Distributed and Adjacent Subchannels in Cellular OFDMA Systems

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***Abstract*— A simulative performance evaluation of a cellular mobile radio system based on Orthogonal Frequency Division Multiple Access (OFDMA) is presented in this paper. The impact of using either distributed or adjacent OFDMA subchannels is investigated concerning both throughput and delay. This incorporates the exploitation of multi-user diversity and uncertainty in the subchannel quality estimation due to fading and interference. The performance analysis is conducted by means of stochastic event-driven simulations. The presented results can be considered as a basic contribution to the understanding of the behavior of OFDMA based dynamic resource allocation in cellular environments.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is considered to be one of the key technologies for future broadband radio systems such as IEEE 802.16, better known as WiMAX [1], or the 3GPP Long Term Evolution (LTE) [2]. It has been shown that exploiting multi-user diversity can significantly increase the system capacity [3]. But in the case of resource reuse in multi-cellular systems, the capacity is to a great extent determined by the interference estimation strategy [4]. Furthermore, also the uncertainty in fading estimation due to mobility of terminals has to be considered [5].

A basic resource element which is allocated for data transmissions in an OFDMA system is defined by subchannel and time slot. Subchannels consist of subcarriers which are either distributed or adjacent in the frequency dimension [6]. The distributed approach results in an averaging effect concerning both interference and fading [7]. Hence, this approach provides accurate estimation of the resource quality regarding SINR. In contrast to that, the use of adjacent OFDMA subchannels provides an efficient exploitation of diversity in multi-user scenarios. However, the SINR estimation is affected with uncertainty. This might result in large delays because of retransmissions in the case of packet errors.

The performance evaluation presented in this paper addresses the tradeoff between diversity exploitation and accuracy in the SINR estimation. We investigate the performance of distributed and adjacent OFDMA subchannels schemes in the downlink of a cellular system. The focus is on the interaction between physical layer (PHY) and medium access control (MAC), and the evaluation is conducted by means of stochastic event-driven simulations.

The rest of this paper is organized as follows. Section II describes the allocation of resources in an OFDMA system. It contains the descriptions of different subchannel structures, frequency adaptive resource scheduling, and handling of uncertainty in the SINR estimation. An overview of the simulated OFDMA system is given in Section III. The detailed simulative performance evaluation, which clarifies the major challenges in the design of cellular OFDMA systems, is presented in Section IV. The paper ends with some concluding remarks and an outlook.

II. OFDMA Resource Allocation

A. OFDMA Subchannel Structure

An OFDMA subchannel consists in general of a set of subcarrier/symbol elements within a MAC frame structure. How theses elements are located in time and frequency domain determines the diversity properties of the subchannel [8]. In this work we consider the case that an OFDMA subchannel is just defined by the frequency domain characteristic. That means that on a subcarrier all symbols belong to the same subchannel.

The two extreme cases of distributed and adjacent subchannels like described in [6] are investigated. 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 point of view no subchannel diversity can be exploited by the resource scheduling. In the mean, all subchannels have the same quality. The averaging regarding interference is achieved by a pseudo-random selection of subcarriers which is not synchronized between the base stations.

In contrast to that, the use of adjacent subchannel offers the possibility to exploit the diversity of a frequency-selective fading channel at the cost of increased uncertainty in the fading estimation. Due to the strong correlation of the fading within an adjacent subchannel each subchannel is either in a good or bad state concerning the effective quality. With the use of adjacent OFDMA subchannels, the effective subchannel bandwidth shall not be larger than the coherence bandwidth of the radio channel.

B. Resource Scheduling

The resource allocation scheme is based on the scheduling algorithm that has been used in [4] and [5]. We consider a centrally controlled MAC scheme like WiMAX with connection oriented data transmission. The resources (time slot and subchannel) within a MAC frame are assigned to data connections in a successive manner which is described in the following.

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 MAC Protocol Data Unit (MPDU) to be transmitted. The according connection then gets the resource with the best quality regarding the effective fading from the set of not assigned resources within the MAC frame. In the next step transmission power and modulation and coding scheme (PHY mode) are selected, and the MPDUs that fit into the allocated resource are removed from the transmission queue. This procedure is repeated until either all active connections have been able to transmit all MPDUs or all resources within the MAC frame are allocated.

Fixed transmission power is used for each MPDU transmission. Hence the adaptation to the current channel state is done via adaptive PHY mode selection. We chose to use Round Robin resource allocation in this paper since it provides maximum fairness concerning the allocation of resources compared to schemes which aim at maximization of system throughput.

C. SINR Estimation

Accurate estimation of the expected SINR level during data reception is inevitable for reasonable PHY mode selection. It is assumed that the channel state is estimated by the reception of pilot symbols, e.g. in the broadcast phase of the centrally controlled system. The SINR estimation comprises the following steps:

- SNR estimation based on pilots (γ)
- Estimation of mean difference between estimated SNR and real SINR (δ)
- SINR estimation (addition of γ and δ)

As shown in (1), the SINR level $\gamma(n)$ of the nth MPDU transmission can be described as a superposition of the SNR level $\tilde{\gamma}(n)$, which is estimated with the use of pilots at the receiver, and an offset $\delta(n)$ due to estimation uncertainty and interference. A negative $\delta(n)$ means that the SINR level during MPDU reception is lower than the estimated SNR level, which may result in transmission errors du to the selection of an improper PHY mode.

$$\gamma(n) = \tilde{\gamma}(n) + \delta(n) \quad (1)$$

$$\gamma_S(n) = \tilde{\gamma}(n) + \tilde{\delta}(n) + \epsilon(n) \quad (2)$$

One reason for this can simply be the existence of interference, which has not been considered in the SNR estimation based on pilots. But additionally also fading level estimation results is imperfect. Generally, there is a superposition of both effect. Which one overweighs depends on scenario and traffic load.

The calculation of the estimated SINR level $\gamma_S(n)$, which is the basis for the PHY mode selection in the OFDMA resource scheduler, is shown in (2). The estimated difference between the estimated SNR and the real SINR is given by $\tilde{\delta}(n)$, and $\epsilon(n)$ is an additional offset which is used to take into account the expected uncertainty in the SINR estimation. In this work we use $\epsilon(n) \equiv 0$ since only the mean SINR shall be estimated.

The determination of $\tilde{\delta}(n)$ is done by the following recursive strategy:

$$\tilde{\delta}(0) = 0 \quad (3)$$

$$\tilde{\delta}(n+1) = \tilde{\delta}(n) + \alpha\left(\delta(n) - \tilde{\delta}(n)\right) \quad (4)$$

It can be shown that (3) and (4) describe an unbiased estimator under stationary conditions if $0 > \alpha > 2$. Otherwise, the estimator is instable.

III. System Description

A. Physical Layer

The system operates on a 20 MHz channel at 5 GHz. The frequency channel is divided into 2048 orthogonal subcarriers, which are grouped into 32 subchannels, each consisting of 48 data subcarriers. The remaining subcarriers are used as pilots and guard subcarriers. The subcarriers of a subchannel are either distributed or adjacent in the frequency channel. The OFDMA symbol length, including the guard time, is 100.8 μs.

TABLE I

SINR bounds and Capacity of used PHY modes

PHY mode	*SINR*	*Resource Capacity*
QPSK ¾	$>$ 11 dB	1 MPDU
16QAM ¾	$>$ 18 dB	2 MPDUs
64QAM ¾	$>$ 24 dB	3 MPDUs

The used PHY modes, the according lower SINR bound for a maximum PER of 0.1%, and the capacity per resource element are given in Table I. MPDUs have a fixed size of 18 bytes. That resource size is used because in combination with the used PHY modes and a fix no capacity is wasted due to clipping. The packet error rates have been calculated from the bit error rates for AWGN channels [10]. A constant channel coding gain of 2 dB is assumed. This is a rather basic model, but general effects of the different OFDMA subchannel schemes in a cellular environment can be revealed anyway. With the use of more realistic channel coder models, the coding gain would depend on the SINR level. However, the effects which are discussed in the performance evaluation generally apply to OFDMA systems.

B. Medium Access Control

The frequency channel is divided into MAC frames with a fixed length of 1 ms. Within the MAC frame 2 time slots, each with a length of 2 OFDMA symbols, are reserved for downlink transmissions. Overall, this results in 2×32 (time slot $\times$ subchannels) downlink resource elements.

The retransmission of corrupted MPDUs is handled by an SR-ARQ scheme with block acknowledgments. It is assumed that the information about received MPDUs is available at the transmitter in the succeeding MAC frame.

Dynamic resource allocation is conducted in a centrally controlled manner by the base station (BS). This allocation is done periodically at the beginning of each MAC frame and reported to the mobile terminals (MTs) in the broadcast phase of the MAC frame. Concerning 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 during the broadcast phase. The results are reported to the BS in the next uplink phase.

IV. Performance Evaluation

A. Simulation Tool

The simulations have been conducted with an OFDMA extension for the NS-2 simulator [11]. This extension has been developed for the simulative performance evaluation of broadband OFDMA system. It comprises a centralized MAC scheme based on IEEE 802.16, an OFDMA physical layer, and a comprehensive channel model with accurate interference calculation. In contrast to conventional link level simulators, this tool is event-driven. And therefore it supports the performance evaluation concerning QoS based on packet delay measurements.

B. Simulation Scenario

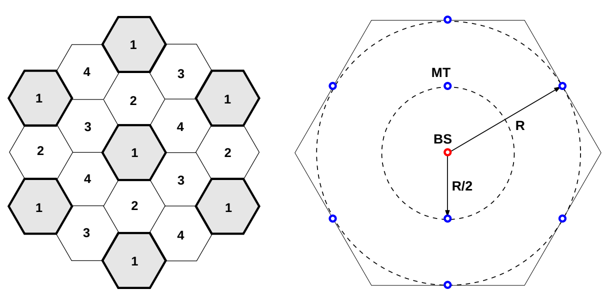

Fig. 1. Simulation scenario (clustering and terminal positions within the evaluated cell in the center)

The simulated scenario is shown in Fig. 1. Each cell comprises one BS and 8 MTs. In the evaluated cell in the center of the scenario 6 MTs are positioned at radius R, which corresponds to the cell edge, and 2 MTs are placed at distance R/2 from the base station. In the interferer cells the MTs randomly move around. For the cell clustering 4 frequency channels of 20 MHz are used. The cell radius R is 150 m.

The downlink connections are modeled as Poisson streams, and in each simulation run all connections have the same traffic load. The downlink transmission power per OFDMA subchannel is 33 dBm. The pathloss coefficient is 3.5, which is a typical value for an urban environment [12], and Jakes' Model [13] is used for the OFDMA subchannel fading. The SINR estimation as described in Section II-C is adapted per MAC frame, and the adaptation factor α for the SINR estimation is set to 0.2.

C. Simulation Results

In the following discussion of the performance evaluation results the downlink connections to the MTs at the cell border are denoted outer connections, the other ones are named inner connections. In the first part of the evaluation distributed and adjacent OFDMA subchannel schemes are compared at a fixed Doppler shift of 100 Hz, which corresponds to a mean velocity of 21.6 km/h at 5 GHz.

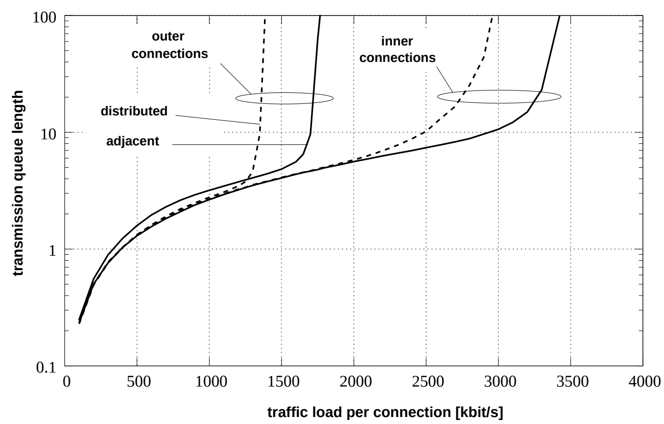

Fig. 2. Mean transmission queue length

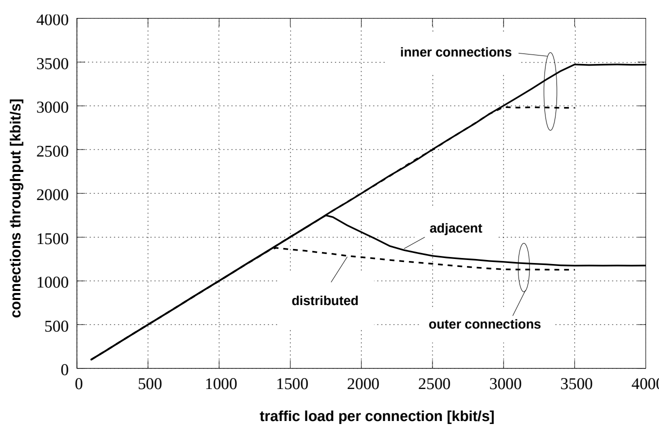

Fig. 3. Connection throughput

Fig. 2 shows the mean transmission queue occupancy of the inner and outer downlink connections. The maximum queue length in all conducted simulations was 256 packets. The throughput per data connection is shown in Fig. 3. As expected, the saturation throughput for inner and outer connections both with distributed and adjacent OFDMA subchannels correspond to the according queue length evaluation. It is obvious that for both subchannel schemes the inner connections can carry a significantly higher traffic load than the outer connections. The reason is higher mean SINR and hence the increased use of high capacity PHY modes. Furthermore it is shown that the adjacent subchannel structure provides higher capacity for both connection types. This is based on the diversity exploitation of the frequency adaptive resource scheduling. The capacity gain for both connection types is approximately 400 kbit/s. Hence the relative gain for the outer connections is much larger than for the inner connections.

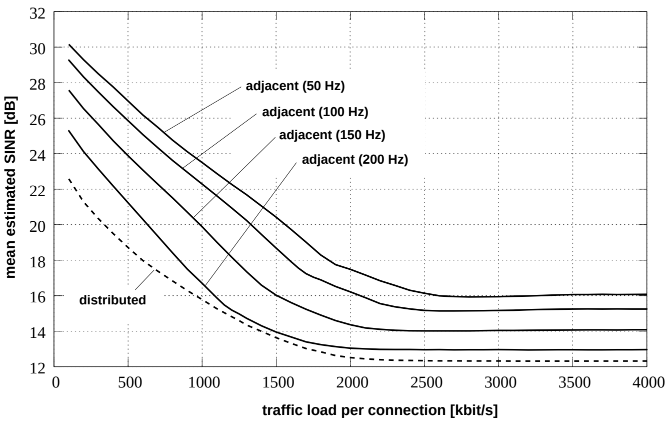

Fig. 4. Mean SINR level for PHY mode selection $\gamma_S(n)$ $(\alpha = 0.2)$

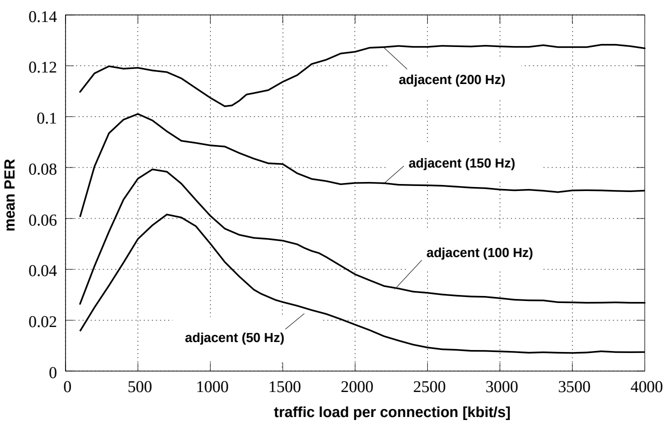

Fig. 5. Mean PER with adjacent subchannles (PER for distributed subchannels is always below 0.001, corresponding to 0.1 %)

In the following presentation of further simulation results only the outer connections at the cell border are discussed. The performance evaluation is focused on the impact of Doppler shift, interference, and the resulting uncertainty in the SINR estimation. The mean estimated SINR based on the scheme described in Section II-C is shown in Fig. 4. This SINR is the basis for the PHY mode selection within the scheduler. Two effects are revealed in the evaluation of the SINR estimation. The first is that the estimated SINR strongly depends on the system load. The higher the system load, the higher is also the mean interference. And due to this the mean SINR is reduced. When the system is saturated the interference level is stable and an accurate estimation is possible. These saturation points can be clearly seen in Fig. 4. The second effect is that the estimated SINR of the used scheme depends on the Doppler shift. An increased Doppler shift results in uncertainty in the estimation. Hence, the difference between estimated SNR based on pilots $\tilde{\gamma}(n)$ and real SINR $\gamma(n)$ increases. Since the estimation scheme corrects the mean error between estimated SNR and real SINR, the SINR level $\gamma_S(n)$, which is used for the PHY mode selection, is reduced.

The mean packet error rate (PER) depending on the traffic load per connection is given in Fig. 5 for adjacent subchannels. The results show the impact of uncertainty in the SINR estimation due to both Doppler shift and interference. The lower bound PER for the PHY mode selection is 0.001 (corresponding to 0.1 %). The curve for distributed subchannels is not shown because, due to averaging effect, it does neither depend on traffic load nor Doppler shift. The mean PER with distributed subchannels is always below 0.1 %.

It can be seen that the PER of the adjacent subchannels significantly increases when with large Doppler shifts. The reason is that the time between channel estimation and resource scheduling becomes larger than the coherence time. Concerning the impact of the traffic load it can be seen that the PER first increases linearly with the load, and then after reaching the maximum (at approx. 50 % resource utilization) it is again reduced until it remains on a stable level. That level is reached when the system is saturated and the uncertainty in the SINR estimation depends just on the channel characteristics in terms of Doppler shift.

The variation of the PER over the traffic load is reduced with large Doppler shifts. This shows that the uncertainty in the channel state estimation more and more exceeds the impact of the uncertainty due to interference.

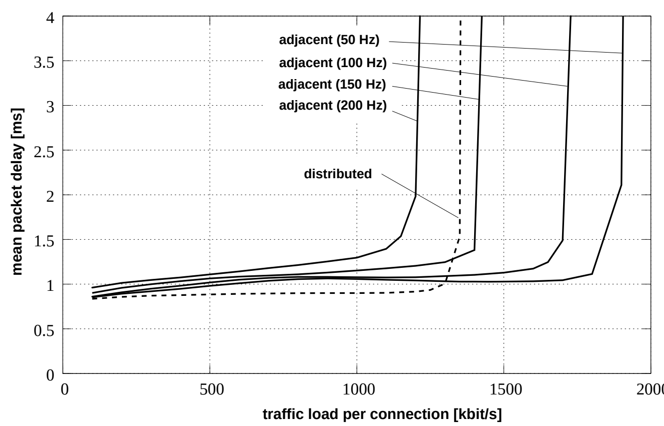

Fig. 6. Mean packet delay depending on traffic load per connection

The throughput-delay characteristics of the the connections at the outer connections at the cell border are shown in Fig. 6. As expected it can be seen that the performance strongly depends on the Doppler shift which determines the accuracy of the fading level estimation. Furthermore, it is shown that in the case of an unsaturated system and distributed subchannels the mean delay is reduced compared to the use of adjacent subchannels. This is based on the high degree of accuracy in the SINR estimation with distributed subchannels. Retransmissions of MPDUs or not required. These results show clearly that with large Doppler shifts the capacity loss due to the compensation of the uncertainty in the SINR estimation exceeds the possible gain based on the exploitation of diversity.

Although the mean SINR level, which is used for the PHY mode selection (Fig. 4), is larger then with the use of distributed subchannels, at a Doppler shift of 200 Hz the adjacent subchannel approach provides a lower capacity. The reason for this effect is that the SINR estimation scheme does correct the mean estimation error, but not the according variance.

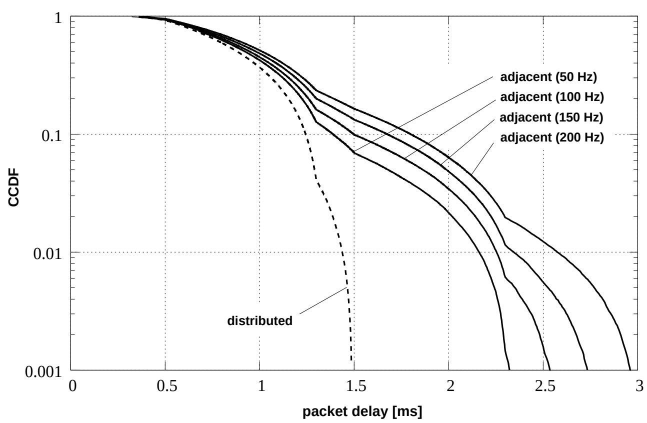

Fig. 7. Complementary cumulative distribution function of packet delay (500 kbit/s per downlink connection)

The distribution of the MPDU delay has been also been investigated. The results for a traffic load of 500 kbit/s per connection are given in Fig. 7, which depicts the complementary cumulative distribution function. Since the system is not saturated in all simulated cases the delay is basically determined by retransmissions due to disturbed MPDUs. In Fig. 6 it can be seen that the mean delay with distributed and adjacent subchannels does not differ much, but here it is shown that the variance shows significant differences. Corresponding to the PER results, the delay grows with increased Doppler shifts.

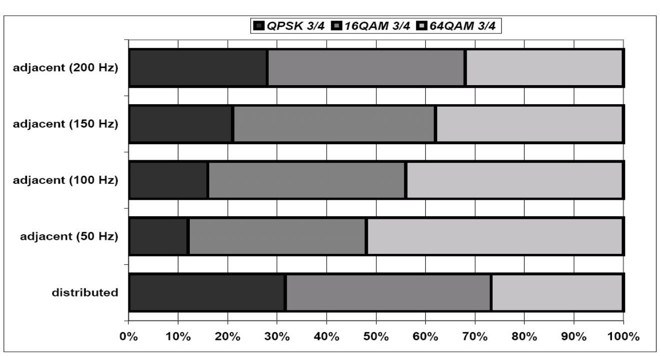

Fig. 8. PHY mode usage (1300 kbit/s)

The PHY mode usage for the downlink resources depending on the Doppler shift is shown in Fig. 8. This result comprises both inner and outer connections at 1300 kbit/s. This figure clearly demonstrates the major effect of uncertainty and the according compensation in the SINR estimation with adjacent subchannels. When the Doppler shift is increased, the usage of the high capacity PHY mode 64QAM3/4 is reduced. This corresponds to the evaluation of the mean estimated SINR of the outer connections in Fig. 4.

V. Conclusion and Outlook

In this paper we presented a simulative performance comparison of distributed and adjacent subchannels in a cellular OFDMA system on MAC level. The results show that the system performance with adjacent OFDMA subchannels is to a great extend determined by inaccuracy in the SINR estimation. The reason for that is the reduced coherence time of the channel with large Doppler shifts. Furthermore, uncertainty in the interference estimation has a strong impact on the system performance.

The results show that the possible capacity gains due to exploitation of multi-user diversity can be significantly reduced in case of imperfect SINR estimation. An efficient exploitation of multi-user diversity with adjacent OFDMA subchannels cannot be provided in scenarios with large Doppler shifts, corresponding to high user velocities.

To handle these effects, more sophisticated SINR estimation strategies, which consider also the variance of the expected estimation error have to be investigated. This is the topic of current research activities which will extend this paper.

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