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PERFORMANCE OF IEEE 802.16e OFDMA IN TIGHT REUSE SCENARIOS

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ABSTRACT

Mobile networks based on the IEEE 802.16e standard are promising candidates for providing broadband wireless access to mobile users. Due to the flexibility of the physical layer definition based on Orthogonal Frequency Division Multiple Access (OFDMA), it is possible to adjust the networks according to IEEE 802.16e to meet different requirements, e.g., system bandwidth. However, these networks cannot guarantee a reliable transmission in scenarios with frequency reuse of 1 to users at the cell border which achieve only poor Signal to Interference plus Noise Ratio (SINR) conditions due to the high amount of interference from neighbouring cells. Link level simulations provided in this paper show that transmission with a sufficiently low block error probability is achieved for SINR conditions above 4 dB. To improve the SINR conditions at the cell border, a system design is proposed that coordinates the resource allocation among the cells. The available subcarriers shall not be used in an omnidirectional way within the cell, but instead shared among the sectors of a cell that neighbouring sectors do not utilise the same subcarriers and interference can be reduced. System level simulations show that the sector and user throughput can be double with the proposed system design compared to an omnidirectional transmission, although the average amount of allocated radio resource units to each user is equal in both scenarios.

I. INTRODUCTION

Broadband Wireless Access (BWA) systems have gained importance over the last years. Several systems are defined by different standardisation bodies. One promising candidate for BWA is defined by working group 16 of the IEEE 802 LAN/MAN standards committee. The IEEE 802.16 standard [1] is also known as Worldwide Interoperability for Microwave Access (WiMAX) and first products have already come to the market. With networks according to IEEE 802.16, it is possible, e.g., to provide BWA to areas with mostly stationary users which are currently served by wired broadband systems like digital subscriber line.

In 2006, an amendment was finalised which enhances [1] towards user mobility [2]. In case of stationary users, the cells are designed according to a constant user distribution. Often areas between two neighbouring cells are not served due to missing population. This is different in scenarios with mobile users. The network has to provide full coverage and to allow intercell handover. Therefore, neighbouring cells get closer together and aspects like frequency planning get more important.

In [1] several physical layers (PHY) for single carrier, Orthogonal Frequency Division Multiplexing (OFDM) with Time Division Multiple Access (TDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) are defined. The performance of IEEE 802.16 networks is widely investigated, e.g. [3, 4], and problems concerning scenarios with tight frequency reuse are shown in [5, 6] for the OFDM PHY of IEEE 802.16. Those scenarios suffer from a low Signal to Interference plus Noise (SINR) for users at the cell border which therefore, experience a very low throughput. Similar effects are observed in an IEEE 802.16e network with tight frequency reuse utilising Orthogonal Frequency Division Multiple Access (OFDMA) PHY. There is some related work which provides solutions to improve the SINR conditions for Subscriber Stations (SSs) at the cell border. In [7], a new scheduling algorithm is proposed which removes SSs temporally from the scheduling list whenever they have a poor SINR. [8] shows that SINR conditions in a cell and especially at the cell border can be improved if smart antennas and beamforming is used compared to scenario without smart antennas.

The scope of this paper is the design of networks according to IEEE 802.16e OFDMA. The system design of IEEE 802.16e has many degrees of freedom. The subcarrier allocation and frame setup of IEEE 802.16e OFDMA is investigated in this paper. Rules are provided on how to design a network according to IEEE 802.16e so that reliable transmission even at the cell border can be achieved. It is shown that coordination of the subcarrier allocation and the frame setup among the cells improves the SINR conditions at the cell border. A performance comparison is done for single link scenarios showing that a minimum SINR is required to achieve a sufficient low bit error probability. Additionally, different scenarios for subcarrier allocation schemes are investigated showing the influence of the system design on the SINR distribution and on cell and user throughput.

This paper is structured as follows. In section II-A, the different schemes to allocate subcarriers to subchannels in IEEE 802.16e OFDMA are described. Section II-B, provides an overview of the IEEE 802.16e OFDMA frame structure. In section III, rules are described for the system design of networks according to IEEE 802.16e that SINR conditions of SSs at the cell border can be improved compared to a scenario when no coordination is applied among the cells. Section IV gives an overview about the simulation model used for the investigation with description of the performed link and system level simulations. Section V presents the performance results obtained in the investigation. Conclusions are drawn in section VI.

II. IEEE 802.16E SYSTEM MODEL

A. Subcarrier Allocation

In this section, the subcarrier allocation in IEEE 802.16e OFDMA is described. The OFDMA PHY provides a high flexibility, e.g., the FFT size can be adapted on the given system bandwidth conditions [9]. It is possible to use the same subcarrier spacing for different system bandwidth by adapting the FFT size. Furthermore, different schemes for allocation of subcarriers are defined in [2]. During this paper only Downlink (DL) transmission is investigated so that the subcarrier allocation schemes for DL transmission are described briefly in the following. A detailed description of the subcarrier allocation can be found in [2].

In [1], it is distinguished between adjacent and distributed subcarrier allocation. With adjacent subcarrier allocation, subcarriers which are physically neighboured are combined together. A combination of subcarriers in frequency domain is called subchannel in [1]. The adjacent subcarrier allocation requires a fast feedback channel to adapt the resource allocation of the user on the channel conditions. With distributed subcarrier allocation, subcarriers which are combined to one subchannel are distributed over the whole bandwidth. The way how subcarriers are allocated to subchannels is defined in [2] by a permutation formula which depends on the identifier (ID) of the cell. Therefore, the permutation of subcarriers to subchannels is different in cells with different IDs. This leads to frequency diversity and interference averaging effects when using distributed subcarrier allocation. Frequency diversity is achieved due to distribution of subcarriers of one subchannel over the whole system bandwidth. Interference averaging is achieved by using different permutation sequences in neighbouring cells so that each subchannel achieves an average interference from all subchannels in the neighbouring cell [10].

Distributed subcarrier allocation is the default configuration of IEEE 802.16 networks and is used in scenarios when limited channel knowledge is available at the sender or adaptive resource allocation is not possible, e.g., due to high user velocity. Adjacent subcarrier allocation is used in scenarios when channel knowledge is available at the sender as for instance in multi antenna systems. The scope of this paper is on the distributed subcarrier allocation. In [2], it is distinguished between Partial Usage of Subchannel (PUSC) and Full Usage of Subchannels (FUSC). In FUSC all subcarriers have to be allocated in one cell or sector. PUSC is designed that only a set of the subcarriers can be allocated to one cell or sector depending on the traffic conditions and to reduce interference. In FUSC lower overhead in terms of pilot and guard subcarriers is needed compared to PUSC so that more subcarriers are available for data transmission.

B. Frame Structure

In this section the IEEE 802.16 OFDMA frame structure is described which is very flexible. IEEE 802.16 provides both Frequency Division Duplex (FDD) and Time Division Duplex (TDD). While in FDD DL and Uplink (UL) are transmitted using two different frequency bands, in TDD, the frame is divided into a DL and an UL subframe transmitted in one frequency band. The duration of DL- and UL-subframe is adjustable within the frame duration to adapt to traffic conditions. At the beginning of each frame, each base station (BS) broadcasts control information. The control information consists of a preamble that SSs use, e.g., to synchronise to the BS, and the DL- and UL-Map containing information about the frame setup and the resource allocation. The smallest radio resource unit which can be assigned to one user is called a slot. A slot is limited in frequency and time domain and, e.g., consists of one subchannel and two OFDMA symbols for DL PUSC. The frame is divided into bursts containing several slots which are transmitted using the same Modulation and Coding Scheme (MCS).

Coding and interleaving in IEEE 802.16 is performed over a predefined number of information bits within one burst. The slots containing these bits are called Forward Error Correction (FEC) block in the following. Usually, a Medium Access Control (MAC) Protocol Data Unit (PDU) will contain several FEC blocks. Errors during transmission can be detected on a MAC PDU basis if the optional cyclic redundancy check is used. With BLER_i the FEC Block error probability and i the FEC block index, the error probability for the MAC PDU transmitted using N FEC blocks is calculated by

$$\mathrm{PER} = 1 - \prod_{i=0}^{N} \left(1 - \mathrm{BLER}_i\right). \tag{1}$$

With increasing size of the MAC PDU more FEC blocks are needed and therefore, the MAC PDU error probability also increases when a constant FEC block error probability and an increasing MAC PDU size are assumed.

III. System Design for Scenarios with Tight Frequency Reuse

Networks according to IEEE 802.16e also face problems in scenarios with tight frequency reuse. SSs at the cell border receive an interference power which is in the order or higher than the desired signal power so that SINR conditions below 0dB are achieved. Due to varying channel conditions it is possible to achieve better SINR conditions during transmission but most of the time no reliable transmission is possible. There are different possibilities on how to design a network according to IEEE 802.16 and some constraints are able to improve the quality of transmission in scenarios with tight frequency reuse. These constraints are described in this section.

In case of unsynchronised networks and TDD, it is possible that one cell is in UL and a neighbouring cell is in DL at the same time. This can be avoided if FDD is used or if in TDD the frame duration as well as the duration of UL and DL subframe are equal and synchronised among all cells. In this case all cells will be, e.g., in DL at the same time. However, if all subcarriers are used in all cells, SS at the cell border achieve an SINR below 0dB and a reliable transmission is not possible.

In PUSC as described in section II-A, it is possible to allocate only a set of subcarriers to each cell. Therefore, the available subcarriers are divided into up to 6 groups. For allocating the subcarriers to subchannels, the subcarriers from each group are considered separately. However, the subcarriers containing to one subchannel are still distributed over the whole system bandwidth. This leads to a subcarrier allocation where subchannels from group i do not have any common subcarriers with subchannels from group j, with $i \neq j$. Each group is allocated individually. It is possible to allocate the groups depending on the amount of data which has to be transmitted. If neighbouring cells utilise the same group at the same time in a synchronised network, the subcarriers of this group will interfere each other and at the cell border these subcarriers achieve an average SINR of around 0dB. However, if the allocation of the groups can be coordinated among all cells, it is possible to allocate 2 out of the 6 groups to one cell so that neighbouring cells do not interfere with each other. This is called Coordinated Synchronous Configuration in [1] and is a special usage of the PUSC mode.

IV. Simulation Model

Throughout this paper, a system according to IEEE 802.16e specification is assumed [2]. The FFT size is 1024. The main system parameters are given in Table 1. The network design is chosen to improve the reliability of the transmission at the cell border in scenarios with tight frequency reuse. Therefore, a synchronised network in TDD and the default PUSC mode is assumed. The frame structure is built according to IEEE 802.16e specification. All BSs are synchronised and 70% of the frame duration is used for the DL subframe. Therefore, there is no interference between DL and UL although TDD is assumed. On average three OFDMA symbols at the beginning of each frame are assumed to be used for control information including preamble, DL- and UL-map. The UL is not considered during the evaluation.

Table 1: System model parameters.

Parameter	**Value**
Site-to-site distance	1000 m
Available bandwidth	10 MHz
Centre frequency	2.3 GHz
Propagation Model	Okumura-Hata
Slow fading standard deviation	8 dB, lognormally distributed
Channel profile	ITU Vehicular A
BS transmit power	23 dBm
BS antenna	17 dBi, 70° 3dB bandwidth, 35 dB front-to-back ratio for sector cell, 0 dBi for omnicell,
BS antenna height	30 m above ground
SS antenna	omni, 0 dBi, 1.5 m above ground
SS distribution	uniform, random positioning, on average 20 users per cell
SS velocity	0.1 km/h
OFDMA symbol duration	95.2 μs
Frame duration	5 ms (70 % for DL subframe)
Scheduling	Fair Resource
Traffic model	Full buffer

The analysis is done with the OFDMA based Networks Performance Simulator (ONe-PS) [11]. The analysis model contains a hexagonal cell grid with at least two tiers of interfering cells. A wrap around model is applied to avoid border effects when calculating interference [12]. Snapshot simulations of 1000 frames are made considering a frequency selective Vehicular A channel profile. New user positions are considered for each snapshot within which pathloss and slow fading are assumed to be constant.

A Full Buffer traffic model (FB) is assumed so that each user has always data to transmit. No Quality of Service requirement is considered. It was shown in [13] that FB leads to too optimistic results but this is an upper bound for a fully loaded system. If at least one user is assigned to a BS, all resources of the BS will be used and the BS will transmit with maximum power.

An interference limited system is considered, i.e., additive noise has no dominant influence on the SINR of the users. Fig. 1 shows bit error probability results from link level simulations with additive white Gaussian noise (AWGN) channel for all MCS. Convolutional coding and interleaving is assumed as specified in [2]. The receiver contains a Viterbi-algorithm with soft input and hard output [14]. It is assumed that an FEC block is decoded correctly as long as all bits contained in the FEC block are decoded correctly. The FEC block error probability from link level simulations are mapped to ONe-PS by effective SNR mapping as described in [4]. The effective SNR mapping requires AWGN in the link level while fast fading is considered on system level.

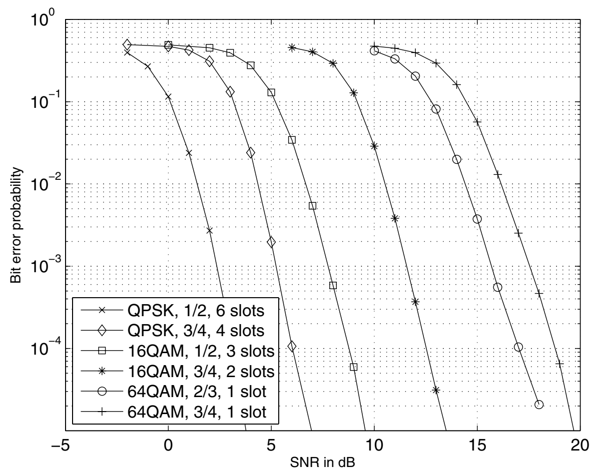

Figure 1: Bit error probability for AWGN channel.

V. Simulation Results

In the following, the results of two different scenarios are presented. In the first scenario, an omnidirectional antenna pattern is used and all resources are utilised in each cell. This is termed Scenario I in the following. The second scenario contains a sectorised cell grid. Each cell consists of three sectors. One third of the available bandwidth is allocated to each sector as explained in section III. This is termed Scenario II in the following. The allocation of subchannels to each sector is performed so that neighbouring sectors do not utilise the same set of subchannels. A frequency reuse of 3 is achieved. In both scenarios, each BS has on average the same number of users to serve. Furthermore each users gets on average the same amount of resources allocated.

As seen from Fig. 1, a minimum SINR of about 4 dB is necessary for a bit error probability of less than 10^{-5}. This leads to an FEC block error probability of around 10^{-3} which is required for reliable transmission. A higher probability can be achieved by the optional usage of Convolutional or Block Turbo Codes or Low Density Parity Check Codes which provide a higher performance in low SINR conditions compared to default convolutional codes [15]. Fig. 2 shows the SINR distribution in an IEEE 802.16e network for Scenario I and Scenario II when only pathloss due to distance and slow fading is considered. It can be seen that Scenario I suffers from high interference. Almost 50% of the SS in Scenario I experience an average SINR below 4dB so that a reliable transmission is not possible. In Scenario II, the interference is much lower and an average SINR above 4 dB can be guaranteed for 95% of the SSs.

Fig. 3 shows the distribution of the achievable throughput in the cells and sectors of the system. It can be seen that the throughput achieved in one sector of Scenario II is smaller than in one sector of Scenario I due to the usage of one third of the bandwidth in each sector. If the three sectors of one cell in Scenario II are considered together, the throughput per cell is on average more than twice the throughput per cell in Scenario I where each cell consists only of one sector. The average user throughput is also doubled for Scenario II compared to Scenario I because each user gets on average the same number of resources allocated in FB while the interference is much lower, as shown in Fig. 2. The average values are summarised in Table 2.

Furthermore, it can be seen by Fig. 4 that the fairness is improved among the users in Scenario II compared to Scenario I. While 25% of the user are not able to establish a reliable connection and achieve no throughput in Scenario I, in Scenario II, 90% of the SS achieve a user throughput of more than 90 kbit/s.

In both scenarios, the average number of users per cell is equal and each user gets on average the same amount of slots allocated. Assuming a scenario where the available bandwidth is allocated to each sector and one cell consists of three sectors, each user gets three times slots allocated as in Scenario I and II. However, the SINR conditions are comparable to Scenario I due to the high interference at the cell border. In addition, there are also areas at the borders of the sectors where the users achieve an average SINR below 0 dB. The throughput per sector is almost equal to the sector throughput obtained from Scenario I, which outperformes the sector throughput of Scenario II but also in this scenario the number of users which cannot

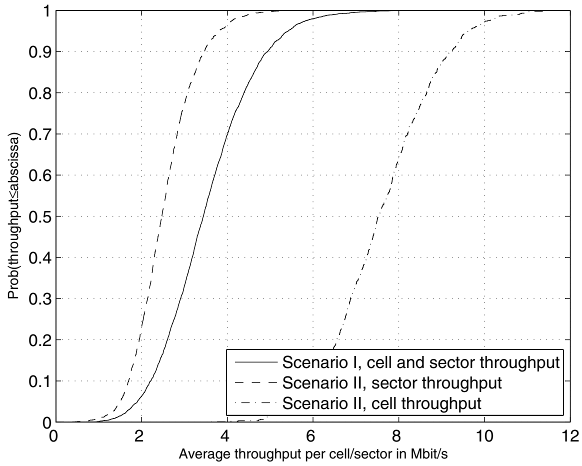

Figure 3: Sector and cell throughput distribution.

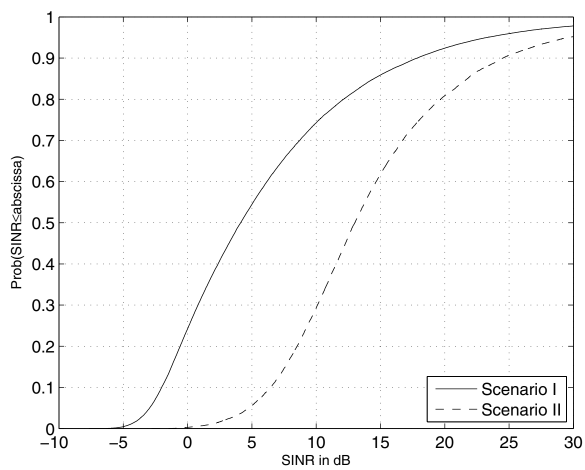

Figure 2: SINR distribution of IEEE 802.16e network.

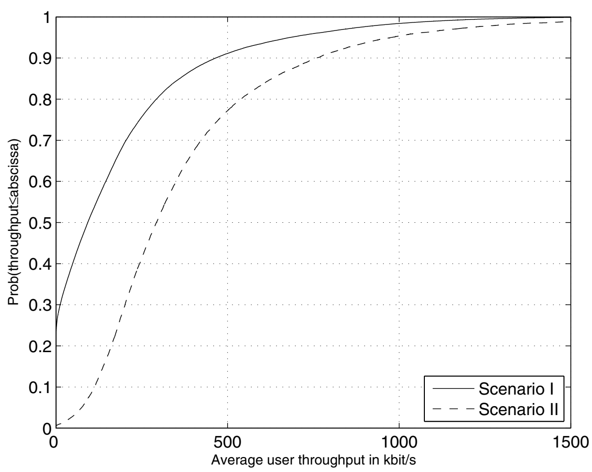

Figure 4: User throughput distribution.

Table 2: Average throughput results.

	Scenario I	Scenario II
Average Sector Throughput	3.2 Mbit/s	2.35 Mbit/s
Average Cell Throughput	3.2 Mbit/s	7.1 Mbit/s
Average User Throughput	160 kbit/s	350 kbit/s

establish a reliable connection remains high.

The results for user and sector throughput obtained for Scenario I can be improved by around 7% when using FUSC instead of PUSC. In FUSC, 768 subcarriers can be utilised for data transmission while in PUSC only 720 subcarriers are used for data transmission. This leads to a performance increase of around 7%. But FUSC can only be used for Scenario I due the allocation of all subcarriers to a sector or cell. Scenario II requires the usage of PUSC as subcarrier allocation scheme. The SINR conditions at the cell border cannot be improved with FUSC compared to PUSC.

Nevertheless the results obtained for FB are not totally comparable to a realistic system with bursty traffic, as for instance web browsing or file download. With FB, a sector is fully loaded as soon as one SS is assigned to the sector. When considering bursty traffic models the probability that a sector is not loaded is higher than with FB. If a sector is not loaded the resources are wasted and should be allocated in another sector of the same BS with higher traffic load. This will increase the interference in the neighbouring sectors due to the usage of common sets of subcarriers in neighbouring sectors. When using reuse partitioning, a predefined set of subcarriers could be assigned to each sector in reuse 3 to serve mainly users at the cell border. A variable set of subcarriers can be adjusted among the sectors based on load conditions to serve users close to the BS which have high SINR conditions.

VI. Conclusion

The performance of an IEEE 802.16e compliant network using OFDMA PHY definition is investigated. If a reliable transmission for mobile users even at the cell border shall be guaranteed, some constraints have to be imposed regarding system design. IEEE 802.16 is very vulnerable in tight reuse scenarios when SINR conditions at the cell border are below 0 dB. One possible solution is given by the Coordinated Synchronous Configuration. All cells have to be synchronised regarding frame structure, UL and DL transmission and subcarrier allocation. Then it is possible to share the available bandwidth among the sectors of a cell so that neighbouring sectors do not interfere each other. This scenario has been termed Scenario II. Compared to a scenario when the whole bandwidth is used in the whole cell, termed Scenario I, the interference conditions, especially at the cell border, can be improved. Furthermore, each user gets the same average amount of slots in both scenarios. Therefore the average cell and users throughput in Scenario II are increased by more than a factor of 2 compared to Scenario I. The reliability also is improved in Scenario II compared to Scenario I. While in Scenario I 25% of the users are not able to receive any data, in Scenario II, no users are excluded.

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