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LINK-LEVEL COMPARISON OF IP-OFDMA (MOBILE WIMAX) AND UMTS HSDPA

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ABSTRACT

Mobile WiMAX is currently aiming to become a member of the IMT-2000 family of systems. After this approval succeeds it may be operated in the same frequency bands as the former IMT-2000 systems. This condition raises questions about the differences between those systems, their advantages and their disadvantages.

Within this paper we first make a comparative analysis identifying the similarities and differences with respect to the physical layer coding and modulation chain. By means of link-level simulations this paper tries to identify capacity boundaries using different receiver techniques.

Results show that both systems in the analyzed configuration have similar efficiencies with respect to the theoretical limits if state of the art receivers are used.

I INTRODUCTION

Based on the Orthogonal Frequency Division Multiple Access (OFDMA) mode of 802.16e [1] a system named IP-OFDMA is aiming to become a member of the International Mobile Telecommunications-2000 (IMT-2000) family of mobile communication systems. After IP-OFDMA, also known as Mobile Worldwide Interoperability for Microwave Access (WiMAX), gets approved as a member of the ITU-R M.1457 [2] recommendation it may be used in the same frequency bands as the former IMT-2000 systems. In detail the IMT-2000 extension bands at 2.496 to 2.69 GHz are of interest here. The major difference between IP-OFDMA and the earlier members of the IMT-2000 family is the Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme, which will also be used for the 3GPP Long Term Evolution (LTE) of the Universal Mobile Telecommunications System (UMTS).

In this paper a comparison of the downlink physical layer performance of IP-OFDMA and the High Speed Downlink Packet Access (HSDPA) of UMTS is performed. A link-level simulator which supports both physical layer configurations is used for this task. A neutral an fair comparison is achieved by using the same channel models and similar physical layer configuration and simulation assumptions.

In section II the most important physical layer similarities and differences are explained. Section III gives a short introduction to the simulation tool used for the evaluation. Simulation results for an Additive White Gaussian Noise (AWGN) and two fading channels are presented in section IV. Finally, we conclude the work in section V.

II PHYSICAL LAYER OF HSDPA AND IP-OFDMA

In this section the most important elements of the physical layer transmission chain of both HSDPA and IP-OFDMA are explained.

Because UMTS Frequency Division Duplex (FDD) typically uses a bandwidth of 5 MHz we have chosen the same bandwidth for the IP-OFDMA system. For a 5 MHz configuration IP-OFDMA uses a Fast Fourier Transform (FFT) of size 512 and a sampling frequency of 5.6 MHz as OFDM parameters. A fixed Cyclic Prefix (CP) duration of $1/8$ the OFDM symbol time is prepended to each symbol. In order to not exceed the bandwidth limitation of 5 MHz, guard carriers are introduced at the outer bins of the FFT. The number of guard carriers depends on the transmission direction (uplink/downlink) and on the chosen subcarrier mapping/permutation scheme. In the following we concentrate on the downlink Partial Usage of Subchannels (PUSC) mapping scheme which is mandatory for both 802.16e and IP-OFDMA.

At the left and right side of the FFT 46 and 45 carriers are left unused, respectively. Additionally to those 91 guard carriers the DC subcarrier in the middle of the FFT does not transmit any information. From the remaining 420 subcarriers 60 subcarriers contain pilot symbols which are used for channel estimation. The remaining 360 data subcarriers are used for data transmission to individual users.

Unlike IP-OFDMA, UMTS uses Direct-Sequence Code Division Multiple Access (DS-CDMA) as a multiple access scheme. Here Orthogonal Variable Spreading Factor (OVSF) codes are used to spread the signal to the available spectrum [3]. The frequency at which the chips of the spreading codes, also known as channelization codes, are transmitted is 3.84 MHz. This chip rate of 3.84 Mcps allows to place the UMTS carriers at spectrum blocks of 4.4 to 5 MHz, depending on the operator and country. The High Speed Downlink Shared Channel (HS-DSCH) which is used for comparison in this paper is able to use up to 15 codes of Spreading Factor (SF) 16. The remaining code of SF 16 can not be used because several codes of a higher SF are allocated for signalling and system management [4].

Both systems allow several modulation schemes to be used for the data subcarriers or the chip sequences. These modulation schemes are switched according to the instantaneous channel conditions. The data resources allocated to one mobile are always modulated with one single modulation scheme at one point in time. The available modulation schemes for IP-OFDMA are Quadrature Phase-Shift Keying (QPSK), 16-State Quadrature Amplitude Modulation (16QAM) and 64-State Quadrature Amplitude Modulation (64QAM). UMTS re-

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lease 5 support QPSK and 16QAM. In release 7 of the UMTS specification 64QAM has been added as a modulation scheme for the HSDPA.

Table 1 lists the available number of bits per second for each modulation scheme under the assumption that all data subcarriers or channelization codes, available for data transmission, are used. Because IP-OFDMA is specified for Time Division Duplex (TDD) we also include the uplink OFDM symbols in order to make a fair comparison. According to [5] the ratio of downlink/uplink OFDM symbols may vary between 35/12 and 26/21. Furthermore, we assume that exactly 3 of the available 47 OFDM symbols are used for the preamble (1 OFDM symbol), the Frame Control Header (FCH) and all MAPs (2 OFDM symbols because of PUSC).

Table 1: Available maximum data bits without coding [Mbit/s]

Modulation	HSDPA 1 code	HSDPA 15 codes	IP-OFDMA 1 symbol	(IP-OFDMA) 44 symbols
QPSK	0.48	7.2	0.144	6.336
16QAM	0.96	14.4	0.288	12.672
64QAM	(1.44)	(21.6)	0.432	19.008

Of major importance in a mobile communication system are the coders used for Forward Error Correction (FEC). In UMTS a Turbo Code (TC) of rate $1/3$ with a constraint length of 4 is used [6]. IP-OFDMA requires a Convolutional Code (CC) of rate $1/2$ with a constraint length of 7 and a Convolutional Turbo Code (CTC) of rate $1/3$ with a constraint length of 4 as mandatory FEC codes. In order to further adapt the coding rate to the requirements of the radio channel both systems make use of puncturing of the coded bits. In IP-OFDMA there is, depending on the type of FEC, either a fixed puncturing pattern or a symbol selection formula used to identify punctured and transmitted bits. Both FEC mechanisms lead to the available Modulation Coding Schemes (MCSs) which can be found in table 2.

Table 2: Modulation and coding schemes of IP-OFDMA

Modulation	Code rate
QPSK	$1/2$
QPSK	$3/4$
16QAM	$1/2$
16QAM	$3/4$
64QAM	$1/2$
64QAM	$2/3$
64QAM	$3/4$
64QAM	$5/6$

In HSDPA the Base Station (BS) has more flexibility to select an Adaptive Modulation and Coding (AMC) scheme. In addition to the modulation schemes the number of codes can be varied between 1 and 15. Furthermore, a large set of effective coding rates are possible due to the Rate Matching (RM) algorithm which maps an arbitrary number of bits from the TC onto the available bits specified by the modulation scheme and number of codes. These coding rates vary between 0.17 (repetition of bits) and 0.89 (puncturing of bits). In order to simplify this study we limit the number of schemes to those which are used for Channel Quality Indicator (CQI) reporting by the mobile (Table 3) [7]. The complete set of possible Transport Block (TB) sizes can be found in [8].

Table 3: CQI table for category 10 and category 14 (release 7)

CQI	Modulation	Codes	TB size	Code rate
0	NA	0	0	0
1	QPSK	1	137	0.168
2	QPSK	1	173	0.205
3	QPSK	1	233	0.268
4	QPSK	1	317	0.355
5	QPSK	1	377	0.417
6	QPSK	1	461	0.505
7	QPSK	2	650	0.351
8	QPSK	2	792	0.425
9	QPSK	2	931	0.497
10	QPSK	3	1262	0.447
11	QPSK	3	1483	0.523
12	QPSK	3	1742	0.613
13	QPSK	4	2279	0.600
14	QPSK	4	2583	0.679
15	QPSK	5	3319	0.696
16	16QAM	5	3565	0.374
17	16QAM	5	4189	0.439
18	16QAM	5	4664	0.488
19	16QAM	5	5287	0.553
20	16QAM	5	5887	0.616
21	16QAM	5	6554	0.685
22	16QAM	5	7168	0.749
23	16QAM	7	9719	0.725
24	16QAM	8	11418	0.745
25	16QAM	10	14411	0.752
26	16QAM / 64QAM	12 / 10	17237 / 15761	0.749 / 0.548
27	16QAM / 64QAM	15 / 12	21754 / 21754	0.756 / 0.630
28	16QAM / 64QAM	15 / 13	23370 / 26490	0.812 / 0.708
29	16QAM / 64QAM	15 / 14	24222 / 32257	0.842 / 0.801
30	16QAM / 64QAM	15 / 15	25558 / 38582	0.888 / 0.893

Because transmission errors typically appear in bursts which are harder to correct by the FEC both HSDPA and IP-OFDMA use block interleavers in order to increase the robustness against such errors. In HSDPA a set of one to three block interleavers of 32 rows and 30 columns is used for each physical code. In IP-OFDMA one block interleaver with 16 rows and the required number of columns to interleave all bits from the puncturing unit is used in case of convolutional coding. for CTC setups an interleaving mechanism between the coding and puncturing takes place.

For the 2-dimensional modulation schemes 16QAM and 64QAM both systems include a mechanism to deal with the imperfectly gray-coded symbol constellation. In IP-OFDMA the bit interleaving shuffles the bits of each symbol within an OFDM symbol in order to avoid long runs of lowly reliable bits. In HSDPA the constellation rearrangement is used to modify the bit to symbol mapping for retransmissions cause by the Hybrid ARQ (HARQ).

In HSDPA a Cyclic Redundancy Check (CRC) field of 24 bit is added to every TB received from the Medium Access Control (MAC) layer. In IP-OFDMA a 16 bit CRC field is used in case HARQ is applied. A further optional CRC check exists in the MAC layer for every MAC Protocol Data Unit (PDU).

Especially in fading environments where channel estimation/prediction is more critical the HARQ is very beneficial for the system performance. Both systems can make use of an HARQ mechanism which combines soft information of either identical transmissions (chase combining) or transmissions with differently punctured bits (incremental redundancy). In this paper an ideal channel estimation and perfect link adaptation is assumed for both systems. Hence, HARQ plays a minor role for our results than in reality and is, therefore, out of the scope of this paper.

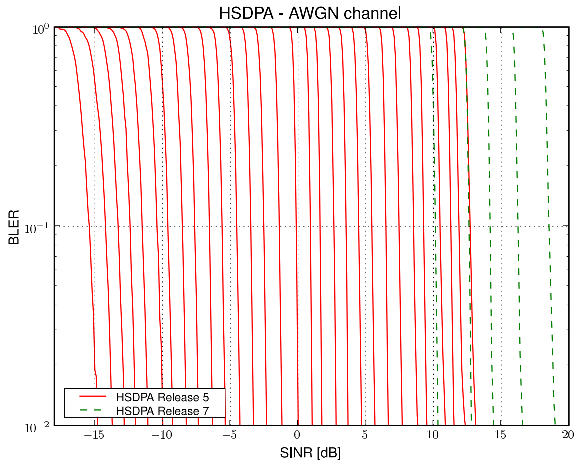

Figure 1: HSDPA BLER mapping for an AWGN channel

III Simulation Model

For the performance evaluation of the physical layer a link level simulator is a useful method. For this paper a link level simulator which contains bit-accurate building blocks of the elements described in the previous section has been used. Wherever possible the same blocks have been used for both transmission chains. In detail these blocks are the traffic source/sink, the modulator/demodulator, the AWGN channel and the Tapped Delay Line (TDL) based International Telecommunication Union (ITU) channels. Presented in this paper are results for the pedestrian model ITU-PA at 3 km/h and vehicular model ITU-VA at 100 km/h. Furthermore, a simple AWGN channel is used for illustration.

Several receiver techniques have been implemented within the link level simulator. For the Code Division Multiple Access (CDMA) system the following receivers are available. A traditional Rake receiver with Maximal Ratio Combining (MRC) of the individual paths. A Zero Forcing (ZF) receiver which tries to completely eliminate Inter Symbol Interference (ISI). A Minimum Mean Square Error (MMSE) receiver which combats the ISI and takes the noise into account. For the reception in the OFDM based system a typical equalization within the frequency domain is made.

IV Simulation Results

The first result in figure 1 illustrates the granularity in which the User Equipment (UE) signals the instantaneous channel condition to the base station. The granularity of these reports is roughly 1dB in release 5. The dotted line represent the 64QAM extension which is added in release 7. The BS may even select MCSs which would result in mappings between the illustrated ones. Noticeable are the mappings in the negative Signal to Interference plus Noise Ratio (SINR) scale which are possible due to the spreading gain and very low coding rates (and throughputs).

The equivalent results for the 8 AMC schemes of the IP-OFDMA system are shown in figure 2. Here no mappings for very low SINR values exist. The difference of the gradients of the curves are caused by the convolutional coder of rate $1/2$. The CTC results in gradients equal to those of the very similar TC of UMTS. Nevertheless, the performance improvement of CTC over the convolutional coding are marginal for short code length [9].

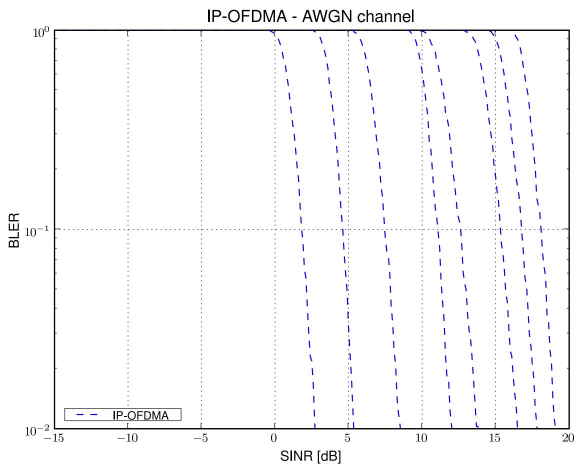

Figure 2: IP-OFDMA BLER mapping for an AWGN channel

In the next step we use those results and calculate the achievable throughput by simply using the best MCS for a given SINR. Depicted in figure 3 are the throughputs for the HSDPA in release 5 and release 7 and the overall throughput achieved with a fully used IP-OFDMA frame (uplink and downlink periods accumulated). Because the variable block sizes affect the achievable throughput both the best case throughput (small blocks) and the worst case throughput (one large convolutionally encoded block) are shown.

Additionally, the theoretical maximum throughput based on

Shannon's formula (0 dB and 3 dB shifted) are included in the figure. This throughput is calculated by

$$C = B \cdot \log_2(1 + \frac{S}{N}) \quad (1)$$

where B is the channel bandwidth in hertz (5 MHz) and $\frac{S}{N}$ is the power ration of the available SINR.

It can be seen that the throughput over SINR on an AWGN channel is up to 4 dB away from the theoretical Shannon limits with a bandwidth of 5 MHz. Because the 5 MHz bandwidth of UMTS includes guard bands and in some countries a carrier spacing smaller than 5 MHz is used the throughput is often compared to a 3.84 MHz bandwidth which corresponds to the 3.84 Mcps of UMTS [10].

In order to really achieve the illustrated throughput an accurate channel measurement and CQI reporting is required. Because the AMC relies on delayed CQI reports the achieved throughput is typically lower [11].

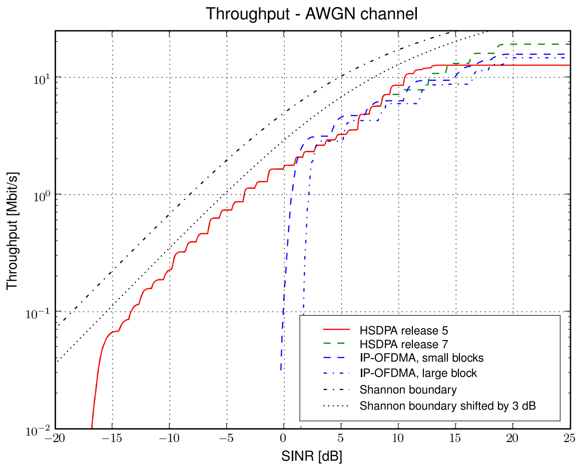

Figure 3: Throughput for AWGN channel

The same figure is now presented for a fading channel with low mobility (figure 4). Again all the curves are very close to each other but the distance to the Shannon boundary grew. This distance could noticeably be reduced by enabling the HARQ feature. In the simulations presented in this paper each block which could not be successfully decoded is thrown away and a Data Link Layer (DLL) retransmission would be required. With HARQ the information which was at the first transmission not completely decodeable improves the second (retransmission) decodeability significantly.

The yellow dashed line in the figure shows the results for a Rake receiver. As already shown in [12] the Rake receiver suffers in fading environments for higher order modulations like 16QAM and 64QAM. Here receivers which try to eliminate the ISI (e.g. MPIC, ZF, MMSE) are superior.

In figure 5 the same setup for a fading channel with a high velocity is shown. At such high velocities the OFDM receiver implemented for this paper performs worse than the MMSE

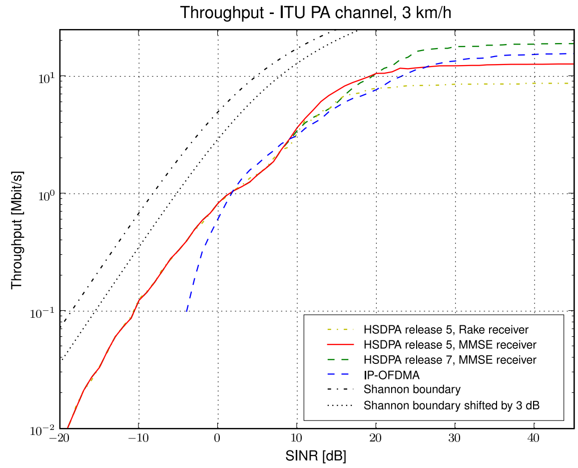

Figure 4: Throughput for ITU PA channel, 3 km/h

receiver of a release 5 UE. Because of the high velocity the channel coefficients change very quickly. The channel estimation and the equalization is only performed one time for each OFDM symbol. Because of the relatively long symbol time caused by the FFT of size 512 the averaging error of the estimated channel increases. The CDMA receiver in our MMSE implementation can update the filter coefficients more frequently based on the reception of the Common Pilot Channel (CPICH) information. For such a receiver the order of the filter significantly influences the performance. For a fading environment as simulated in this scenario a higher filter order improves the throughput for a given SINR significantly as shown for two receiver configurations for UMTS release 7.

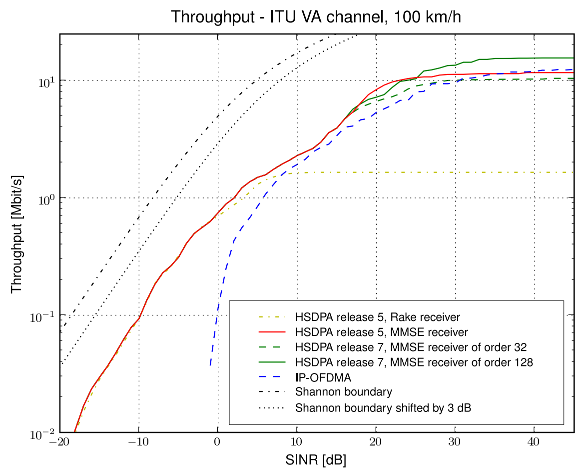

Figure 5: Throughput for ITU VA channel, 100 km/h

V Conclusion

As a conclusion we can summarize that the throughput differences under similar conditions are very small. Depending on the scenario either HSDPA or IP-OFDMA achieved a higher throughput. The receiver which were used within this study showed a greater influence than the system itself. Regarding the throughput in an AWGN environment both systems seem to be close to an economically reasonable bound. It must be mentioned here that the shown throughput results illustrate the maximum theoretical throughput. In a real TDD based IP-OFDMA system only 35 out of the 47 OFDM symbols can be used for the downlink. Furthermore, most UMTS HSDPA mobiles today only support 5 codes [13]. The performance of the link adaptation including measuring of the channel and signalling of the measurements could have a significant impact on the results with perfect link adaptation which were illustrated in this paper. Furthermore, the fading setups including HARQ mechanisms are of interest for performance evaluation of both systems. Last but not least the higher layer performance, especially the scheduling algorithms, could significantly influence the performance of the overall system.

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