Simulative MAC Level Performance Evaluation of an OFDMA System under the Consideration of Frequency Correlated Fading

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***Abstract*—This paper is focused on the performance evaluation of OFDMA systems under the consideration of frequency correlated subchannel fading. A comprehensive model for the generation of correlated fading processes is proposed for the application in MAC level simulations. In contrast to most works in the research field of OFDMA, with this approach it is possible to conduct performance evaluations which incorporate both the traits of the medium access control scheme and of the physical layer. To approve the importance of considering correlation properties of the subchannels fading in an OFDMA system, a centrally controlled system based on IEEE 802.16 is analyzed in detail by means of stochastic event-driven simulations.**

***Index Terms*—OFDMA, medium access control, frequency correlated fading, simulation, resource scheduling**

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 that area focus on that technique, e.g. [1] and [2]. In such a system the frequency channel is subdivided into narrowband subchannels which consist of orthogonal subcarrier sets. These subcarrier sets are either distributed or adjacent in the frequency spectrum [3]. 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 [4]. The shortcoming in the use of distributed subchannels is that from MAC point of view no subchannel diversity can be exploited by the resource scheduling. In the mean all subchannel have the same quality. In contrast to that, the use of adjacent subchannels offers the possibility to exploit the diversity of a frequency-selective fading channel. This approach can significantly increase the system capacity in scenarios with multiple users [5]. It is obvious that the degree of diversity exploitation strongly depends on the correlation properties of subcarrier and subchannel fading in the frequency domain. Two kinds of correlation in general affect the performance of the OFDMA system. At first there is the fading correlation within a single OFDMA subchannel. Furthermore, there is the correlation of the effective fading levels of different subchannels. This correlation decreases the resource diversity since the subchannels show comparable qualities when the correlation is high. The variance of the effective subchannel fading is reduced. Obviously, this also results in a reduction of the subchannel diversity which can by exploited in a multi user scenario. Both of these effects are taken into account in this paper.

The modeling of the PHY (*Physical Layer*) for MAC (*Medium Access Control*) level simulations of an OFDMA system is always a challenging issue. For link level performance evaluations by means of simulations, normally complex implementations of the whole transmission chain are used. This comprises channel coding, modulation, detailed radio propagation models, etc. For the analysis of radio systems on MAC level, especially under the consideration of interference in large scenarios, the link level approach is not feasible. However, the characteristics of the PHY can not be neglected when accurate performance estimations are aspired. This paper provides a comprehensive simulative performance evaluation of OFDMA resource scheduling in a broadband system based on IEEE 802.16 [6]. To achieve that, a method for the generation of correlated subchannel fading has been derived.

The rest of this paper is organized as follows. A detailed description of the proposed OFDMA PHY model is given in Section II, and the investigated system is described in Section III. The performance evaluation results and an interpretation are presented in Section IV. Finally, the paper ends with some concluding remarks and an outlook.

II. Channel Modeling for MAC Level Simulations

For MAC level simulations of OFDMA systems we propose the application of the model structure depicted in Fig. 1. At first, the effective fading is calculated for a subchannel. Then in the next step, the effective SINR is determined. Here we assume that the thermal noise is the same on all subcarriers and that the interference is equally distributed over all subcarriers of a subchannel. The resulting effective SINR is incremented by a coding gain which is in general a function of the SINR and depends on the channel coding scheme. The

BER and PER is determined by the resulting SINR. Under the AWGN assumption and the knowledge of the modulation scheme, the BER can be easily calculated by the equations given in [7]. What we then have is in general the AWGN error mapping with incorporation of an assumed channel coding gain.

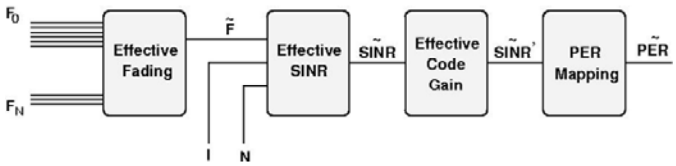

Fig. 1. Simulation chain for MAC level simulations

A. *Effective Subchannel SINR and Fading*

An OFDMA subchannel consists of N subcarriers. Since each subcarrier might exhibit a different SINR level, these have to be combined to an effective SINR for the subchannel. This is required to be able to estimate the quality of the subchannel from MAC point of view. The effective SINR can in general be determined by

$$SINR_{eff} = \alpha_1 I^{-1}\left(\frac{1}{N}\sum_{i=1}^{N} I\left(\frac{SINR_i}{\alpha_2}\right)\right) , \tag{1}$$

which has been used in [8] to compress the quality information of an OFDM subcarrier set. $I()$ is a model specific function and $I^{-1}()$ its inverse. The parameter α_1 and α_2 allow the adaptation to the characteristics of modulation and coding schemes. The performance of different parameter settings and functions has been shown in [8]. For our work we applied the capacity approach:

$$I(SINR) = \log_2(1+SINR) \ . \tag{2}$$

Further we used $\alpha_1 = \alpha_2 = 1$. Under the assumption that the SINR of an OFDMA subcarrier, which is used for data transmission, is much greater than 1, the following approximation can be used:

$$\log_2(1+SINR) \approx \log_2(SINR) \ . \tag{3}$$

The advantage of this approach is that the effective SINR can then easily be subdivided into an SINR without fading superimposed by an effective subchannel fading:

In a mobile radio system, the received signal can be partitioned in terms of two variables by

$$r(t) = m(t)\cdot r_0(t) \ , \tag{5}$$

where $m(t)$ is called the large-scale fading component, and $r_0(t)$ is called the small-scale fading component [9]. Since the large-scale fading component is the same for all subcarriers, it is possible to determine an effective small-scale fading component based on the capacity approach.

For the representation with (5) a normalization of $E[r_0^2] = 1$ is common and useful [10]. So in our case the logarithmic representation of the effective OFDMA subchannel fading is given by

$$y_{eff_0} = 20\cdot\log_{10}\left(r_{eff_0}\right) = \frac{1}{N}\sum_{i=1}^{N} 20\cdot\log_{10}\left(r_{i_0}\right) . \tag{6}$$

Apparently, the logarithmic representation of the effective small-scale fading is the mean of the logarithmic representations of the subcarriers that form a subchannel. In a simulator, the resulting effective fading can then be added to the SINR calculation without subchannel fading.

B. *Generation of Frequency Correlated Effective Fading*

In the previous paragraph, the determination of the effective fading in an OFDMA system has been explained. Now we face the question how the effective fading can be generated for MAC level simulations. Therefore, the measurement of the statistics of the effective fading is required. For this issue an accurate fading generator for the subcarriers has been implemented. This generator exactly produces the aspired cross-correlations in the frequency domain between all subcarriers. After that generation, we calculated the effective subchannel fading as described above. For these effective fading samples we determined the moments and the cross-correlations. The algorithm described in [11] has been used for the generation of the frequency correlated subchannel fading. The application of this algorithm has the advantage that it can generate Rayleigh fading envelopes with any desired correlation. For the frequency correlation of the fading envelopes, the model of Jakes has been used [12]. The envelope correlation of the complex fading depending on frequency separation s = ω_1 - ω_2 and delay spread σ is determined by

$$\rho = \frac{J_0^2(0)}{1+s^2\sigma^2} , \tag{7}$$

where J_0 is the zero-order Bessel function of first kind.

TABLE I
EFFECTIVE FADING DEPENDING ON DELAY SPREAD

σ_{rms}	B_c	μ_r	σ_r	ρ_r
0 ns	--	-2.51dB	5.57 dB	1.00
100 ns	2000 kHz	-2.51 dB	4.54 dB	0.38
250 ns	800 kHz	-2.51 dB	3.50 dB	0.18
500 ns	400 kHz	-2.51 dB	2.71 dB	0.10
750 ns	267 kHz	-2.51 dB	2.28 dB	0.08

The subchannels of the considered OFDMA system consist of 32 adjacent subcarriers. The subcarrier spacing is 78.125 kHz. Hence, the OFDMA subchannels have an effective bandwidth of 2.5 MHz. The measured statistics of the logarithmic representation of the effective subchannel fading depending on the delay spread are given in Table I. The evaluation comprises the mean μ_r, the standard deviation σ_r, and the correlation coefficient of two adjacent subchannels ρ_r. Furthermore, the coherence bandwidth corresponding to the delay spread has been calculated [13]. The calculations show that the coherence bandwidth and due to that the correlation of adjacent effective subchannel fading processes is reduced. Actually, the coherence bandwidth is smaller than the effective subchannel bandwidth of 2.5 MHz in all cases. This demonstrates that an assumption of flat subchannel fading is not valid. This would lead to imprecise performance evaluation conclusions, since the subchannel diversity will be overestimated. In Fig. 2 and Fig. 3 it can be seen that the distribution functions of the effective subchannel fading can be approximated by a Gaussian distribution. The dotted line represents the measured distribution function, and the bold line is the approximated distributed. It can be seen that the accuracy of that approximation in general increases with the delay spread.

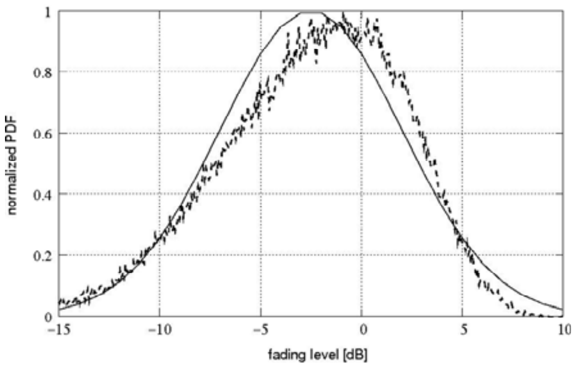

Fig. 2. Effective fading approximated by a Gaussian distribution (σ_{rms} = 100 ns)

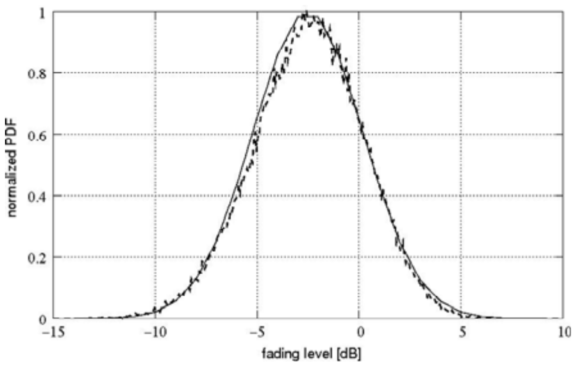

Fig. 3. Effective fading approximated by a Gaussian distribution (σ_{rms} = 500 ns)

The modeling of the effective fading by Gaussian distributions has the advantage that the generation of correlated samples can be conducted easily with the following recursion [14]:

$$X_0 = \sigma Z_0 \tag{8}$$

$$X_n = \rho X_{n-1} + \sqrt{1-\rho^2}\, \sigma Z_n \tag{9}$$

The independent Gaussian random numbers Z_n have a zero mean and unit variance. The resulting Gaussian random numbers have the variance σ^2 and the first order correlation coefficient ρ. In terms of correlated effective OFDMA subchannel fading, ρ is the correlation coefficient of two adjacent subchannels. The correlation coefficients of higher orders, corresponding to increasing distances of subchannels in the frequency domain obeys an exponential decay. Since the measured correlation coefficients of subchannels, which are not located next to each other in the frequency domain, are rather small, that assumption can be used.

III. System Description

A. Physical Layer

The OFDMA system has a bandwidth of 20 MHz at 5 GHz. The frequency channel is subdivided into 256 subcarriers. These subcarriers are grouped into subchannels of 32 adjacent subcarriers. This results in 8 subchannels with an effective bandwidth of 2.5 MHz. The symbols have a length of 13.6 µs, including a cyclic prefix of 0.8 µs to handle inter symbol interference. Three different PHY modes are used for the performance evaluation in this paper, namely QPSK¾, 16QAM¾, and 64QAM¾. The according link adaptation curve for the used PHY modes with the assumption of 2 dB coding gain is given in Fig. 4. 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. The coding gain depends in general 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.

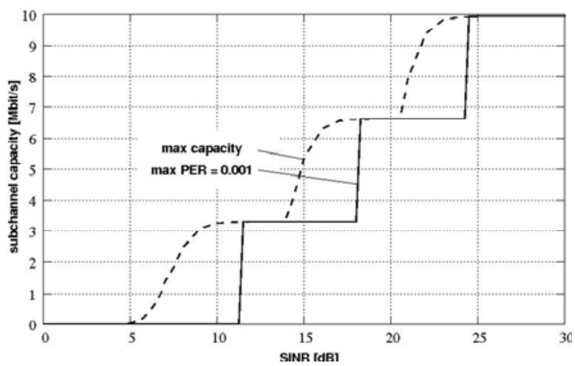

Fig. 4. Link adaptation curve, based on calculations for AWGN channels

B. MAC Layer

We consider a centrally controlled MAC structure that is based on IEEE 802.16. The frequency channel is subdivided into fixed length MAC frames in the time domain. The allocation of resources for data transmissions is conducted in a centrally controlled manner by the BS (*Base Station*). 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 impact of the signaling overhead is not considered. Therefore, a simplified

MAC frame model is used for the simulations. The according structure is shown in Fig. 5.

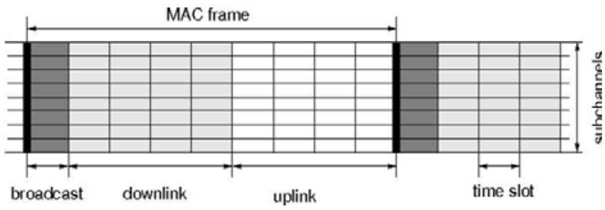

Fig. 5. MAC frame structure

The frame consists of 9 timeslots, each with a length of 108.8 µs. This corresponds to 8 OFDMA symbols per slot and a total frame length of 979.2 µs. The first time slot is reserved for broadcast transmissions like downlink and uplink resource allocation announcements. For both downlink and 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 [15]. However, the signaling overhead can be significantly decreased when the resource allocations of consecutive MAC frames are correlated [16]. We assume a fixed broadcast overhead (~11.11%) since we focus on the OFDMA scheduling and not on the signaling. Due to the use of fixed length MPDUs (*MAC Protocol Data Units*), 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.

C. *OFDMA Resource Scheduling*

The resource allocation scheme is based on the basic scheduling algorithm that has been analyzed in [17] and [18]. Since we investigate the downlink a centrally controlled system like IEEE 802.16, the resource scheduling is conducted in the BS. 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 in a Round Robin fashion [19]. 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.

IV. PERFORMANCE EVALUATION

A. *Simulation Environment*

All simulations have been conducted with an event driven simulator that is based on NS-2 [20]. Comprehensive extensions have been implemented for the analysis of OFDMA systems. These extensions comprise a detailed physical layer and channel model including the frequency correlated subchannel fading proposed in this paper. Furthermore, a MAC scheme that is based on IEEE 802.16 and an SR-ARQ scheme have been integrated.

B. *Simulation Scenario*

The simulation scenario consists of a single BS and 32 MTs. 31 MTs randomly move around within a mobility region with 200m radius around the BS, and one MT has a fixed position at 200m distance from the base station. The latter is considered as a reference for the worst case position. Only downlink data transmissions are investigated and each MT has one downlink connection. All connections of the scenario always have the same traffic load in the simulations. Prioritization is not considered. The traffic load is modeled by a Poisson source which generates 100 byte packets. These are segmented into 40 byte MPDUs. Although there is no interference in the simulated scenario, the term SINR will be used in the following discussion of performance results.

In addition to the adjacent subchannel scheme with different delay spreads, also the distributed approach has been simulated. This is considered as the worst case concerning the diversity exploitation. Hence, it forms the lower bound of the system performance. The assumption of uncorrelated Rayleigh fading per subchannel forms the corresponding upper bound. This fading process provides the highest degree of diversity due to a large variance compared to the correlated cases. A detailed performance analysis of both extreme cases without any correlation has been conducted in [17] and [18].

C. *Simulation Results*

Fig. 6 depicts the cumulative distribution function of the SINR of the MT which is positioned at the cell border (200m distance to the BS). It shows the expected effect that a large delay spread reduces the subchannel diversity. Due to this diversity reduction, the SINR is also reduced. Since the uncorrelated Rayleigh fading provides the highest degree of diversity it also results in the largest SINR. As expected, the application of the distributed subchannel scheme results in the lowest SINR. The mean SINR gap between the two extreme cases of uncorrelated adjacent subchannels with Rayleigh fading and distributed subchannels due to diversity exploitation is 5.3 dB.

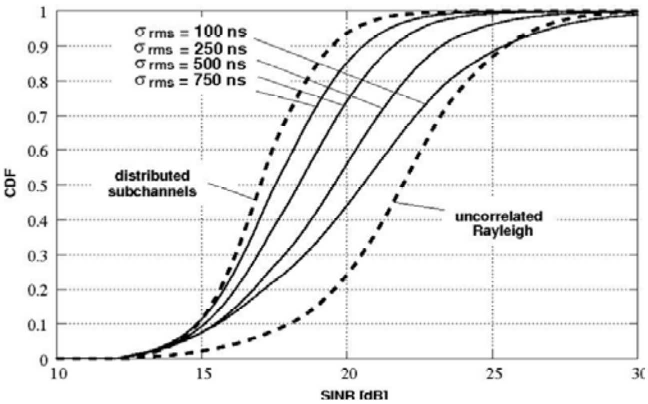

Fig. 6. SINR CDF of a mobile terminal at the cell border (400 kbit/s)

The complementary distribution function of the downlink packet delay of the MT at the cell border is depicted in Fig. 7.

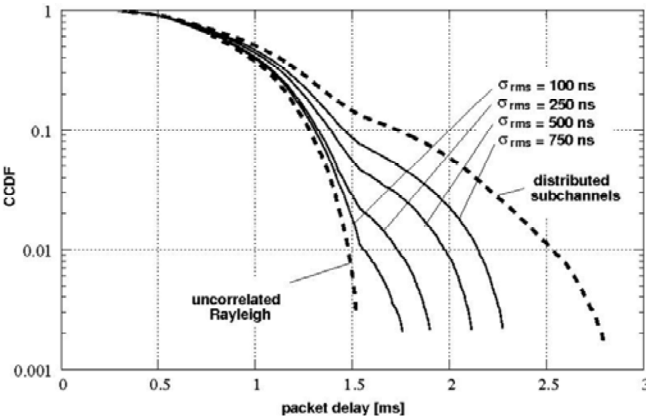

Fig. 7. Packet delay CCDF of a terminal at the cell border (400 kbit/s)

It is shown that the packet delay increases with the delay spread. Since perfect channel knowledge is assumed and the maximum PER is 0.001, the packet delay is increased due to the waiting time in the transmission queues rather than due to MPDU retransmissions. In coincidence with the SINR evaluation, the distributed subchannel scheme shows the largest delay. The mean packet delay depending on the traffic load per connection is shown in Fig. 8. It is revealed that the system capacity decreases when the delay spread is increased. The according mean overall resource utilization within a MAC frame is shown in Fig. 9. It can be seen that the utilization in general increases linearly with the traffic load per connection. The gradient of the curve thereby depends on the delay spread. This shows that the efficiency of the resource utilization increases with the degree of subchannel diversity.

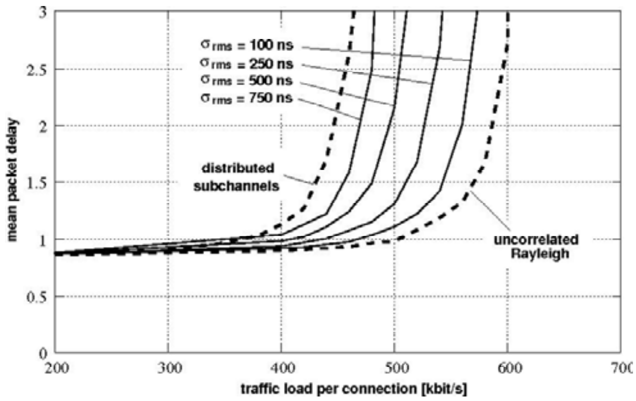

Fig. 8. Mean packet delay of a mobile terminal at the cell border

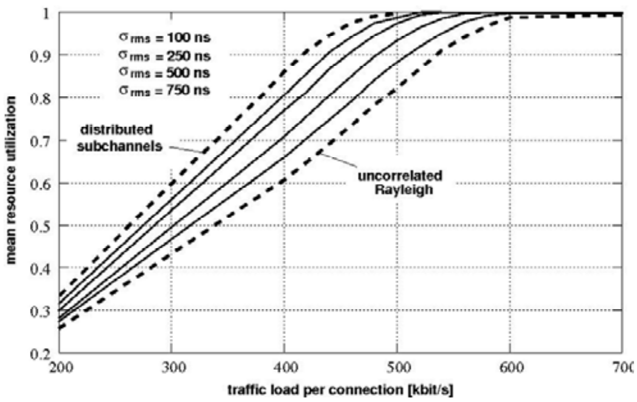

Fig. 9. Mean cell resource utilization

How the increased diversity results in efficient resource utilization is presented in Fig. 10. It depicts the PHY mode usage within the MAC frame at 400 kbit/s traffic load per downlink connection. This corresponds to a mean resource utilization between 0.6 and 0.86 depending on the subchannel diversity. The probability that the high capacity PHY mode 64QAM¾ is used is significantly increased when the delay spread and due to this the diversity is reduced. In the extreme case of uncorrelated Rayleigh fading, 64QAM¾ is used in approximately 70% of the MPDU transmissions. In the case of distributed subchannels, this PHY mode is only used with a probability of 22%.

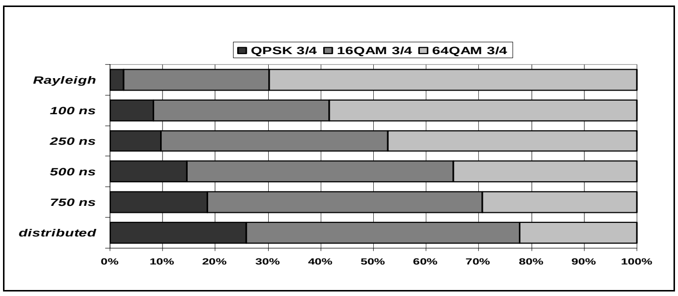

Fig. 10. PHY mode usage

The numbers of transmitted MPDUs per MAC frame are shown in Fig. 11. Furthermore, the maximum capacity (all

MPDUs are transmitted with 64QAM¾) and the capacity under the assumption of uncorrelated Rayleigh subchannel fading and distributed subchannels are shown. The corresponding numbers of MPDUs are 96, 78.5, and 59.3.The bold line represents the number of MPDUs depending on the delay spread. In correspondence with the previous results it is revealed that the capacity is significantly reduced when the delay spread in increased.

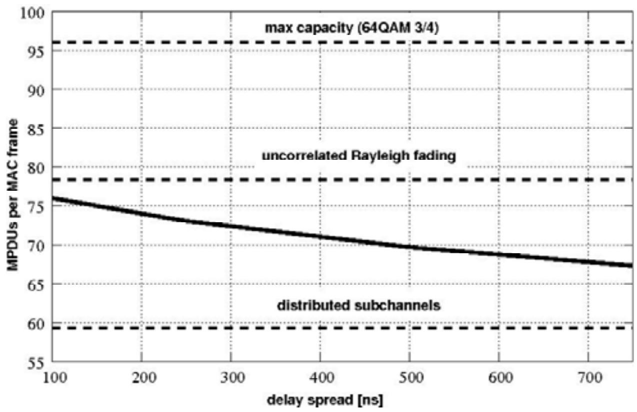

Fig. 11. MAC frame capacity (number of MPDUs per frame)

V. CONCLUSION

An efficient scheme for the generation of frequency correlated subchannel fading for MAC level simulation of OFDMA systems has been proposed in this paper. Simulative performance evaluations of an exemplary system have shown that the capacity strongly depends on the correlation properties of the fading. Therefore, these effects can not be neglected in the analysis of the medium access control and resource scheduling. The NS-2 based simulation tool that has been developed and used for the performance evaluation can in general be used for the detailed analysis of any OFDMA based system, like for example IEEE 802.16. In addition to the OFDMA PHY model it contains also a comprehensive MAC and resource scheduler implementation. Hence, it is possible to analyze the QoS of such a system depending on the PHY characteristics like fading statistics. This is an important achievement since it is obvious, as shown in the presented results, that the correlation properties of the OFDMA subchannel fading can not be neglected when accurate results are aspired. Currently, we are working on the analysis of different OFDMA resource scheduling strategies under the consideration of OFDMA subchannel characteristics. The focus of these research activities is on QoS support. Especially the analysis of multi-cellular scenarios is of great interest. The outcome of this paper forms an important basis for theses research activities.

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