MAC Level Performance Comparison of Distributed and Adjacent OFDMA Subchannels in IEEE 802.16

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***Abstract*—This paper provides a comprehensive simulative performance evaluation of the OFDMA subchannel schemes which are used in the IEEE 802.16 standard. The subchannels are either distributed or adjacent in the frequency channel. The analysis is focused on the tradeoff between accuracy in the SINR estimation due to time-correlated fading processes and the exploitation of diversity. The adjacent subchannel scheme provides a high degree of diversity in the subchannel quality compared to the distributed approach. The reason for that is the averaging effect of the latter scheme. At the same time that effect is also responsible for the more accurate SINR estimation in the distributed subchannel scheme. The performance comparison is conducted for the downlink in a multi user reference scenario with mobility.**

***Index Terms*— OFDMA, IEEE 802.16, subchannel schemes, resource scheduling, medium access control, fading, SINR estimation**

I. INTRODUCTION

The OFDMA transmission scheme (*Orthogonal Frequency Division Multiple Access*) is of great prominence in the design of future broadband radio systems. This technique is also used in the recently defined standard IEEE 802.16 [1], which is considered to play a key role in fixed broadband wireless metropolitan area networks [1]. Furthermore, also several research projects are focused on the use of that transmission technique, e.g. [3][4]. In combination with adaptive modulation this transmission technique is capable to provide both high spectral efficiency and high power efficiency in [5]. In such an OFDMA system, the frequency channel is subdivided into subchannels which consist of orthogonal subcarrier sets. These subcarrier sets can be either distributed or adjacent in the frequency spectrum [6]. The first approach results in an averaging concerning both fading and interference. This is based on the effect that low quality subcarriers can be compensated by high quality subcarriers due to the use of channel coding schemes with long constraint lengths [7]. The shortcoming in the use of distributed subchannels is that from MAC (*Medium Access Control*) point of view no subchannel diversity can be exploited by the resource scheduling. In the mean, all subchannels have the same quality. In contrast to that, the use of adjacent subchannel offers the possibility to exploit the diversity of a frequency-selective fading channel. In scenarios with multiple users this approach can significantly increase the system capacity [8]. Concerning the uncertainty in the quality estimation of an OFDMA subchannel, the distributed schemes provides higher accuracy than the adjacent approach. In general, there is a tradeoff between uncertainty in the subchannel estimation and the exploitation of diversity. The outcome strongly depends on the ratio of the coherence time of the subchannel fading and the duration between subchannel estimation and data transmission. In this paper, the performance of the distributed and adjacent OFDMA subchannel schemes is compared for the downlink by means of stochastic event-driven simulations. The PHY (*Physical Layer*) parameters concerning the subchannel structure are taken from the IEEE 802.16 standard. Concerning the MAC, a simplified frame structure model is used. Especially the signaling is not considered in the performance evaluation.

The paper is organized as follows. Section II describes the different OFDMA subchannel schemes. An overview of the analyzed system is given in Section III. This comprises PHY, MAC and the OFDMA resource scheduling scheme. The results of a detailed simulative performance evaluation are presented and discussed in Section IV. Finally, the paper ends with some concluding remarks.

II. OFDMA SUBCHANNEL SCHEMES

An important aspect which has to be incorporated in a comprehensive system analysis of an OFDMA system is the impact of uncertainty in the channel state estimation. The degree of that uncertainty strongly depends on the applied OFDMA subchannel scheme. The channel state estimation of a distributed subchannel is normally rather accurate. This is based on the averaging character. The fading level of different subcarriers of a distributed subchannel might change significantly between channel state estimation and data transmission. But when the number of subcarriers is large and the according fading processes are uncorrelated, the effective fading level of the distributed subchannel exhibits a rather marginal variation over the time. In this work we consider the mean fading level of the subchannels as the effective fading. This is a common assumption, e.g. in [9]. In the case of adjacent OFDMA subchannels, the according fading processes of the subcarriers show a strong correlation. Hence, also the mean of the fading levels obeys a variation over the time which is correlated to the subcarrier fading. The effective subcarrier fading of both subchannel schemes is depicted in Fig. 1. Flat fading is assumed for the adjacent subchannel, and the effective fading of the distributed subchannel is the mean of 32 uncorrelated fading processes. This is based on the fact that the overall set of subcarriers is grouped into 32 adjacent subsets each with the assumption of flat fading. An adjacent subchannel is directly mapped onto such a subset. The subcarriers of a distributed subchannel are equally distributed over all subsets.

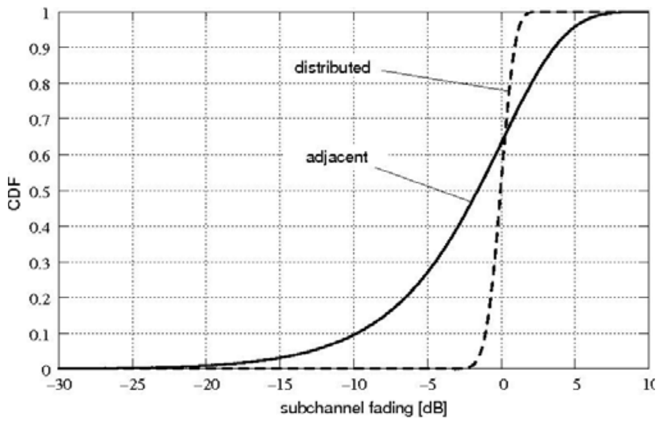

Fig. 1. Effective subchannel fading CDF

When there is a large number of terminals and a large number of subchannels, the diversity of the adjacent OFDMA subchannel scheme can be exploited. This means that resources are only used, when the fading level is high compared to the distributed scheme. This increases the mean SINR and due to that the system capacity.

The time correlation properties results in the fact that the fading level estimation is normally afflicted with uncertainty since the channel state changes between the estimation and the data transmission. The degree of this uncertainty depends on the ratio between coherence time and the duration between channel state estimation and data transmission. The coherence time is thereby proportional to the reciprocal of the Doppler shift [16]. This becomes a problem with the adaptive selection of modulation and coding schemes, which are called PHY modes in the rest of the paper. They are normally used to adapt the data transmission to the current channel state in order to maximize spectral efficiency. When the channel is in a “good” state, which means that the estimated SINR is high, a high capacity modulation scheme like 64QAM can be used. When the channel is in a “bad” state, more robust modes like QPSK have to be used. When the estimated SINR is afflicted with uncertainty, it can be either assumed to low or to high. The first case might lead to the use of a PHY mode which is more robust than required. Since the capacity decreases with the robustness of a PHY mode, this will results in an inefficient exploitation of radio resources. The case where the SINR level is overestimated might lead to the use of a high capacity PHY mode which is not so robust. Hence, this will result in an increased probability of transmission errors. The impact of these effects on the overall system performance is investigated in the simulative performance evaluation in this paper.

III. System Description

A. Physical Layer

The OFDMA parameters of the investigated system correspond to IEEE 802.16. The system operates at 5 GHZ with 20 MHz channel bandwidth. The channel is divided into 2048 orthogonal subcarriers. The latter are grouped into 32 subchannels each consisting of 48 data subcarriers. This overall results in 1536 data subcarriers. The remaining subcarriers are used as pilots and guard subcarriers. These settings correspond to optional FUSC (*Fully Used Subchannelization*) and AMC (*Advanced Modulation and Coding*) subcarrier permutations [6]. The first scheme is the distributed approach and the second accords to the adjacent subchannels. The OFDMA symbol length, including the guard time, is 100.8 µs.

B. Medium Access Control

The MAC frame structure of the analyzed OFDMA system in depicted in Fig. 2. The frame consists of a transmission phase which is reserved for broadcast signaling, N_{DL} time slots for the transmission of downlink data, and the uplink transmission phase. The downlink slots consist of 2 OFDMA symbols. The resource element which comprises one time slot and one subchannel is the smallest entity which can be assigned to a downlink connection in the conducted simulations. That resource size is used because in combination with the used PHY modes and a fixed packet size of 18 bytes no capacity is wasted due to clipping. This does not correspond exactly to the IEEE 802.16 standard, but the general achieved results are valid anyway.

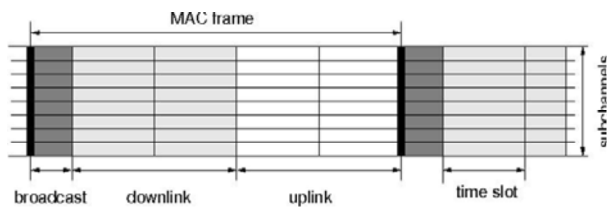

Fig. 2. MAC frame structure

The general frame structure corresponds to IEEE 802.16. The dynamic resource allocation for both up- and downlink is conducted in a centrally controlled manner by the BS (*Base Station*). This allocation is done periodically at the beginning of each MAC frame.

Concerning the channel state estimation, which is required for the OFDMA resource scheduling in the downlink, it is assumed that the measurement is conducted by the MTs (*Mobile Terminals*) during the broadcast transmission phase.

The results are reported to the BS in the next uplink phase. Starting with a frame length of 0.5 ms and one downlink slot, both parameters are increased proportionally. Hence, the fraction of downlink resources is the same for all frame lengths. The resulting parameter settings are given in the following table. The frame lengths which are supported by the IEEE 802.16 standard are highlighted in grey. The standard supports frame lengths up to 20 ms, but frames longer than 2.5 ms are not considered in this paper since with that frames the adjacent OFDMA subchannel scheme is not applicable under the considered conditions.

TABLE 1 : FRAME PARAMETERS

MAC frame length	N_{DL}
0.5 ms	1
1.0 ms	2
1.5 ms	3
2.0 ms	4
2.5 ms	5

In the simulations, a fixed broadcast length of one OFDMA symbol is assumed. Generally, the length of the broadcast transmission depends on the OFDMA resource scheduling because the BS has to inform the MTs periodically about the resource allocations [10]. Since this paper is focused on the analysis of the downlink, it is assumed that the length of the broadcast transmission affects only the length of the uplink phase.

C. *OFDMA Resource Scheduling*

The resource allocation scheme is based on the basic scheduling algorithm that has been used in [11] and [12]. The resources within a MAC frame are assigned to downlink connections to MTs by a process which incorporates a general loop. The basic steps of that loop are depicted in Fig. 3 and described in the following.

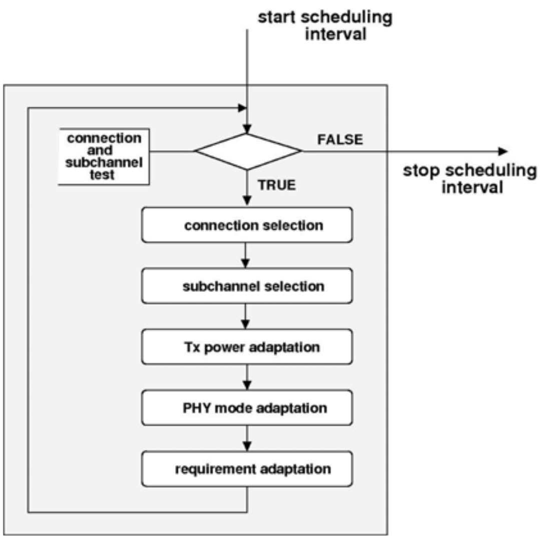

Fig. 3. OFDMA resource scheduling process

At first, a queue is selected from the set of active connections in a Round Robin fashion. 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 level 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. The latter is considered as an adaptation for the requirements for the next scheduling step. 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.

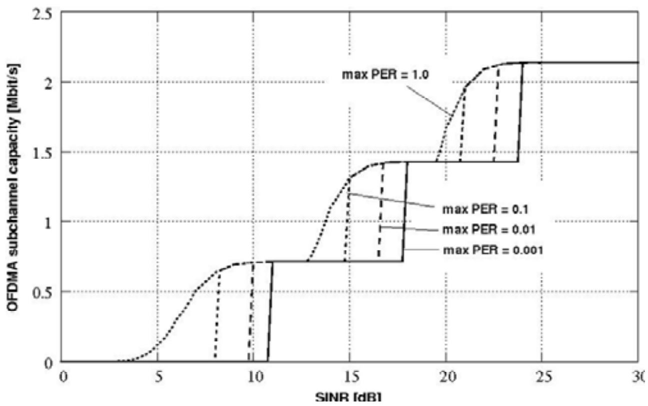

Fig. 4. Link adaptation curve

QPKS¾, 16QAM¾ and 64QAM¾ are used as PHY modes. Fig. 4 shows the corresponding link adaptation curves which are subject to different maximum PERs (Packet Error Rates). QPSK¾ is the most robust PHY mode and 64QAM¾ provides the highest capacity. The transmitted packets have a fixed size of 18 bytes. Regarding the dimensions of the smallest assignable resource (one subchannel and two symbols), QPSK¾ corresponds to one packet per resource, 16QAM¾ provides a capacity of 2 packets per resource, and 3 packets can be transmitted with 64QAM¾.

The PERs have been calculated by the equations for an AWGN channel given in [15]. The coding gain is a function of the SINR, but in this work we use a simple model with a fixed gain of 2 dB. Nevertheless, the general propositions which are based on the results of this paper are valid anyway. The focus of this work is on the impacts of different OFDMA subchannel schemes and the according uncertainty in quality estimation and not on the channel coder properties.

As already explained in Section II, one of the major problems in the OFDMA resource scheduling is that the estimated SINR level of a data transmission is normally afflicted with uncertainty. A simple example will explain the effect. It is assumed that the estimated SINR level on a resource is 25 dB and the maximum accepted PER is 0.01. When the capacity shall be maximized this means according to Fig. 4 that the PHY mode 64QAM¾ will be used. But when the SINR during the data transmission is below 21 dB this will result in a PER which is larger that the previously assumed during the resource allocation and PHY mode selection.

IV. PERFORMANCE EVALUATION

A. Simulation Environment

All simulations have been conducted with an event driven simulator that is based on NS-2 [17]. For the analysis of OFDMA systems comprehensive extensions have been implemented. These extensions comprise a detailed OFDMA physical layer and channel including time-correlated Rayleigh subchannel fading. Furthermore, a MAC scheme that is based on the centrally controlled IEEE 802.16 and an SR-ARQ scheme have been integrated. This simulation tool provides powerful means to conduct performance evaluations of OFDMA systems on a very detailed level from MAC point of view. Especially QoS (*Quality of Service*) constraints like packet delay can be evaluated depending on different system parameters.

B. Simulation Scenario

The simulated scenario consists of a single BS with 16 associated MTs. The latter randomly move around within 200 m radius around the BS. Each MT has one active downlink connection with the BS. The traffic load is modeled as Poisson traffic with a fixed packet size of 18 bytes. All downlink connections have the same traffic load during a simulation run.

The radio channel characteristics are modeled as a superposition of mean pathloss, depending on the distance between sender and receiver, and a frequency-selective fading process [13]. The Jakes model [14] has been used for simulation of the time-correlated fading process for each OFDMA subchannel. These processes are assumed to be flat and mutually uncorrelated. The pathloss exponent is 2.5 and the overall downlink transmission power is 30 dBm. This power is equally shared between all parallel transmissions. The maximum PER constraint for the OFDMA resource scheduler is 0.1. Concerning the time correlation properties of the fading, a Doppler shift of 100 Hz is assumed. This corresponds to a MT velocity of 21.6 km/h.

C. Simulation Results

Fig. 6 shows the cumulative distribution function of the estimated SINR of a single downlink connection which is the basis for the resource allocation decisions. The traffic load is 300 kbit/s and the MAC frame has a length of 0.5 ms. The results exhibit that the adjacent subchannel scheme provides a large SINR gain compared to the distributed scheme due to the exploitation of multi user diversity. This corresponds to the results presented in [11].

With the assumption of perfect channel knowledge at the scheduler these SINR distributions would coincide with the SINR at the receiver side during the data reception. Since this is not the case in a real system, the dynamics of the channel state, i.e. fading level, has to be incorporated. This leads to uncertainty in the SINR estimation because the channel state has changed between the channel measurement and the data transmission.

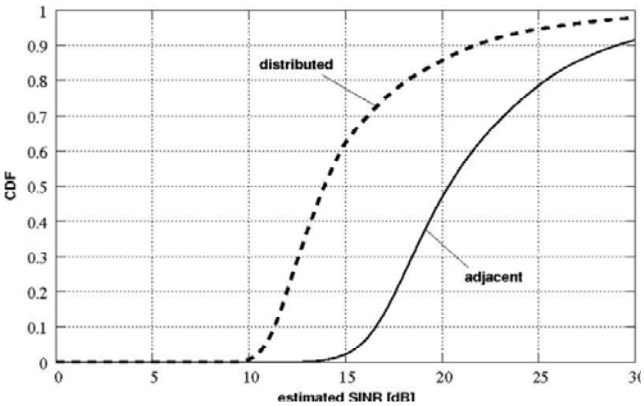

Fig. 5. Estimated SINR CDF

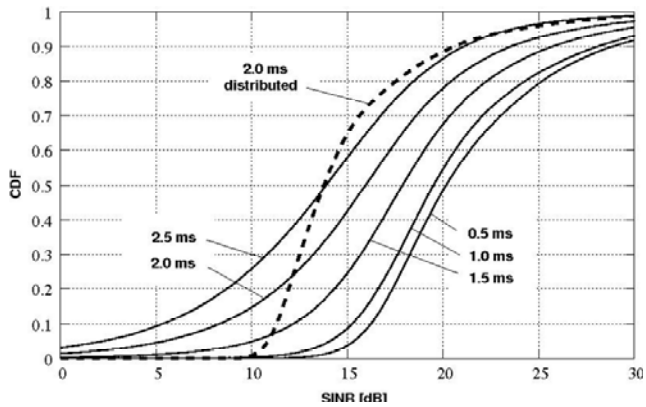

Fig. 6. SINR CDF (300 kbit/s)

The SINR during the data reception is shown in Fig. 6. The MAC frame length has been varied between 0.5 and 2.5 ms. In comparison with the estimated SINR in Fig. 5 it is revealed that the distributed subchannel approach provides a quite exact SINR estimation. In the case of adjacent subchannels, the accuracy strongly depends on the MAC frame length. The longer he frame, the larger is the degree of uncertainty.

These results reveal the two basic effects of the different OFDMA subchannel schemes. The adjacent subchannel scheme provides a large SINR gain compared to the distributed scheme due to multi user diversity. Fig. 7 illustrates the according impact on the PHY mode usage for a MAC frame length of 0.5 ms. According to the estimated SINR, the use of the adjacent subchannel scheme results in a higher probability of using the high capacity mode 64QAM¾.

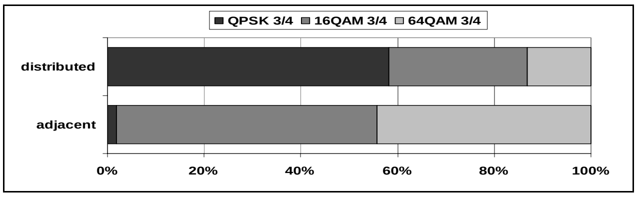

Fig. 7. PHY mode usage (300 kbit/s)

On the other hand, the adjacent subchannel scheme is prone to inaccuracies in the channel state estimation. This may cause wrong decisions in the PHY mode selection and therefore result in large packet error rates. This effect will be discussed in detail in the following.

Fig. 8 shows the effective SINR reserve during the data reception of a downlink connection. That is the gap between the SINR limit for the different PHY modes and the actual SINR during data reception. With the maximum PER constraint of 0.1 these SINR limits are 8.25 dB for QPKS¾, 15 dB for 16QAM¾, and 21 dB for 64QAM¾. An effective SINR reserve of 0 dB corresponds to a PER of 0.1. When the effective SINR is positive, the PER is lower than 0.1. When the reserve is negative, the PER exceeds the given PER constraint.

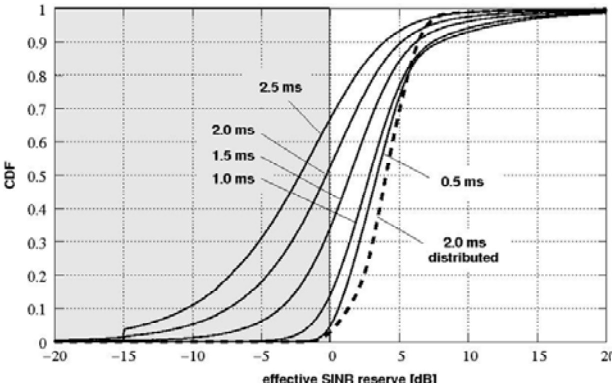

Fig. 8. Effective SINR reserve (300 kbit/s)

The results show that for adjacent subchannels the probability of SINR levels that are below the SINR limit for each PHY mode increases with longer frames. With the use of distributed subchannels, the effective SINR gain has no considerable dependency on the frame length. The mean of the effective SINR reserve for the adjacent subchannel scheme and the standard deviation depending on the frame length are given in the following table.

TABLE 2 : FRAME PARAMETERS

MAC frame length	N_{DL}	μ_R	σ_R
0.5 ms	1	4.14 dB	2.00 dB
1.0 ms	2	3.41 dB	2.47 dB
1.5 ms	3	1.49 dB	3.76 dB
2.0 ms	4	-0.64 dB	4.82 dB
2.5 ms	5	-2.71 dB	5.40 dB

The impact of the effective SINR reserve on the PER is revealed in Fig. 9. It can be seen that the PER in general increases with the frame length since the PHY mode selection of the OFDMA resource scheduler does not meet the actual SINR. In correspondence to the statistics of the effective SINR reserve, the distributed subchannel scheme guaranties the lowest PER due to minimum uncertainty in the SINR estimation. Obviously, the PER results in Fig. 9 exactly match to the SINR distribution in Fig. 8. Consider for example a frame length of 1.5 ms (N_{DL} = 3). The probability that the PER is larger than 0.1 is approximately 0.35. This corresponds to the probability that the effective SINR reserve is below 0 dB.

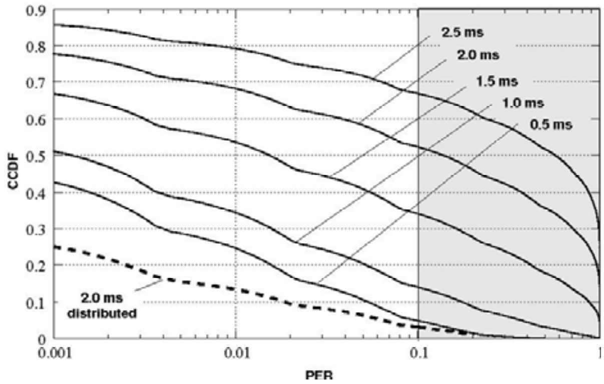

Fig. 9. PER CCDF (300 kbit/s)

The recapitulating performance comparison of the adjacent and distributed OFDMA subchannel schemes is given in Fig. 10 and in Fig. 11. The first figure displays the throughput-delay characteristics depending on the frame length, and the second contains the according utilization of downlink resources within a MAC frame. The resource utilization shows the general effect, that it grows linear with the traffic load until it reaches the saturation point. That point corresponds to the system capacity. The slope of the resource utilization cure comprises information about the spectral efficiency. The steeper the curve is, the small is the spectral efficiency. For the use of adjacent OFDMA subchannels it can be seen that the efficiency in the resource utilization increases when the MAC frame length is reduced. This is based on the reduced uncertainty in the SINR estimation.

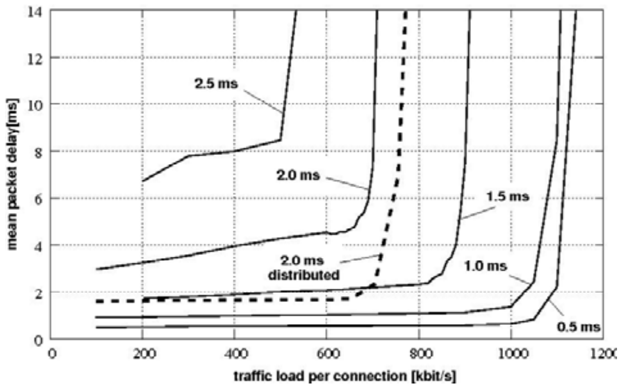

Fig. 10. Throughput-delay characteristic

Fig. 10 shows that the system capacity with the use of an adjacent OFDMA subchannel scheme is reduced when the

MAC frame length is increased. When the frames are short (0.5 and 1 ms) the capacity does not differ much. It has to be noted that the signaling overhead is not analyzed in this paper.

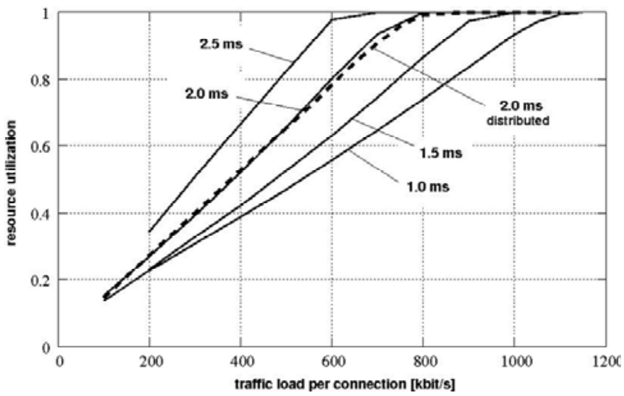

Fig. 11. Resource utilization

An interesting affect is revealed in the comparison of the distributed and adjacent subchannel schemes with a frame length of 2 ms (N_{DL} = 4). The resource utilization approximately coincides. When the MAC frames are short, the adjacent subchannel scheme provides a higher capacity than the distributed scheme. With longer MAC frames the mean packet delay is significantly larger, even for low traffic loads. The reason is the high PER due to uncertainty in the SINR estimation. But the throughput-delay characteristic in Fig. 10 shows that the mean packet delay of the adjacent scheme is significantly higher than with the distributed scheme for all traffic loads. The reason is that the adjacent scheme favors the use of high capacity PHY modes like 64QAM¾ due to the exploitation of diversity which would normally increase the efficiency of the resource utilization. But due to the high uncertainty compared to the distributed schemes, the mean PER is high (compare Fig. 9) and hence several packet retransmissions are required. Obviously, at a frame length of 2 ms (N_{DL} = 4) the capacity gain, which is based on the exploitation of diversity, is compensated by the number of retransmissions.

V. CONCLUSION AND OUTLOOK

In this paper, the performance of the adjacent and distributed OFDMA subchannel schemes in IEEE 802.16 have been analyzed in detail by means of stochastic event-driven simulations. The focus was on the tradeoff between diversity exploitation and estimation accuracy concerning the effective subchannel fading level which is required for a reasonable selection of modulation and coding scheme. The performance of the OFDMA subchannel schemes strongly depends on the ration of the MAC frame and the Doppler shift. It has been shown for a typical reference scenario that the standard Mac frame length parameters of IEEE 802.16 are not sufficiently short to provide an overall capacity gain due to the exploitation of diversity in the use of the adjacent subchannel scheme.

Also the performance evaluation is done for the OFDMA subchannel parameters of IEEE 802.16 and a basic model for the PER calculation for different PHY modes, the conclusions can be considered as a basic contribution to the design decisions for the development of future broadband OFDMA systems. Anyway, the results that have been presented form only a first step on the way to a comprehensive simulative analysis of OFDMA systems, which means that the focus is not just on the PHY but also on the impacts on the MAC. Due to limited space, only a single reference scenario could be analyzed. Current activities focus on the consideration of correlation properties of the subcarrier and subchannel fading processes in the frequency domain in addition to the time domain. Further research topics are the detailed evaluation of different OFDMA resource scheduling schemes, the analysis of the according signaling overhead, and the incorporation of more detailed models concerning the channel coding.

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