaptation*
5. *requirement adaptation*

In the first step of the scheduling cycle, a connection is taken from the set of active connections. A connection is considered active if there is as least one packet to transmit. To provide fairness, that selection procedure is implemented as a round-robin scheme.

In the next step, the selected connection gets the subchannel with the smallest estimated fading loss from the set of the subchannels that have not been allocated yet. After that assignment, the transmission power and the modulation scheme are adapted for all already allocated subchannels. Then the number of data packets that can be transmitted for each connection is calculated. Based on that information, the resource requirements (i.e. the number of packets to transmit) for the next scheduling cycle are calculated. Here it has to be noted that it is possible that the resource requirements of a connection can increase during a cycle. That may happen when the modulation scheme for that connection changes within a cycle (e.g. from 64QAM ¾ to QPSK ¾) due to changes in the power allocation.

4. Performance Evaluation

4.1. Simulation Model and Scenario

The performance evaluation of the OFDMA scheduling algorithm has been conducted by the means of stochastic event driven simulations. Therefore the well know simulator ns-2 [9] has been extended by an OFDMA transmission model and an according channel model including path loss, subchannel fading, and the mapping of SINR levels onto packet errors.

A single cell which consists of one base station (BS) and 32 associated mobile terminals (MTs) has been investigated. Each mobile terminal has one active downlink connection which is modeled by a Poisson source with a fixed packet size of 100 bytes. For the mapping of data bursts onto resource elements the segmentation process described in Section 3 is used. In each simulation all downlink connections have the same traffic load. Simulations have been conducted for different cell radii and the MTs randomly move around within the cell area. The position update interval thereby corresponds to the duration of 20 MAC frames.

The radio wave propagation is modeled with a basic path loss model whereby the received power is proportional to the *n*th power of the distance between sender and receiver [9]. A value of 2.5 has been chosen for *n*. A thermal noise of -100 dBm is assumed per subchannel. The overall downlink transmission power is fixed to 30 dBm.

The performance of the scheduling algorithm has been compared with a random subchannel selection in the case of adjacent subcarriers. The random subchannel selection can be considered as a worst case estimation for the proposed scheduling algorithm. Since the algorithm requires accurate CSI for an efficient exploitation of the multi user diversity, the performance will decrease with a growing duration between CSI estimation and the transmission of data bursts. Therefore, in the worst case the subchannel allocation decision based on outdated CSI accords to a random subchannel assignment concerning the real CSI at the moment of the data transmission. Due to a fair comparison, a link adaptation procedure based on perfect channel knowledge is also assumed for the random subchannel selection. Concerning the modeling of the subchannel fading, the fading levels for all subchannels are randomly drawn at the beginning of a new MAC frame and they are assumed to be constant during that frame. Except the constant level within a MAC frame all subchannel fading processes are assumed to be uncorrelated both in time and in frequency.

4.2. Simulation Results

For the first simulation runs the cell radius was 200m. Figure 5 shows the SNR distribution of one MT within that scenario. The dotted line represents the IEEE 802.16a OFDMA transmission scheme with the pseudo-random distribution of subchannels (averaging). Since the bandwidth of the investigated OFDMA system is rather large (i.e. 80 MHz), the variance of the effective fading level of a distributed subchannel is very small (Figure 1).

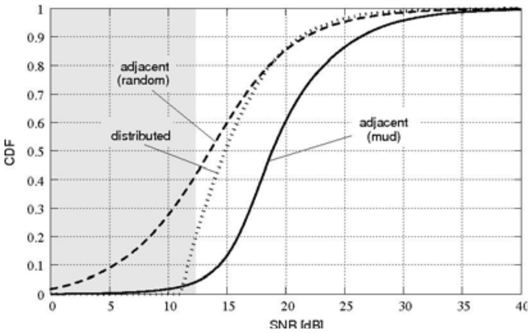

Figure 5 : SNR distribution function
(200m cell radius, 2000 kbit/s per connection)

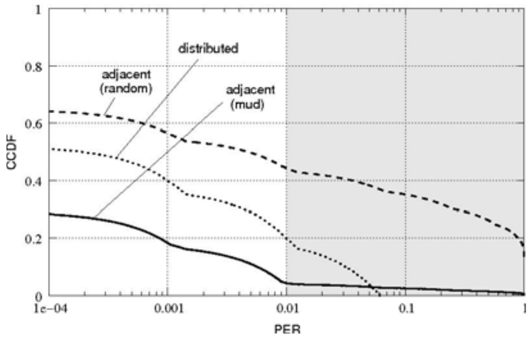

Figure 6 : PER complementary distribution function
(200m cell radius, 2000 kbit/s per connection)

The shaded area illustrates the SNR range within which a maximum PER of 0.01 can not be provided. The results reveal that the proposed OFDMA scheduling algorithm in combination with the adjacent subchannel scheme can achieve 4 dB SNR gain compared to the distributed scheme. Only for low SNR values the latter outperforms the adjacent scheme. These SNR levels correspond to terminal and connections respectively at the cell border that have to use subchannels with unfavourable fading levels since all other subchannels are already assigned to other connections. As expected, the random subchannel selection shows the worst performance.

Figure 6 shows the complementary distribution function of the PER for the different transmission schemes. These results correspond to the SNR results shown in Figure 5. The distributed approach has a mean PER of 0.008 and the adjacent scheme with exploitation of multi user diversity a mean PER of 0.0177. These mean values may seem to be confusing compared to the SNR distribution, but it has to be considered that with diversity scheduling the rare event of high PER values (cell border position and "bad" subchannel assignment) stands in contrast to a large number of packet reception with a lower PER. Figure 6 shows that the variance of the PER is increased by the adjacent subcarrier approach. This problem can be solved by more stringent constraints in the OFDMA scheduling algorithm, e.g. prohibition of subchannels assignments with less than 10 dB estimated SNR. But this may also have impacts on the resource utilization and the fairness. In the worst case, a terminal at the cell border would never get any resources.

Figure 7 shows the cumulative distribution function of the packet delay (including retransmissions) of an exemplary downlink connection with 2000 kbit/s traffic load. Anyway, due to scenario settings (all connections have the same traffic load) these results apply for all connections. The results reveal that the proposed OFDMA scheduling for the adjacent subcarrier scheme shows the best performance compared to the distributed approach and to the random subchannel selection. It is interesting to see that the diversity scheduling outperforms the distributed scheme although it has the higher mean PER. This effect is based on the more efficient utilization of resource elements and the high variance of the PER (many packets with a very low PER, and only a few with a very high PER). As expected, the random subchannel selection scheme shows the poorest performance. This corresponds to the according SNR and PER results.

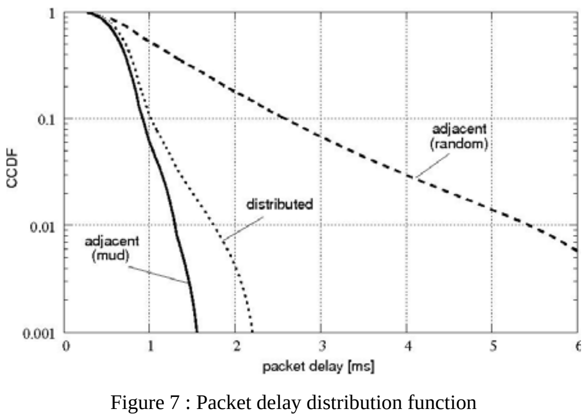

Figure 7 : Packet delay distribution function
(200m cell radius, 2000 kbit/s per connection)

In Figure 8, the throughput-delay characteristics of the compared OFDMA transmission schemes are shown. The mean packet delay of all connections is considered here. This figure shows the capacity gain that can be achieved by the proposed scheduling scheme. A mean packet delay of 2 ms can be provided for a maximum of 2100 kbit/s with the distributed scheme. With the diversity scheduling approach, a traffic load of 2200 kbit/s can be supported at the same delay. This corresponds to an overall capacity gain of 3200 kbit/s since there are 32 downlink connections in parallel in that scenario. The results in Figure 8 also present the possible capacity loss due to an unprofitable, namely random, subchannel assignment. The latter can be considered as a bound for a worst case allocation. With the random subchannel selection there is in general an increased mean packet delay. This corresponds to the higher PER due to a critical subchannel allocation that does not consider the fading characteristics. Concerning the capacity, the possible gain with the application of the diversity scheduling scheme is approximately equal to the capacity loss due to the random subchannel allocation.

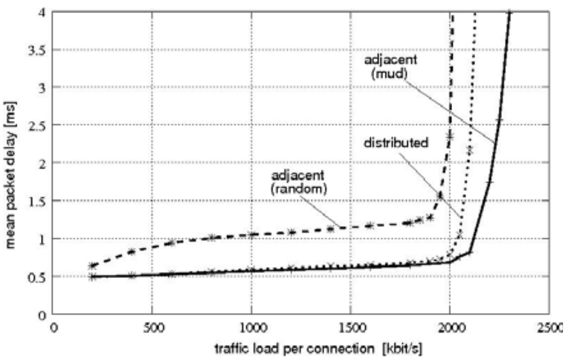

Figure 8 : Throughput-delay characteristic (200 m cell radius)

Regarding these results it has to be noticed that the increased overhead due to an OFDMA scheduling scheme that exploits the multi-user diversity is not considered in this work. The overhead thereby includes CSI estimation and the exchange of CSI between the MTs and the BS. Nevertheless, the performance gain forms a bound for the maximum acceptable signaling overhead. The diversity scheduling scheme only makes sense if the additional overhead is below that bound.

For the second set of simulation runs, a cell radius of 150 m is considered. The according throughput-delay characteristics are given in Figure 9. It is revealed that the reduced cell radius results in a capacity increase of 250 kbit/s with the application of the distributed scheme. With the use of adjacent subchannels and diversity exploitation, the capacity gain per connection consists of 900 kbit/s. This shows that the OFDMA scheduling scheme which exploits the diversity benefits more from the reduced cell radius than a scheduling approach which applies an averaging of the subchannels.

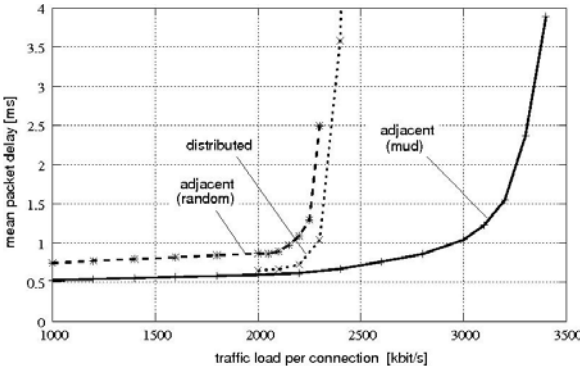

Figure 9 : Throughput-delay characteristic (150 m cell radius)

Figure 10 further shows the complementary distribution function of the utilization of resource elements within a MAC frame for different traffic loads per connections. As expected due to the results in Figure 9, the diversity scheduling scheme in general leads to a reduced resource utilization compared to the averaging scheme.

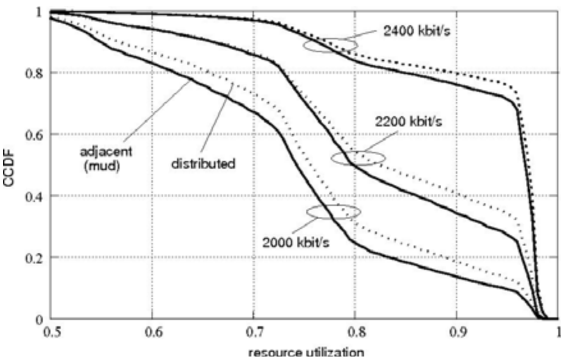

Figure 10 : Resource utilization (150 m cell radius)

Figure 11, the distribution of the PHY mode usage for all downlink transmissions are shown for different cell radii. This PHY mode distribution corresponds to the diversity scheduling scheme with adjacent subchannels. It can be seen that the usage of the high rate schemes 16QAM¾ and 64QAM¾ increases with the reduction of the cell radius. That is clear since a reduced cell radius results in a higher mean SNR level. But as the results presented above show, the diversity scheduling scheme is in the position to better exploit the advantages of a small cell radius compared to an averaging approach.

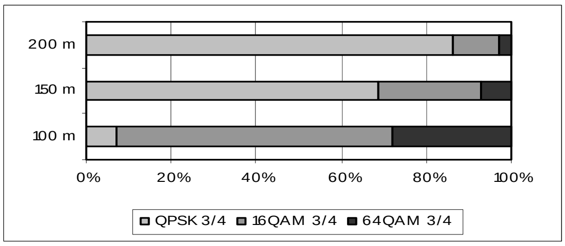

Figure 11 : PHY mode usage depending on cell radius

5. Conclusion

In this paper, a basic OFDMA scheduling algorithm for the transmission of data packets has been proposed. The proposed algorithm provides an efficient exploitation of the multi-user diversity and at the same time supports fairness. The performance of that algorithm has been evaluated in detail by the means of simulations for an exemplary scenario. Thereby the performance of the proposed scheme has been compared with the IEEE 802.16a OFDMA transmission scheme. Further, an estimated lower bound for the capacity loss due to inaccuracy in the subchannel allocation is provided. The simulation results show that the diversity scheduling outperforms an averaging scheme. Further is has been shown that the performance gain to a great extent depends on the size of a cell. The results presented in this paper form a basis for further investigations. Since only a basic OFDMA scheduling algorithm is considered it is expected that further capacity gains can be achieved with more enhancements, e.g. more intelligent power allotment schemes like water-filling. Further it would be interesting to apply more realistic fading models which are correlated both in time and in frequency. Also the realistic modeling of a channel coder would be interesting.

Acknowledgement

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

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