Performance Evaluation of Joint Downlink Scheduling in Multi-Cellular OFDMA Systems based on IEEE 802.16a

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ABSTRACT
The employment of the OFDMA transmission technique in broadband radio systems shows several benefits. Especially the exploitation of multi-user diversity with the help of sophisticated scheduling algorithms can significantly increase the system capacity. In this paper, the performance of joint scheduling of downlink data transmissions for access point sets is evaluated in a multi-cellular system. The latter is compared with an independent scheduling on orthogonal subchannel sets in the access points. The general MAC structure of the investigated system is thereby based on IEEE 802.16a. However, concerning the Physical Layer there is an important difference. In IEEE 802.16a, the exploitation of multi-user diversity is not possible since the OFDMA subchannel scheme is based on an interference and fading averaging approach. The technique examined in this paper in contrast can be regarded as an avoidance approach which is subject to diversity in the subchannel quality. A basic OFDMA scheduling algorithm, which is able to exploit multi-user diversity and provide fairness, is used both for the joint and for the independent scheme.

Categories and Subject Descriptors
C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless communications.*

General Terms: Algorithms, Performance

Keywords
OFDMA, Joint Downlink Scheduling, Access Point Controller, Multi User Diversity, Resource Partitioning, QoS, IEEE 802.16a

1. INTRODUCTION
Currently, it has turned out that multi-carrier transmission schemes like Orthogonal Frequency Division Multiple Access (OFDMA) are promising transmission techniques for future broadband radio systems. The most established system which employs OFDMA is at the moment IEEE 802.16a [1]. Further, several research projects consider OFDMA or resembling schemes as the technique of choice [2][3]. In general, with that transmission scheme a broad frequency channel is subdivided into a set of narrowband subchannels which each comprise a number of subcarriers, whereby these subchannels can be used by a single user in parallel or by different users at the same time. Such an approach has several advantages compared to single carrier schemes.

Especially in combination with adaptive modulation and power allocation, the adaptive subchannel selection has shown to be quite beneficial [4]. 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. By using scheduling algorithms which map parallel transmissions onto appropriate subchannel patterns the efficiency of the system can increase. Performance evaluations presented in [5][6] have revealed that the system capacity can be significantly increased when the subchannel diversity is exploited.

In this paper, the dynamic subchannel allocation for downlink data transmissions in a multi-cellular OFDMA system, comprising a set of access points (APs) and associated mobile terminals (MTs), is investigated. The assignment of transmission resources to the APs is done in a centrally controlled manner by an access point controller (APC). So there is a hierarchical management of the trans-mission resources. The APC assigns resources to the APs, and the APs further subdivide these resources for the transmission of data packets. We consider an assignment of orthogonal resource sets to the different APs and cells respectively. Hence, the impact of interference is not regarded. In general the partitioning of transmission resources for APs can be conducted in the time, frequency, or code domain. In this work the resource partitioning is accomplished in the frequency domain, meaning that the different APs operate on different OFDMA subchannels. Anyway, a subchannel pattern can also be considered as a code in this context.

The performance of two dynamic resource allocation schemes is compared. In the first approach fixed orthogonal subchannel sets are assigned to the APs by the APC. Within these subchannel sets the APs independently perform a dynamic OFDMA scheduling which adapts the subchannel allocations to changes in the subchannel quality (fading) and the occupancy of output queues of terminals competing for transmissions. In the second scheme the OFDMA scheduling for all connections is done in the APC. Most of the current publications concerning the performance

IWCMC'06, July 3-6, 2006, Vancouver, British Columbia, Canada.

evaluation of OFDMA transmission schemes focus on the achievable capacity. In contrast to that, this paper also provides a QoS evaluation by means of packet delay.

This paper is organized as follows. In Section II the investigated OFDMA system is described in detail, comprising the Physical Layer (PHY) and the structure of the Medium Access Control (MAC). Section III introduces the dynamic resource allocation within the OFDMA system. The focus is there on the scheduling algorithm and the effects of joint scheduling. Simulation results for a reference scenario are presented in Section IV. Finally, the paper ends with some concluding remarks.

2. SYSTEM DESCRIPTION

2.1 OFDMA Transmission Scheme

The investigated OFDMA system has a bandwidth of 80 MHz. The frequency channel is subdivided into 1024 subcarrier. These subcarriers are grouped into 32 subchannels resulting in 32 subcarriers per subchannel. The symbols have a length of 13.6 μs, including a cyclic prefix of 0.8 μs to handle inter symbol interference. The subcarriers that form a subchannel are adjacent in the frequency domain. This is in contrast to IEEE 802.16a where the subcarriers of an OFDMA subchannel are distributed over the frequency spectrum in a pseudorandom manner. The subchannel scheme of IEEE 802.16a results in an averaging concerning the channel characteristics [7]. This has the effect that in the mean all subchannels show the same characteristic concerning fading and interference. The subchannel scheme used in this paper in contrast comprehends subchannel diversity which can be exploited by scheduling algorithms to increase the capacity.

Three different PHY modes are used for the performance evaluation in this paper, namely QPSK¾, 16QAM¾, and 64QAM¾. 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 respectively for the different modulation schemes are calculated on the assumptions of an AWGN channel [8].

2.2 Medium Access Control

We consider a centrally controlled MAC structure that is based on IEEE 802.16 [9]. The frequency channel is subdivided into MAC frames in the time domain. These frames have a fixed length, and the allocation of resources for data transmissions is conducted in a centrally controlled manner by the AP. In general, the MAC frames consist of control and data phases. In the control phase, the messages of a resource request/grant scheme are transmitted. In this work, the signaling overhead is not considered. Therefore, a simplified MAC frame model is used for the simulations. The according structure is shown in Figure 1. The frame consists of 5 timeslots, each with a length of 108.8 μs. This corresponds to 8 symbols per slot and a total frame length of 544 μs.

Within each time slot resources are allocated for data transmissions based on an OFDMA scheduling algorithm. In the following the smallest assignable resource is called resource element (RE). It has the dimension of one timeslot and one OFDMA subchannel.

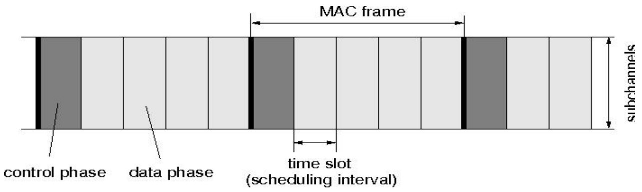

Figure 1 : MAC frame structure

For the mapping of data packets onto REs, a segmentation process is required. Network Layer Protocol Data Units (NPDUs) are fragmented into MAC Protocol Data Units (MPDUs) with an adequate size. The process can be considered as an adaptation of the packet size to the PHY characteristics. In contrast to IEEE 802.16, fixed length MPDUs are used in this paper. This approach resembles the technique used in HiperLAN/2 [11]. All MPDUs have thereby a 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 REs without a waste of capacity due to clipping for the PHY modes used in this work.

The resulting net capacity per subchannel depending on the PHY mode, whereby the control phase overhead is considered, is shown in the following table.

Table 1. Subchannel capacity

PHY mode	bits per symbol	packets per RE	capacity
QPSK¾	60	1	2.35 Mbit/s
16QAM¾	120	2	4.70 Mbit/s
64QAM¾	180	3	7.06 Mbit/s

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

3. Dynamic Resource Allocation

We consider the dynamic resource allocation in the investigated OFDMA system as consisting of two complementary processes, namely the resource partitioning between APs and the OFDMA scheduling. Concerning the frequency of allocation updates the resource partitioning constitutes a slow resource adaptation (SRA) which adjusts the allocations due to long term interference and traffic estimations. The OFDMA scheduling is the fast resource adaptation (FRA). It reacts to the varying impact parameters like fast fading and the occupancy of the transmission queues. Theses processes and the effects of joint scheduling on the APC level are described in the following.

3.1 Resource Partitioning

With resource partitioning we denote the subdivision of transmission resources sets into subsets that are assigned to APs. These resources are used to multiplex data packets based on a scheduling algorithm within the service area of a given AP. In general the partitioning can be conducted either in the time, frequency, or code domain. Resource partitioning in the time domain has already been analyzed in [10]. In this paper we focus on a partitioning in the frequency domain. Hence, subchannel sets are assigned to the APs by the APC. Since all APs are considered synchronized, there is no adjacent channel interference. Also the dynamic allocation due to long term traffic estimations and the support of spatial reuse of resources is not considered. We employ a fixed allocation scheme whereby all APs get the same amount of resources, namely OFDMA subchannels.

3.2 OFDMA Scheduling Algorithm

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. Further, the overall transmission power has to be allotted to the subchannels that are used in parallel for data transmissions. From the information theoretic point of view the water-filling solution provides the maximum capacity [12]. But in real OFDMA systems the power allocation has to be performed in combination with an adaptive PHY mode selection. Another important issue is that the application of OFDMA scheduling algorithms, which exploit multi-user diversity, requires detailed channel state information (CSI) of all scheduled terminals and connections respectively. This normally implies an increased signaling overhead compared to an averaging approach like the technique applied in IEEE 802.16a.

The basic OFDMA scheduling algorithm used in this paper is outlined in Figure 2. The actions within a so-called scheduling interval are explained in the following. Within such an interval the downlink scheduler at the AP repeats a scheduling cycle until all available subchannels are allocated or the demands of all connections are met.

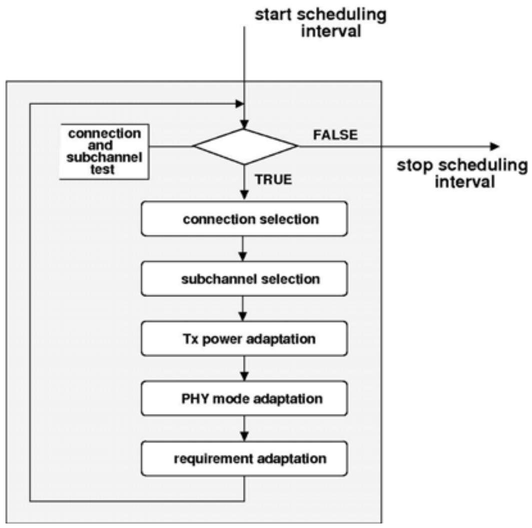

Figure 2 : Basic OFDMA scheduling algorithm

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 PHY mode 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 requirements of a connection can increase during a cycle. That may happen when the PHY mode for that connection changes within a cycle (e.g. from 64QAM ¾ to QPSK ¾) due to changes in the power allocation.

In this paper we assume perfect channel knowledge during the scheduling. The link adaptation curve for the PHY mode selection is shown in Figure 3. The dotted line therein represents the curve on which the maximum capacity on the Physical Layer can be achieved, and 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. These PHY capacity curves correspond to the MAC capacity calculations in Table 1.

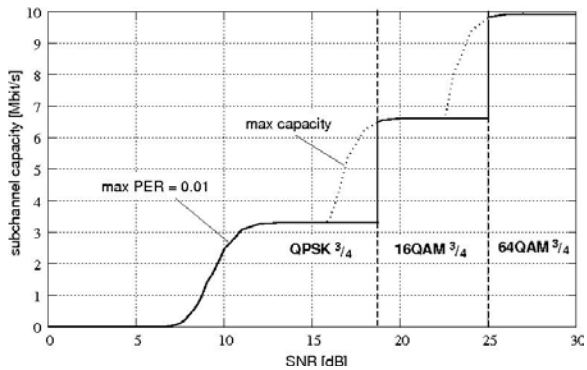

Figure 3 : Link adaptation curve

3.3 Effects of Joint Scheduling

With the application of joint scheduling in the APC, the resource partitioning between the APs is done in the context of the OFDMA scheduling. Regarding the update frequency of resource allocations in the whole system, only fast resource adaptation is used. This approach offers mainly two advantages. Since the pool of all subchannels is available for all data transmissions, it is possible to exploit the multi-user diversity within the whole system. In contrast to that, the resource partitioning in the frequency domain reduces the degree of freedom concerning the subchannel allocation in each AP since the number of subchannels usable for an AP is reduced. The second benefit of the joint scheduling is the achievable trunking gain. The trunking allows the system to accommodate a large number of connections in a limited set of resources since this technique exploits the statistical behavior of the data connections [13]. This can be considered as a statistical multiplexing of the connections.

The drawbacks of the joint scheduling in the APC is that it generally leads to an increased signaling overhead and computational complexity since all connections have to be considered to achieve an optimal resource allocation. This effect is not considered in this paper.

4. PERFORMANCE EVALUATION

This section is focused on the performance evaluation of the joint scheduling of downlink data connections in an reference scenario for a multi-cellular OFDMA system.

An event-driven simulator, which has been developed by the authors, was used for all simulations. The developed simulator is based on the well-known NS-2 [15]. It provides considerable extensions for the statistical performance evaluation of OFDMA systems comprising the implementation of an IEEE 802.16 like MAC, an OFDMA PHY with the mapping of SINR onto packet errors, and a channel model including subchannel fading and shadowing and interference.

4.1 Simulation Model and Scenario

The simulation scenario is shown in Figure 4. It consists of 4 cells and APs respectively. Each cell contains 16 MTs. Each AP has a downlink data connection to all associated MTs. The MTs move randomly around within the circular cell area (shaded circles) and the positions are updated every 10ms. This corresponds to approximately 20 MAC frames.

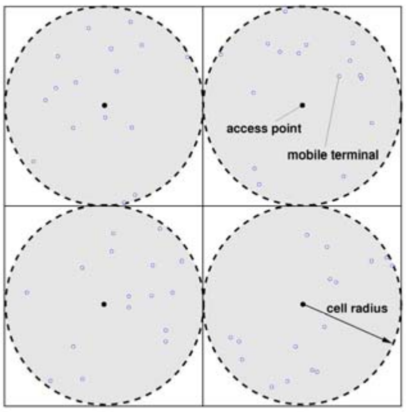

Figure 4 : Simulation Scenario

The traffic load of the connections is modeled by a Poisson source with a fixed packet size of 100 bytes.

A basic path-loss model is used where the received power is proportional to the *n*th power of the distance between sender and receiver [14]. A value of 2.5 has been chosen for *n*. The analyzed OFDMA system operates at 5 GHz. A thermal noise of -100 dBm is assumed per subchannel and the overall downlink transmission power is fixed to 30 dBm.

Independent Rayleigh fading processes, which are uncorrelated both in time and in frequency, are used for the subchannels. At the beginning of each MAC frame the fading levels for all subchannels are drawn independently. Due to the short MAC frames (544 µs) constant fading levels are assumed within the frame. This is a rather elementary fading model, but the general effects of the different OFDMA scheduling strategies can be shown anyway. Yet, the results of the performance evaluation can be regarded as an upper bound since it is obtained with perfect channel knowledge at the transmitter. Concerning the evaluation of the packet delays, additional delays due to the communication between the APC and the APs are not considered in the simulations.

Three scheduling schemes have been compared. The first is the independent scheduling of connections in the APs on non-overlapping resource subsets (resource partitioning). For this approach, the set of 32 OFDMA subchannels is subdivided into 4 sets each with a number of 8 subchannels. That assignment is fixed during the whole simulation run. The second scheme is the joint scheduling of all connections in the APC without any further constraints. And the last investigated approach is the joint scheduling with the constraint that the maximum number of subchannels assigned to one AP in parallel is 8. Concerning the transmission power allocation per subchannel this results in a minimum of 21 dBm. The minimum transmission power with the joint scheduling without such a constraint is 15 dBm.

4.2 Simulation Results

In the first simulations a cell radius of 200m has been chosen. The traffic load per connection is 1500 kbit/s.

Figure 5 shows the resulting cumulative distribution function of the SNR for the different scheduling schemes. The number in the brackets denotes the number of subchannels that can be used in parallel by one AP. It is visible that the joint scheduling scheme with the constraint of 8 subchannels shows the best performance. Compared to that, the joint scheduling without any constraints causes an SNR reduction of approximately 0.75 dB. The independent scheduling of the APs results in an SNR reduction of approximately 3 dB compared to the joint scheduling with the subchannel constraint.

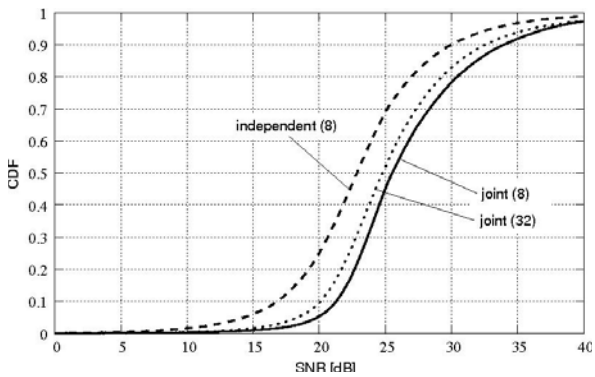

Figure 5 : SNR distribution (1500 kbit/s)

An interesting effect is revealed when the results of the different joint scheduling schemes are compared. Although the joint scheduling without the any constraints offers the highest degree of freedom in the subchannel allocation, the joint scheduling with the subchannel constraint performs better. This is based on the difference in the power allocation for the subchannels.

The complementary cumulative distribution function of the transmission power per subchannel during the downlink data transmission is shown in Figure 6. The maximum is 30 dBm, corresponding to the transmission on a single sub-channel only. When all 32 subchannels are used in parallel, this leads to a transmission power of 15 dBm since the overall power is uniformly distributed to all subchannels. It can be seen that transmission power in the case of joint scheduling without constraints has the highest variance. Concerning the results for the independent scheduling and the joint scheduling with the subchannels constraint, it appears that the independent scheme on average provides a slightly higher transmission power. When this is compared with the respective SNR results in Figure 5, it is clear that the SNR gain due to the joint scheduling is achieved due to the increased degree of freedom in the subchannel allocation.

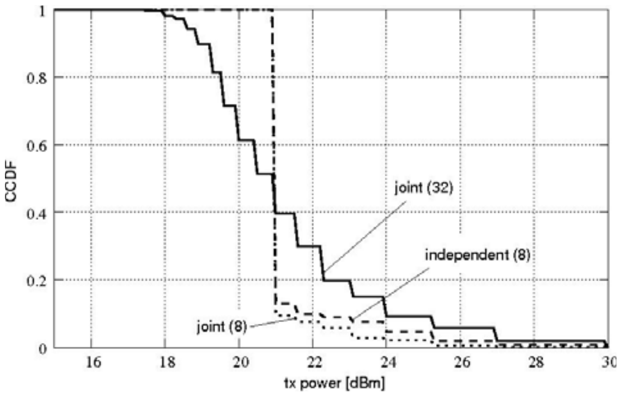

Figure 6 : Transmission power per subchannel (1500 kbit/s)

Figure 7 shows the complementary cumulative distribution function of the PHY mode usage for the different scheduling approaches. Corresponding to the SNR results in Figure 5, the joint scheduling both with and without subchannel constraint outperforms the independent scheduling approach. With the joint scheduling schemes, the usage probability of 64QAM¾ is significantly higher than in the case of independent scheduling. Also the probability of QPSK¾ is clearly minor. The differences between the joint scheduling schemes are rather marginal.

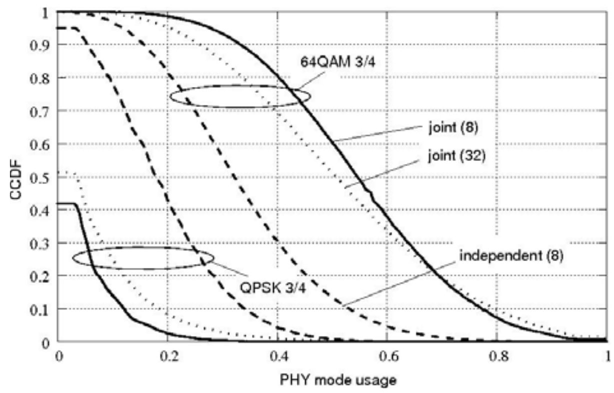

Figure 7 : PHY mode usage (1500 kbit/s)

In Figure 8, the PHY mode usage in the evaluated cell depending on the traffic load per connection is shown. The joint scheduling scheme with the constraint of maximal 8 subchannels is considered. This is done to eliminate the impact of the transmission power distribution shown in Figure 6. The results show that the PHY mode usage in general depends on the traffic load, independent of the applied scheduling scheme. A higher traffic load results in a reduced usage of the high rate PHY mode 64QAM¾. The reason is the higher probability of using several subchannels in parallel for data transmission in an AP. This has two impacts on the performance. At first, the mean transmission power per subchannel is reduced. Further, the gain due to the subchannel diversity is reduced since in high load situations all resources have to be used for data transmissions, independent of the according quality concerning the fading level.

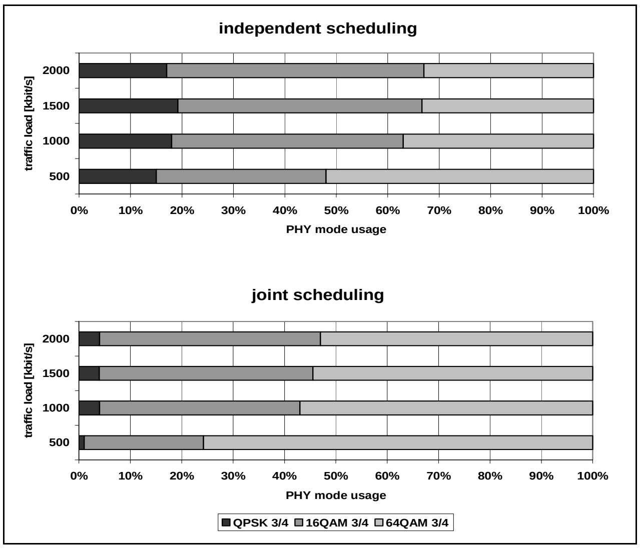

Figure 8 : PHY mode usage (200m cell radius)

The mean packet delay for the different cell radii depending on the traffic load per connection is shown in and Figure 9 and Figure 10. It is revealed that the capacity can be significantly increased with the application of a joint scheduling approach. Nevertheless, the performance gain of the joint scheduling depends on the constraint that defines the maximum number of subchannel.

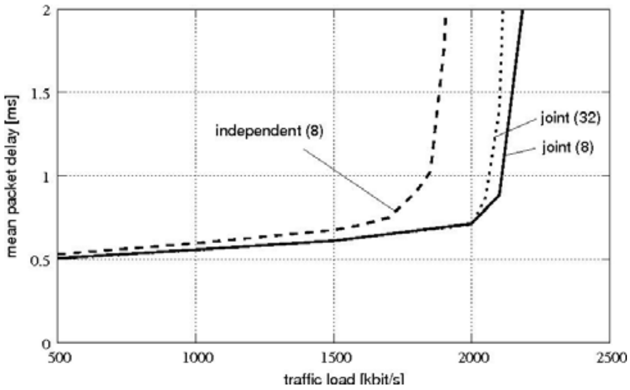

Figure 9 : Throughput-delay characteristic (200m)

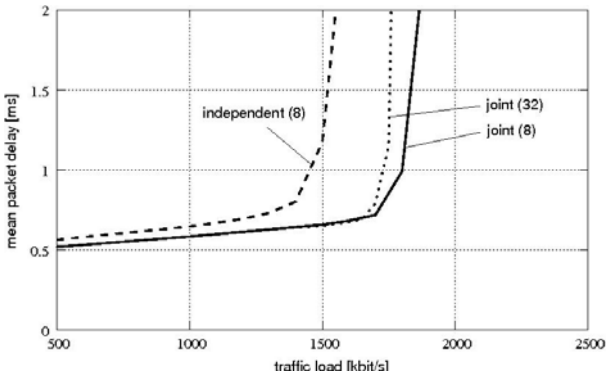

Figure 10 : Throughput-delay characteristic (250m)

Based on the traffic-delay characteristics, the estimated cell capacity with a maximum mean packet delay of 1.5ms (approx. 3 MAC frames) is shown in Table 2. Further, also the capacity gain the given for the joint scheduling schemes. The according calculation considers that there are 16 downlink connections in parallel per cell. These calculations exhibit that the joint scheduling, especially with the restricted number of parallel usable subchannels per AP, can significantly increase the cell capacity.

Table 2 : Estimated cell capacity

scheduling scheme	cell capacity (200m)	cell capacity (250m)
independent (8)	~ 30.4 Mbit/s	~ 24.0 Mbit/s
joint (32)	~ 33.6 Mbit/s (+ 10.5%)	~ 28.0 Mbit/s (+ 16.7%)
joint (8)	~ 34.4 Mibt/s (+ 13.2%)	~ 29.6 Mbit/s (+ 23.3%)

5. CONCLUSION

In this paper, we analyzed the joint scheduling of downlink data transmissions in a multi-cellular (IEEE 802.16a like) OFDMA system. A detailed performance analysis by means of event driven stochastic simulation is presented, whereby the joint scheme is compared with an independent scheduling scheme in the access points in combination with a fixed resource partitioning. The impact of dynamic power allocation and the exploitation of subchannel diversity have been shown. The results reveal that such a joint scheduling approach can significantly increase the system capacity, especially in combination with the use of constraints concerning the maximum number of parallel usable subchannels per access point.

The work presented in this paper is considered as a basis for further research activities that are currently ongoing. The focus is on the development of more sophisticated OFDMA scheduling algorithms and the consideration of uncertainty in the resource allocation concerning the channel state information.

6. ACKNOWLEDGEMENTS

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.

7. REFERENCES

[1] Air Interface for Fixed Broadband Wireless Access Systems – Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11 GHz, IEEE Std 802.16a, 2003

[2] G. Fettweis and R. Irmer, WIGWAM: System Concept Development for 1 Gbit/s Air Interface, 14th Wireless World Research Forum (WWRF 14), San Diego, USA, July 2005

[3] IST WINNER Project, www.ist-winner.org

[4] C.H. Wong, R.S. Cheng, K.B. Letaief, R.D. Murch, Multiuser OFDM with Adaptive Subcarrier, Bit, and Power Allocation, IEEE Journal on Selected Areas in Communications, vol. 17, no. 10, pp. 1747-1758, Oct. 1999

[5] W.Rhee, J.M.Cioffi, Increase in Capacity of Multiuser OFDM Systems Using Dynamic Subchannel Allocation, VTC 2000, Tokyo, Japan, pp. 1085-1089

[6] Z. Shen, J.G. Andrews, B.L. Evans, Optimal Power Allocation in Multiuser OFDM Systems, IEEE GLOBECOM 2003, pp. 337-341

[7] I. Koffman, V. Roman, Broadband Wireless Access Solutions Based on OFDM Access in IEEE 802.16, IEEE Communications Magazine, vol. 40. 4 pp, 96-103, April 2002

[8] J.G. Proakis, Digital Communications 4th Edition, McGraw-Hill, 2000

[9] Air Interface for Fixed Broadband Wireless Access Systems, IEEE Std 802.16, 2004

[10] B. Walke, A. Krämling, M. Scheibenbogen, Dynamic Channel Allocation in Wireless ATM Networks, Wireless Networks, vol. 6, no.11, 2000, pp. 381-389

[11] Broadband Radio Access Networks (BRAN). HIPERLAN Type 2; Data Link Control (DLC) Layer; Part 1; Basic Transport Functions, Standard TS 101 761-1, ETSI, February 2001

[12] T.M. Cover, J.A. Thomas, "Elements of Information Theory" Wiley, New York, 1991

[13] T.S. Rappaport, Wireless Communications 2nd Edition, Prentice-Hall, 2002

[14] B. Sklar, Rayleigh Fading Channels in Mobile Digital Communication Systems, IEEE Communications Magazine, Sep. 1997, pp. 135-146

[15] The Network Simulator, www.isi.edu/nsnam/ns