MAC Layer Concepts to Support Space Division Multiple Access in OFDM based IEEE 802.16

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***Abstract* — Advanced antenna technologies and algorithms have been developed during the last years. But until today, advanced antenna algorithms in the physical layer and the modes of operation in medium access layers have not been integrated in modern wireless systems. As one of the first standards the metropolitan area network IEEE 802.16 provides means to support smart antenna techniques.**

After a detailed introduction of the medium access control layer this article outlines the support of space division multiple access (SDMA) techniques by the wireless metropolitan area network IEEE 802.16. New concepts are introduced that allow and further optimize the use of SDMA techniques brought by intelligent antennas. First, the possibility to enable SDMA in the IEEE 802.16a-2003 protocol is investigated, and second the support of SDMA in the revised 802.16-2004 standard is elaborated in detail. To overcome current limitations of 802.16a-2003, an enhanced control structure is introduced in 802.16-2004 that masters a concurrent transmission and reception of data to/from several different subscriber stations. The approach facilitates a fully flexible structure which significantly improves system capacity.

Keywords—SDMA, IEEE 802.16, WiMAX, MAC, Beamforming, OFDM, Performance Evaluation

I. Introduction

The wireless metropolitan area networks (MAN) IEEE 802.16-2001 and its amendment for frequencies between 2 and 11GHz IEEE 802.16a-2003 have been standardized until 2003 [1] [2]. It specifies three different physical (PHY) layers, whereof only the orthogonal frequency division multiplex (OFDM) layer is considered here. The revision of the standard has been published in October 2004 as IEEE 802.16-2004 [3]. It includes the MAN base document, the amendment for lower frequencies, i.e., below 11 GHz, and the amendment for the system profiles. From the date of publication the previous volumes are superseded by the new one.

As one of the first standards, IEEE 802.16-2004 includes means to integrate adaptive antenna techniques into the systems. Comparable approaches are currently being standardized by the 3GPP for UMTS or IEEE for 802.11n. These advanced antenna techniques are expected to have a significant impact on the capacity and service quality provided by wireless links and the efficient use of the available spectrum [4]. An initial approach to support space division multiple access techniques in wireless ATM systems has been presented in [5]. The simultaneous transmission of different signals can be accomplished by pre-distortion or beamforming techniques. The concurrent reception of different signals is known as joint detection techniques. In general, the concurrent transmission and reception of data to/from different spatially separated channels is called space division multiple access (SDMA). It provides another degree of freedom to the medium access control (MAC) layer. Besides the ordinary time division multiple access (TDMA) decision which station is allowed to transmit for which duration, the MAC can also schedule more than one station simultaneously.

Following this introduction, a short introduction to smart antenna techniques that are used to allow SDMA is given in section II. The IEEE 802.16a-2003 MAC frame is described in section III. The different downlink (DL) and uplink (UL) transmission phases of the frame are outlined. Section IV details about the enhanced MAC protocol IEEE 802.16-2004. It shows the evolution of the MAC frame structure. Section V introduces the event-driven simulation environment and the scenario description used to gain the simulation results shown in this article. The implemented smart antenna algorithm and the link level interface used by the simulator are outlined. Section VI investigates how the IEEE 802.16a-2003 MAC frame is able to support SDMA. It is figured out that only the DL can transmit data in parallel, but not the UL. This leads to section VII where possible enhancements of the standard 802.16-2004 are introduced and discussed. This enhanced standard enables the MAC frame structure to fully support SDMA techniques. Both sections present performance results that evaluate the different approaches to support SDMA. Finally, section VIII investigates the influence of intra-cell interference on the system capacity. It outlines why intelligent scheduling strategies are necessary.

II. Smart antenna techniques allowing SDMA

If an antenna array is applied at the 802.16 base station (BS), beamforming algorithms allow to focus the transmit power into certain directions to increase the receiver signal-to-noise ratio (SNR). It is also possible to steer nulls into certain directions to decrease co-channel interference. A beam is steered by applying a weight, i.e., a complex number to each antenna element. Thus, a beam is represented by a weight vector w_i which contains one weight per antenna element (see Figure 2). If multiple beams are applied, one weight vector per beam has to be calculated (w_0, w_1, w_{K-1}). Beamforming or pre-equalization maximizes the SNR by focusing the transmitted energy into the desired direction. At the same time it minimizes the emitted energy towards (all) other directions. This

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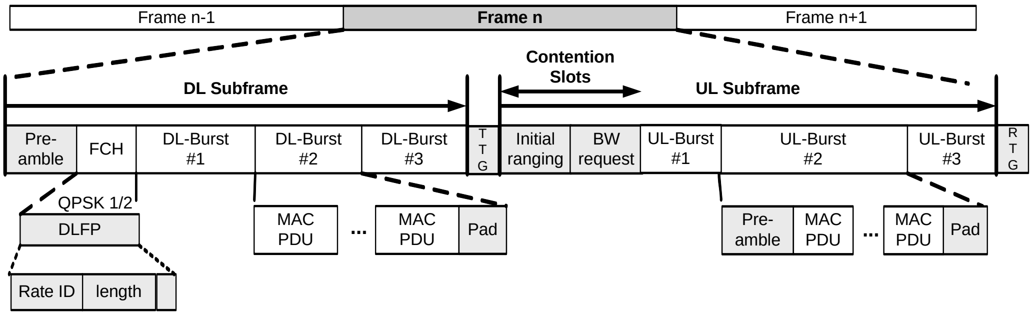

Figure 1: IEEE 802.16a-2003 MAC frame

technique, together with the linear nature of the antenna element, enables an antenna array to transmit a signal into one direction while it transmits another signal at the same time, on the same frequency into another direction. Both receivers do experience a sufficient SNR. Since an antenna is a reciprocal element, the same principle goes for the reception of signals [6]. Here, joint detection techniques allow an antenna array to receive different signals simultaneously. The signals can be separated and the transmitted bit stream can be recovered individually.

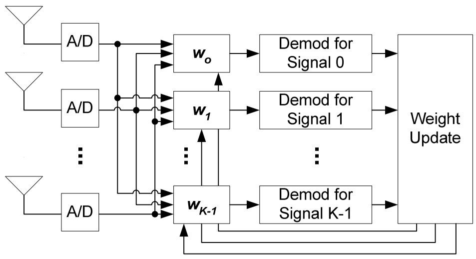

Figure 2: Beamformer for multiple signals

An example is shown in Figure 3. By applying an optimized antenna pattern (solid line), a signal can be directed to user 1, and a null can be placed in the direction of user 2, assuming the different users can be separated well enough by the applied algorithm.

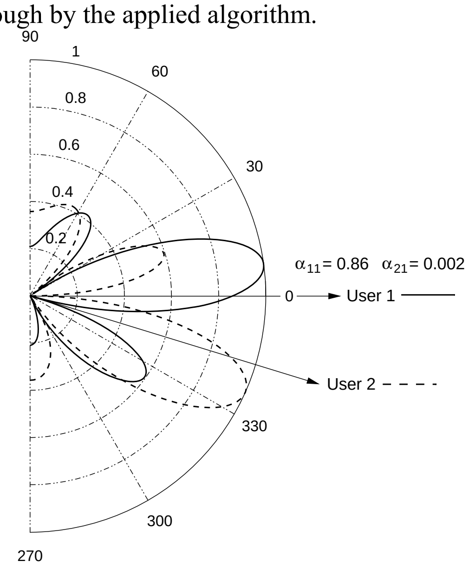

Figure 3: Two optimized beam patterns and corresponding amplitude factors (α)

At the same time, on the same frequency a different signal can be sent through a different optimized antenna pattern (dotted line) which is directed to user 2 and has a null steered to user 1. The resulting amplitude factors α_{11} and α_{21} pointing at user 1 are shown in Figure 3 where four antenna elements are utilized in a two-user scenario. Similarly more users can be served simultaneously without significant interactions. This principle can be applied in downlink as well as in uplink.

III. IEEE 802.16A-2003 MAC FRAME

The IEEE 802.16 MAC layer relies on a frame-based transmission, in which the MAC frame has a variable length. Operating in time division duplex (TDD) mode, each frame consists of a DL- and an UL subframe, with the DL subframe always preceding the UL subframe (refer to Figure 1). Each subframe itself is composed of one or several bursts. The bursts contain the MAC packet data units (PDU). A DL subframe starts with a long preamble (2 OFDM symbols) used for synchronization. The following frame control header (FCH) contains the DL frame prefix (DLFP) to specify the modulation/coding (PHY mode given in field "Rate ID") and length of the DL burst 1. DL burst 1 contains the broadcast MAC control messages: the DL-MAP defines the access to the DL channel, and the UL-MAP allocates access to the UL channel. Among others the MAPs contain one information element (IE) for each burst of the frame. Each IE in the DL-MAP specifies a DL burst and an IE in the UL-MAP specifies one UL transmission burst. The last IE of each MAP indicates the end of the MAP and refers to the end of the subframe. In both MAPs the very last IE is empty and indicates the end of the subframe.

The DL-MAP IE is made up of only two values, the start time and the PHY mode. Thus, all subscriber stations (SS) have to start decoding the DL burst at the specified start time. The information to which connection (respectively station) the received MAC PDU belongs can be taken from the MAC header of the particular PDU. When the start time of the next DL burst is reached, the receiver switches to the PHY mode specified in the corresponding DL-MAP IE and starts again to decode all MAC PDUs. This means the burst duration is implicitly given by subtracting the burst start time from the start time of the following burst. This calculation is based on a sequential nature of bursts.

In contrast to the DL-MAP IE, the UL-MAP IE is made up of three elements: (1) a unique address of the station which is scheduled for the particular UL burst, (2) the PHY mode to be used and (3) the duration of the UL burst. Thus the SSs, which have been scheduled to transmit data in the UL direction, know the duration and the PHY mode of their

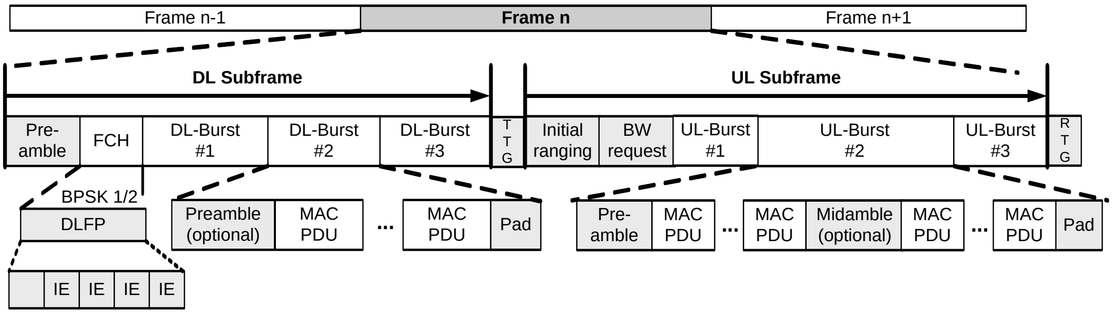

Figure 4: IEEE 802.16-2004 MAC frame

UL bursts. The start time is simply the addition of all durations of the preceding UL transmission bursts.

Following DL burst 1 other DL bursts containing data are transmitted. The UL subframe consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple UL transmission bursts for data, each transmitted from a different SS. Each UL transmission burst starts with a short preamble (1 OFDM symbol). A more detailed description of the MAC layer and an analytical performance evaluation as well as simulation results were presented in [1] [2] and [7].

IV. IEEE 802.16-2004 MAC FRAME

There were several changes introduced to the standard during the revision process. This chapter will focus on the ones that are relevant for the support of smart antenna techniques to support SDMA.

In order to extend the system range the robust modulation BPSK in conjunction with a code rate ½ has been introduced. This new PHY mode is mandatory for basic control elements.

As shown in Figure 4, the DLFP transmitted in the FCH has been expanded. Instead of specifying only the very first DL burst 1, the DLFP now contains up to four IE which can specify up to four DL bursts. If the DL subframe is made up of more than four bursts, the DL-MAP specifies the remaining ones. If there are less bursts present, the DLFP is sufficient and no DL-MAP has to be transmitted. The DLFP IE contains the start time and the PHY mode. It can additionally inform about the optional preamble at the beginning of the DL burst. Controlling the DL subframe in SDMA mode, the DLFP does not differ from the DL-MAP of the former standard and thus does not benefit.

The new DL MAP IE includes the connection identifier (CID) of the addressee of the burst. If the DL burst contains PDUs for several SSs, the CID is set to the broadcast CID. All SSs will decode such a burst. If all PDUs belong to only one SS, the burst is addressed to it. No other SS has to decode it. The basic DL-MAP IE still contains the start time only and no burst duration. But the IE might be extended to contain the duration. Therefore the special "DL-MAP concurrent transmission IE format" is used. Having the start time and the duration allows the BS to flexibly arrange concurrent DL bursts in SDMA mode. The explicit indication of the duration overcomes the restriction of the implicitly given burst duration. Like it has been mentioned above, a short preamble might be appended to the DL burst additionally to the long preamble at the beginning of the DL subframe. This short preamble is used by the SSs for channel estimation and synchronization purposes. This optional preamble is extremely useful in SDMA mode since the antenna pattern of the BS's transmit antenna array is adapted for each DL burst individually.

The new UL MAP IE has been enhanced to include the burst's start time. Beside the duration and the CID, the start time of the burst enables the BS to schedule the UL burst in a parallel way. By giving the start time explicitly, it does not need to be calculated. Thus the UL subframe does not rely on a sequential structure. It can now be signalled that SSs transmit simultaneously separated in space. Additional to the mandatory preambles appended to each UL burst, midambles might be included in the UL burst on a periodic basis. The use of midambles is indicated by the UL-MAP IE. Together with the UL preamble the midambles allow for an advanced joint detection of SSs by the BS during the UL subframe.

In order to differentiate between simultaneously transmitted preambles they might be cyclically shifted in DL as well as in UL direction. In DL the BS generates each preamble individually for each SS by means of a cyclic shift. The simultaneous synchronization and channel estimation at the SS side is improved. In UL the SSs generate the preambles and the midambles under consideration of a cyclic shift in order to improve the capability of the BS to jointly detect simultaneous bursts of different SS.

V. SIMULATION ENVIRONMENT

A software-based simulator with a prototypical implementation of the IEEE 802.16 protocol has been developed at RWTH Aachen University, Chair of Communication Networks. The protocol stack is specified formally with the Specification and Description Language (SDL) and is translated to C++ by means of a code generator. The structure of the stochastic, event-driven simulator is shown in Figure 5.

The protocol stacks of the SS and the BS are implemented. The stack is composed of the convergence layer (CL), the MAC and the PHY layer. Stochastic traffic models generate a well defined traffic load according to characteristic applications such as MPEG, Ethernet or constant bit rate (CBR). Control blocks manage the simulation, configure the scenarios and evaluate the transmitted packets.

A physical channel transmits the bursts between the SSs and the BS. Based on the path loss of the carrier, the interference introduced by other stations and the receiver noise, the channel calculates the signal to interference plus noise ratio (SINR) for the particular packet. The SINR is mapped to the corresponding error ratio look up table.

These tables introduce the specific behavior of the PHY layer and the wireless channel. The look-up tables are generated by a sophisticated link layer simulation chain, which has been developed during the IST-STRIKE project [8], [9].

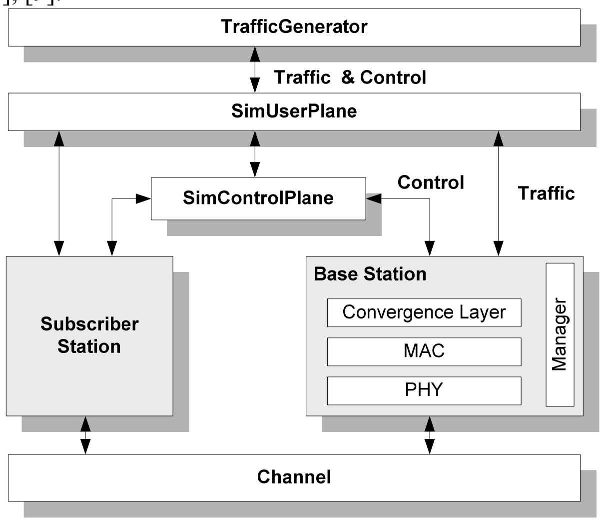

Figure 5: Structure of SDL-based simulator

The link layer simulation chain models the behavior of transmitters and receivers of 802.16 systems. It implements all relevant transmit and receive blocks such as randomizer, coder, interleaver etc. Beside the transceivers the simulation chain models realistic channel characteristics by means of MIMO channel models proposed for broadband fixed wireless applications, i.e., Stanford University Interim (SUI) models [3].

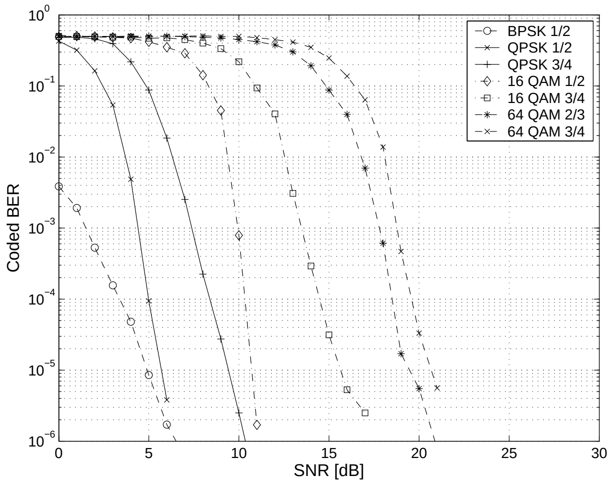

Figure 6: Coded bit error ratio vs. SNR

Figure 6 plots the coded bit error ratio (BER) versus the SNR. The results have been obtained with the simulation chain by using an additive white Gaussian noise (AWGN) channel. Since the payload length in 802.16 systems is not fixed the resulting packet error ratio has to be individually calculated based on smaller units like bit, byte, or OFDM symbols. Due to the concatenated Reed-Solomon and convolutional channel coders the occurrence of bit errors is correlated over time. Using SUI channel models instead of AWGN the frequency-selective fading introduces even more burst errors. Simulations have shown that errors of OFDM symbols are not correlated and thus they are used as the interface to the protocol simulator. The resulting packet error ratio of a PDU (p_{PDU}) which is N_{OFDM} OFDM symbols long can be calculated to

$$p_{PDU} = 1 - (1 - p_{OFDM})^{N_{OFDM}}$$

p_{OFDM} is the OFDM symbol error ratio. The OFDM error ratio is calculated by the link layer simulation chain and it is shown in Figure 7.

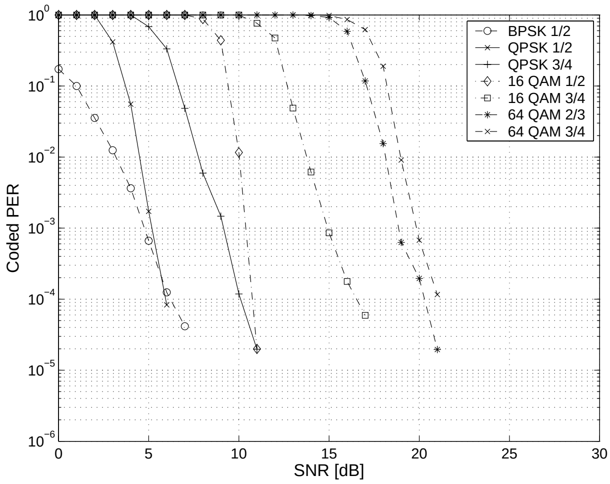

Figure 7: OFDM error ratio vs. SNR

The simulator is used to evaluate the support of SDMA by different MAC layer concepts within the IEEE 802.16 standards. In order to model antenna characteristics of the antenna array at the BS a beamforming algorithm is implemented. The chosen algorithm is an optimal beamformer such that it does not only steer nulls to interfering stations but it also maximises the SINR at the required station [6]. For an unconstrained array, the weights that optimize the SINR are

$$\hat{\vec{w}} = \mu_0 R_N^{-1} \vec{s}_0$$

R_N is the noise-only array correlation matrix and does not contain any signal from the look direction. For an array constrained to have a unit response in the look direction, the constant μ_0 becomes

$$\mu_0 = \frac{1}{\vec{s}_0^H R_N^{-1} \vec{s}_0}$$

This is also known as the maximum likelihood (ML) filter, as it finds the ML estimate of the power of the signal source, assuming all sources as interferences. If the noise-alone matrix is not available, the total array correlation matrix R (signal plus noise) can be used instead. In the absence of errors, the processor performs identically in both cases. The weights are then

$$\hat{\vec{w}} = \frac{R^{-1}\vec{s}_0}{\vec{s}_0^H R^{-1} \vec{s}_0}$$

These weights solve the following optimization problem:

$$\begin{aligned} &\text{minimize} && \vec{w}^H R \vec{w} \\ &\text{subject to} && \vec{w}^H \vec{s}_0 = 1 \end{aligned}$$

Thus, the processor weights are selected by minimizing the mean output power of the processor while maintaining unity response in the look direction. The constraint ensures that the signal passes through the processor undistorted. The minimization process minimizes the total noise, including interferences and uncorrelated noise. Minimizing the total output noise while keeping the output signal constant equals the maximisation of the output SNR.

The processor that calculates these weights is referred to as the optimal processor. The output SINR α of the processor is given by

$$\hat{\alpha} = p_s \bar{s}_0^H R_N^{-1} \bar{s}_0 .$$

The estimated SINR values calculated by the beamforming algorithms might be used by the smart scheduling algorithm to find an optimal DL- and UL schedule. Therefore the estimated SINRs have to be communicated from the beamformer located in the physical layer to the scheduler located in the MAC layer. An interface to exchange the necessary information across both adjacent layers is to be defined.

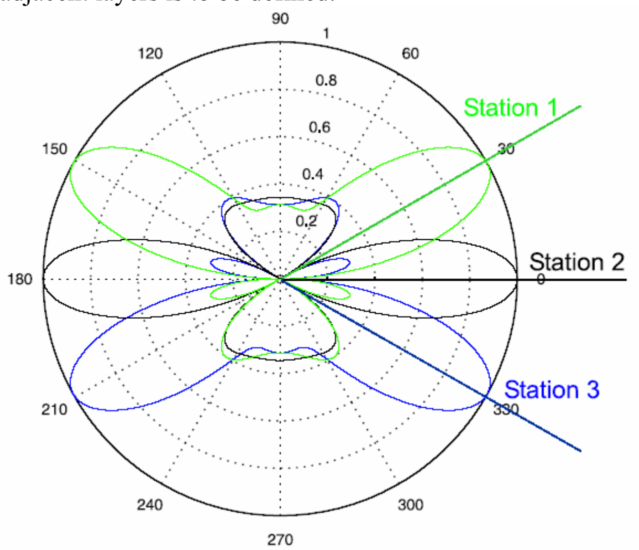

Figure 8: Three beam patterns of a 4-element ULA

Figure 8 shows three example beam patterns calculated by the optimal beamformer. The patterns are calculated assuming a uniform linear array (ULA) with four antenna elements deployed along the y-axis. Having four degrees of freedom allows placing the maxima of the transmitted power towards the desired direction and suppressing the signal towards the direction of the other stations. Figure 8 illustrates an overlay of three antenna patterns, each one optimized for the corresponding station. Note that an ULA is symmetric to the axis of its deployment.

For the beamformer to operate as described above and to maximize the SINR by cancelling interferences, the number of interferers must be less than or equal to *L-2*, as an array of *L* elements has *L-1* degrees of freedom (free parameters, possibilities to place nulls or maxima). One free parameter has been utilized by the constraint in the look direction. In the presence of multipath propagation the look direction occupies more than one parameter and the beamformer might not be able to achieve the maximum output SINR by suppressing every source of interference perfectly.

The presented optimal beamforming algorithm produces results similar to the Minimum Mean Squared Error (MMSE) algorithm. The MMSE is successfully used to jointly detect stations in UL direction that are simultaneously transmitting. Thus, the simulator uses the optimal beamforming algorithm to model beamforming in DL as well as joint-detection in UL. The look direction is the direction of arrival (DoA) and the direction of departure (DoD), respectively. In the simulation the location of the stations and therewith the DoA and DoD is assumed to be perfectly known.

An exemplary system with 20 MHz bandwidth operating in TDD mode is evaluated. The frame length is set to 10 ms and a cyclic prefix of ¼ is chosen. The payload was assumed to be Ethernet traffic with a fixed packet size of 1518 byte. First, simulation results have been obtained without transmission errors, so that they can be seen as an upper limit of the MAC capacity. Secondly the consideration of transmission errors shows the influence of intra-cell interference. This interference is introduced by pre-distortion techniques in DL or joint-detection in UL. Several beams configured by the antenna array do influence each other due to imperfections of the applied algorithms and the channel propagation. The signal power towards simultaneously receiving/transmitting stations, i.e., interference cannot be entirely cancelled.

The simulation scenario supports multiple SSs with different modulation schemes. In order to decide the number of SSs per modulation / coding scheme, the surface area of each modulation scheme has been considered. Therefore the maximal distance between BS and SSs depending on the modulation schemes must be known. This distance can calculated by means of the minimum SNR a SS should receive to avoid data loss. References [2] and [3] propose switching points between modulation schemes depending on receiver SNR. With the maximal SNR, the maximal distance a SS should have from its BS can be calculated. In a real system the noise depends on the used bandwidth of the system and on the temperature of the receiver. The noise N can be calculated by the formula [10]:

$$N = f_\Delta \frac{4.0\, pW}{GHz}$$

f_Δ is the bandwidth of the system. The outcome of N is $8 * 10^{-14}$ Watt = -100.97 dBm. According to [11] the path loss between transmitter and receiver in a free space without any obstacle interfering the radio wave can be calculated by:

$$L_F\,[dB] = 20 * \log_{10} \frac{4\pi d}{\lambda}$$

The receiver SNR can be found with:

$$P_r\,[dBm] = P_t\,[dBm] - L_F\,[dB]$$

$$SNR\,[dB] = P_r\,[dBm] - N\,[dBm]$$

With all equations above the distance between BS and SS in dependence on the BS's transmit power and the noise can be calculated:

$$d = \frac{\lambda * 10^{\frac{P_t\,[dBm] - SNR\,[dB] - N\,[dBm]}{20}}}{4\pi}$$

It is assumed that the system is being operated in the upper 5 GHz band. As an example, this unlicensed band starting at a frequency of 5.47 GHz is restricted to outdoor use in Germany. A BS is assumed to have a transmission power of P_t = 1 W which equals 30 dBm. The calculated SNR and the switching points can be seen in Figure 9.

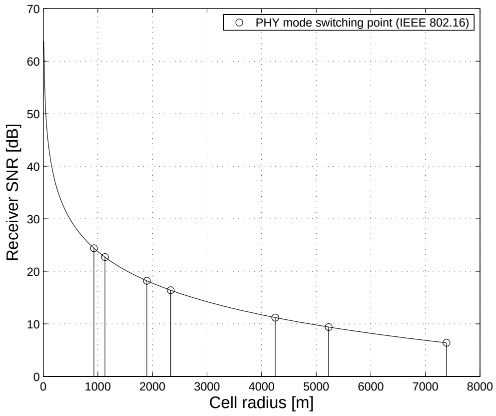

Figure 9: Receiver SNR vs. distance

Each switching point between two different PHY modes results in a certain radius. The radius of the last switching point, i.e., BPSK ½ marks the cell boundary. In this example the cell area has a maximum radius of approximately 7.4 km. The parts of the cell that are covered by specific PHY modes are lying between two concentric circles. The area of the annulus ($F_{Annulus}$) formed by two circles of radii R_1 and R_2 is

$$F_{Annulus} = \pi \cdot \left(R_1^2 - R_2^2\right)$$

The cell boundary in an ideal cellular deployment is a hexagonal cell so that the area belonging to the last mode, i.e., BPSK ½ is not a whole annulus but certain fractions of it are cut. The area covered by BPSK 1/2 can be calculated as

$$F_{BPSK\,1/2} = \frac{3}{2}\sqrt{3}R_{BPSK\,1/2}^2 - \pi R_{QPSK\,1/2}^2$$

The area per PHY mode is a certain fraction of the whole cell area. Note that the distribution of PHY modes in a hexagonal cell neither depends on the frequency band in use nor on the transmission power. In Figure 9 one can easily see that the annulus where the robust PHY modes are in use are represented super proportionately. The sensitive and powerful modes in the inner circles of the cell can not be utilized very often because their range is limited to a small area.

Modulation	Coding Rate	Receiver SNR (dB)	Number of SS
BPSK	1 / 2	6,4	-
QPSK	1 / 2	9,4	3
	3 / 4	11,2	4
16 QAM	1 / 2	16,4	1
	3 / 4	18,2	1
64 QAM	2 / 3	22,7	0
	3 / 4	24,4	0

Table 1: Usage of PHY modes

Assuming a constant density of SSs within the whole cell, the proportion of the annulus of a PHY mode can be converted to a proportion of SSs using this modulation and coding scheme. The example scenario is made up of a total number of 9 active SS per BS. Now the number of SSs using a certain PHY mode can be calculated as the proportion of this mode times the total number of users. The resulting number of SSs corresponding to the percentages of PHY mode utilization is listed in Table 1. IEEE 802.16a-2003 does not support BPSK. SSs that are not able to receive with QPSK ½ would not be considered. To set up comparable scenarios for both standards, BPSK users are not taken into account although they are supported by the new version IEEE 802.16-2004. SSs are located within an angle of 180° as depicted in Figure 10.

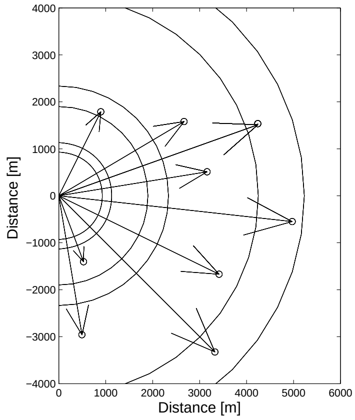

Figure 10: SSs' location within the example scenario

Each SS of the multi-user scenario has a data rate (CBR traffic) of 1/9 of the overall data rate. Having, e.g., an offered data rate of 2 Mbps for each SS (1 Mbps DL, 1 Mbps UL) an overall data rate of 18 Mbps is offered to the system.

VI. IEEE 802.16A-2003 SUPPORT OF SDMA

The BS is assumed to have several receive antennas (antenna array) which allow pre-equalization (beamforming) in DL and joint detection in UL direction. The application of a spatial filter, e.g., MMSE, enables the BS to receive several data streams coming from different directions simultaneously. Having a bi-directional link, which is the case in systems running in TDD mode, the channel state information is known. Thus the BS can send different data streams to different users by means of antenna beams steered to different SSs (or groups of SSs). Since perfect filters are assumed in the following, this work concentrates on the effect of SDMA techniques to the MAC layer. The SSs are assumed to have only one antenna element. They are not capable to use advanced antenna techniques. They always send and receive omni-directionally.

Although the 802.16a MAC frame was originally not designed to support SDMA techniques, Figure 11 illustrates how the standard-compliant MAC frame is able to support SDMA. The antenna characteristics are drawn above the frame. Different characteristics are applied to the BS antenna array for the particular phase and for the corresponding SSs which are served. Inside the DL burst 1 of the MAC frame, the DL- and the UL-MAP is highlighted. The arrows coming out of the MAPs show the timing information which is included in the MAPs, i.e., start time in DL-MAP and burst duration in UL-MAP. Starting with the DL preamble, the first part of the frame is sent omni-directionally. Preamble, FCH and DL burst 1 are broadcast as the antenna pattern above the frame indicates. This is necessary because all SSs need to decode the DL- and especially the UL-MAP. At the beginning of DL burst 2 the antenna characteristic is adapted. The BS is able to determine the antenna weight factors it has to apply to

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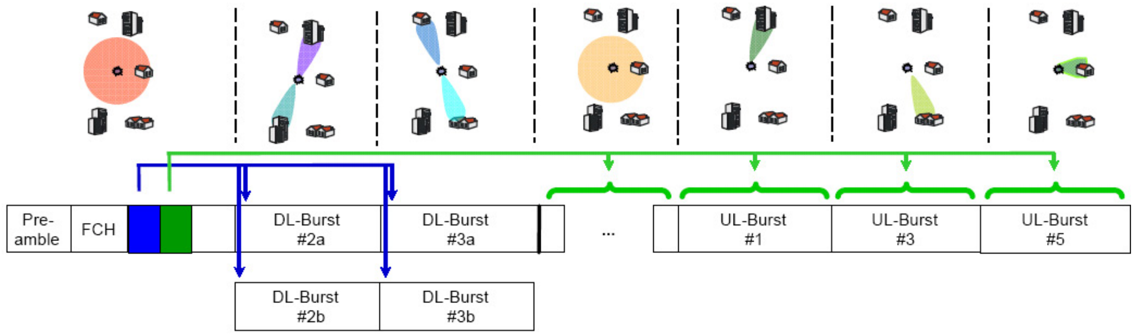

Figure 11: SDMA support of IEEE 802.16a-2003

each antenna element, because it has already received at least the registration (and maybe data) from the corresponding SSs. During this initial reception of the registration message, the spatial filter for pre-equalization could be calculated at the BS. Thus, the BS can send one data stream containing DL burst 2a in the direction of a SS while at the same time the BS can send a different data stream containing DL burst 2b in the direction of another SS. The number of data streams is only limited by the capability of the antenna array to form lobes which sufficiently separate the different signals. The SSs only know the start time and the PHY mode of the burst from the corresponding DL-MAP IE. They will start decoding the received signal at the indicated time. The SS itself is not aware whether it is served in parallel to someone else or not. Thus, the only restriction to the parallel transmission of, e.g., burst 2a and 2b is the same start time and the same PHY mode. Since the start time of the following burst, e.g., burst 3, is also known, the duration of the two bursts is equal. In this way, two different data streams with the same PHY mode can be sent during the same DL burst to different SSs.

After the transmission of DL burst 2 the antenna pattern changes again. Within DL burst 3 other SSs are scheduled by the BS. So the antenna weight factors have to be changed to send data to these SSs. Again the start time and the PHY mode are known by the SSs. The BS sends different data streams, i.e., DL burst 3a and 3b to different SSs simultaneously.

The UL subframe starts with the contention slots for initial ranging and bandwidth request. During this phase the BS antenna array must receive omni-directionally, because the BS does not know which SS is using the contention slots. After the contention slots, dedicated UL transmission bursts are following. As already mentioned, the UL MAP IE only contains the burst duration as time information. The start time is calculated as the addition of all durations of preceding bursts. This behaviour leads to a succession of UL transmission bursts. There is no way to communicate a simultaneous transmission of different SSs. Note that the BS antenna array can be used to increase the receiver SNR by leveraging several antenna elements, e.g., applying maximum ratio combining (MRC). This can increase the quality of only one link, but SDMA techniques are still not applicable.

Hence, the parallel transmission of data to different SSs is only possible in DL direction. Start times, durations and PHY modes of simultaneously transmitted bursts must be equal. In UL direction a parallel reception of different data streams coming from different SSs is not possible with the standard-compliant MAC frame build-up.

Figure 12 shows the overall system throughput gained by means of the simulation environment described in section V. Throughput is plotted with respect to the offered traffic. The IEEE 802.16a-2003 frame type is evaluated. The parameter that is varying within the graph is the maximum number of parallel data streams (DS). In a system with 1 DS only omni-directional transmission is possible, i.e., no SDMA is performed at all. Having at least a two-element antenna array deployed at the BS, two degrees of freedom can be set. Thus, the SNR can be maximized in one direction and a null can be steered in another direction. Doing this twice, i.e., applying two different weight vectors, a maximum of 2 beams can be steered. A maximum of 2 data streams is possible. Having more elements at the BS's antenna array more parallel antenna beams and therewith more simultaneous data streams can be handled.

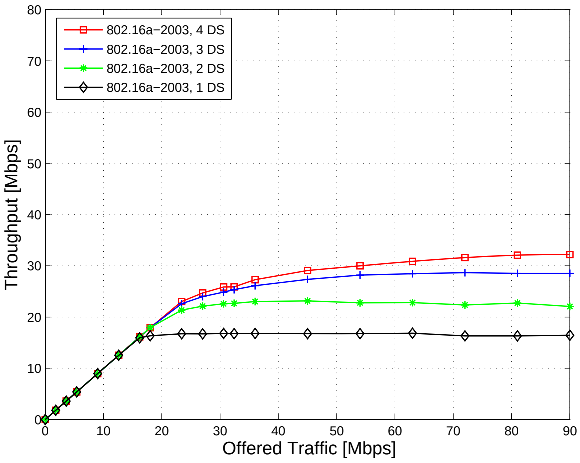

Figure 12: System throughput of IEEE 802.16a-2003

Being in low-load situations, the offered traffic can be carried entirely by the system. But reaching a certain level the system runs into saturation. The MAC frame is totally filled up with PDUs and additional data can not be transmitted but has to be delayed. The maximum throughput of the conventional non-SDMA system (1 DS) is approximately 17 Mbps. This is far below the maximum level of the single 64-QAM ¾ user scenario, i.e., 55 Mbps but it is significantly higher than the 12 Mbps for the single QPSK ½ user scenario [12]. Since the scenario is a mixture of different SSs using different PHY modes, the evaluated

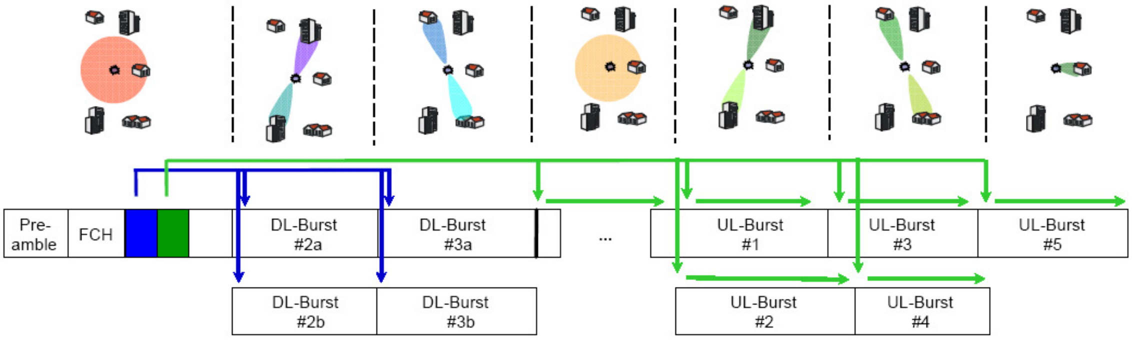

Figure 13: SDMA support of IEEE 802.16-2004 using basic DL MAP IEs

system throughput lies in the middle of those upper and lower bounds.

Having an advanced antenna array deployed at the BS which supports two concurrent data streams, the system throughput increases. The saturation level of the curve representing 2 DS is approximately 22 Mbps. This is an improvement by 30%. In the DL subframe two DL bursts can be transmitted by the BS, provided that the same PHY mode is used.

A maximum of 3 simultaneous data streams further increases the system throughput. The BS has got the possibility to schedule three SSs using the same PHY mode in parallel. In the scenario considered here, this can be done only with the SSs using the PHY modes QPSK ½ and QPSK ¾. All other PHY modes are used by a single SS only (refer to Table 1). Thus, the level of saturation increases by 7 Mbps up to 29 Mbps. Since there is only one PHY mode (QPSK ¾) used by 4 SSs, the upgrade to 4 concurrent data streams increases the system throughput only by 3 Mbps. The resulting throughput of 32 Mbps of a system using 4 DS is nearly twice the capacity of a conventional, omni-directional 802.16 system.

Another approach to enable SDMA in IEEE 802.16a-2003 leverages standard-compliant DL- and UL-MAPs which are transmitted omni-directionally, but whose addresses in the MAC header are not set to the broadcast CID but to the private address of a SS. Thus an SDMA-like frame structure in UL- and in DL direction can be signalled to each SS individually. Since the revision of the standard enhances the MAP IEs, this approach is not being followed in this article. A detailed description can be found in [13].

VII. Enhanced SDMA concepts for IEEE 802.16-2004

The constraint of IEEE 802.16a-2003 standard to support only parallel DL bursts leads to the revised standard where possible enhancements to the MAC frame were included. The enhancement of the control structure, namely extensions to the DL- and UL-MAP IE, has been introduced in chapter III. How they can support the use of SDMA techniques is explained in the following.

A. Use of basic DL MAP IE format

To enable a parallel reception of different data streams at the BS, the UL-MAP IE has been revised. The IE now contains the start time of each UL burst, which overcomes the restriction of the implicit calculation of the start time by adding up all preceding burst durations.

Figure 13 shows the enhanced MAC frame. The control and management elements of the frame, the DL preamble, the FCH and DL burst 1, are still sent omni-directionally as indicated by the antenna pattern above the frame structure. The basic DL-MAP and its IEs still contains the start time only. The duration of the corresponding DL burst has to be calculated based on the start time of the following DL MAP IE. Thus, the restrictions of the DL subframe are still valid.

The UL-MAP included in DL burst 1 is no longer specifying only the duration but also the start time of each UL transmission burst. This is indicated by the arrows above the frame pointing from the UL-MAP to the corresponding UL burst. With the enhanced UL-MAP IE it is possible to let different SSs start their UL transmission bursts at the same time, i.e., parallel data transmission is possible in UL direction. Beside the address of the SS, the UL-MAP IE now contains the start time, the duration and the PHY mode. Thus, the duration of parallel UL transmission bursts and even their PHY modes might be different. In order to allow for a better channel estimation at the receiver of the BS midambles might be included during the UL burst. They occur several times during the burst based on a periodic interval. Thus, there is a short preamble at the beginning of the UL burst and midambles occurring periodically within the UL burst.

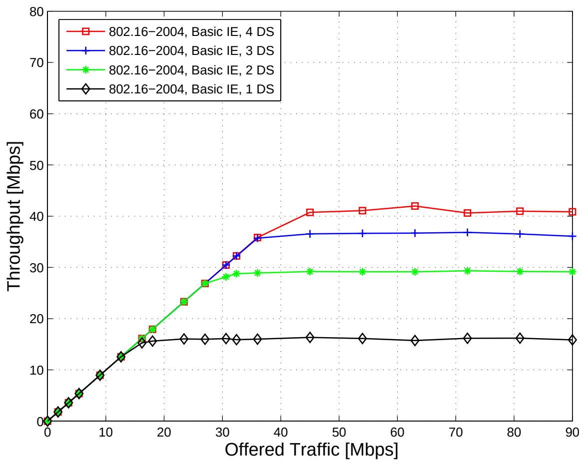

Figure 14: System throughput of IEEE 802.16-2004 using basic DL MAP IEs

The overall system throughput of the scenario is shown in Figure 14. The graph shows the capacity of an IEEE 802.16-2004 system using the basic DL MAP IEs. Again the lowest curve represents the omni-directional case (1 DS). Because this case can be seen as a non-SDMA case, there is nearly no difference between both versions of the standard. Figure 14 shows a maximum system

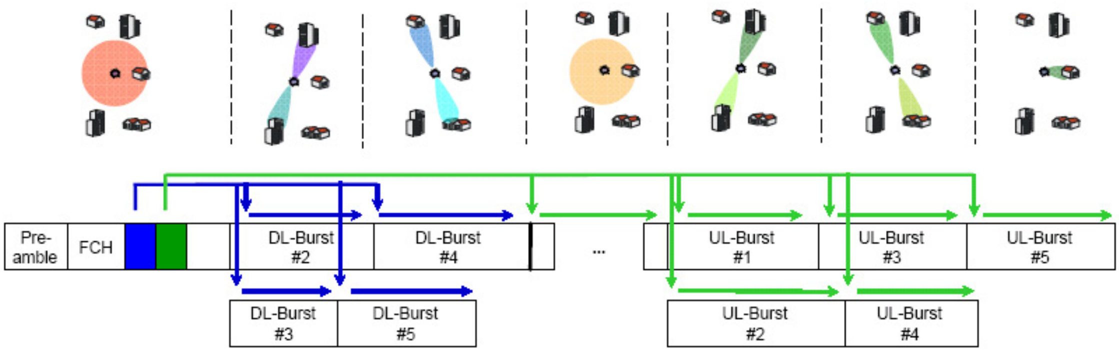

Figure 15: SDMA support of IEEE 802.16-2004 using concurrent transmission DL MAP IEs

throughput for 1 DS of approximately 16.5 Mbps which is the same level as in Figure 12.

Having an intelligent antenna at the BS which supports 2 DS the system throughput increases to 29.5 Mbps. In contrast to the former standard, bursts can not only be transmitted but they can also be received in parallel so that the saturation level is much higher. The scenario benefits a lot from the SDMA capability. The system throughput increases by 78% even if only 2 DS can be applied.

The possibility to support 3 concurrent data streams further increases the system throughput to a saturation level of 37.5 Mbps. Applying the former 802.16a-2003 UL MAP format the impact of a higher number of DS decreased because only equal PHY modes could be scheduled in parallel. With the new 802.16-2004 UL MAP IEs this restriction has been partly overcome. Due to the enhanced IEs, UL bursts can be received simultaneously even if they use different PHY modes. But the DL restriction is still valid. When 4 DS are used the system capacity is increased by a factor of 2.5 referred to the non-SDMA case (1 DS). The level of saturation is close to 42 Mbps.

B. Use of DL MAP concurrent transmission IE format

In order to enable a fully flexible DL transmission with simultaneous bursts, the DL MAP IE has to be extended. The possibility to use the extended "DL-MAP concurrent transmission IE format" has been included during the revision of the standard. The extension allows specifying the duration of the corresponding DL burst explicitly.

The first part of the frame, the DL preamble, the FCH and the burst 1, is again sent omni-directionally. In Figure 15 the enhanced MAC frame can be seen. The DL-MAP included in DL burst 1 is now specifying the start time as well as the addressee, i.e., the CID, of each DL burst. By extending the DL-MAP IE with the IE for concurrent transmission, the burst duration can be specified additionally. This is indicated by the arrows above the frame. Now, the duration of parallel DL bursts and even their PHY modes might be different. In order to allow for a better channel estimation at the SS receiver, short preambles might be included at the beginning of each DL burst. Thus, there is a long preamble at the beginning of the DL subframe and short preambles preceding each DL burst.

Figure 16 shows the overall system throughput of this scenario. The IEEE 802.16-2004 MAC frame using the extended "DL MAP concurrent transmission IE format" is evaluated. The MAC frame has SDMA capability in UL and DL. Like in the previous scenarios the lowest curve with only 1 DS represents the omni-directional case.

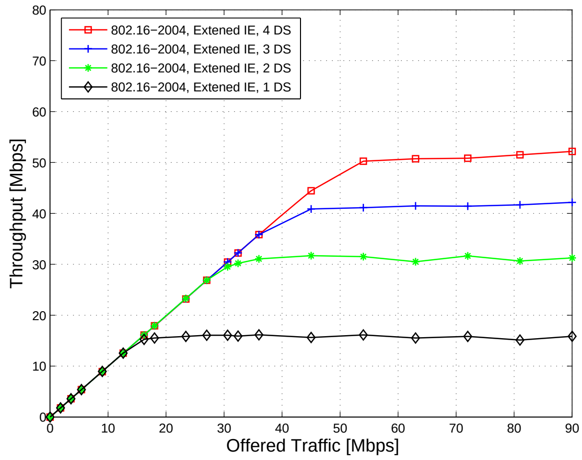

Figure 16: System throughput of IEEE 802.16-2004 using concurrent transmission DL MAP IEs

Having an antenna array at the BS multiple simultaneous data streams might be supported. Supporting 2 DS the throughput increases to approximately 31 Mbps. This is nearly twice the non-SDMA capacity of 16.5 Mbps. Compared to 802.16a-2003 the additional overhead is the larger UL- and DL-MAP and the short preambles which are included at the beginning of each simultaneous DL burst.

The support of 3 concurrent data streams further increases the system throughput to a saturation level of 42 Mbps. Due to the enhanced DL MAP IE, DL bursts can be sent simultaneously even if they use different PHY modes. When 4 DS are used the system capacity increases to 51 Mbps, which is more than 3 times the non-SDMA capacity. The enhanced MAC frame structure allows grouping the scheduled stations in a flexible and efficient manner. No idle times have to be included like in the previous scenario. The resulting SDMA enhanced system capacity scales with the number of parallel data streams

Like it has been outlined in chapter III, there is another possibility to enable smart antenna techniques in the MAN network. This approach makes use of the AAS part of the MAC frame. The AAS part of the frame is dedicated to SSs which have an enhanced pool of MAC functionality to support all AAS requirements. Only these AAS-enabled SS can operate in AAS mode. Since the presented concept to support SDMA only affects the BS, the SS does not need to implement enhanced MAC functions. They do not even notice the SDMA mode of operation. Thus, all IEEE

802.16-2004 compliant SSs fit into the SDMA concept introduced in this article.

VIII. INFLUENCE OF INTRA-CELL INTERFERENCE

Simulation results shown in the previous chapter evaluate the maximum capacity of the IEEE 802.16 MAC layer utilizing smart antenna arrays to operate in SDMA mode. They do not take transmission errors into account. This chapter will outline the effect of intra-cell interference on the system capacity.

The same simulations as in chapter VII have been executed again based on realistic channel conditions: the beamforming algorithm calculates the optimized antenna pattern, the wireless channel models the path loss, and the link level results consider the capability of the PHY layer to decode received PDU under certain channel conditions.

Background and receiver noise as well as inter-cell interference generated by neighbouring stations that are operating in the same frequency bands affect the transmission. Operating in SDMA mode introduces additional interference. Intra-cell interference generated by concurrent transmission and reception of bursts additionally influences the receiver SINR. The reduced signal quality introduces a higher probability of packet errors. Packet errors reduce the system capacity.

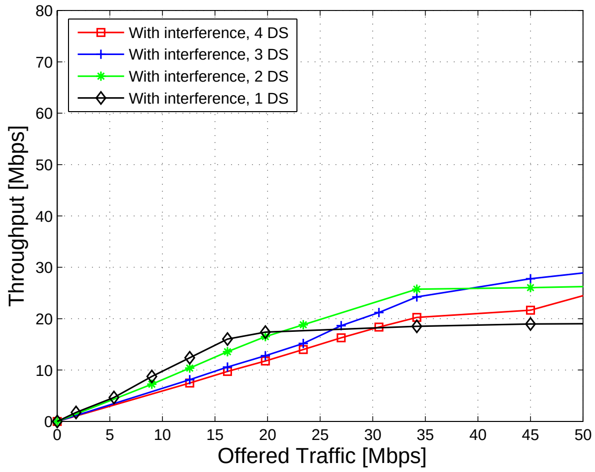

Figure 17: System throughput considering transmission errors

Figure 17 plots the system throughput of the previously considered single cell scenario considering transmission errors. In low-load situations the influence of intra-cell interference degrades the throughput of systems using multiple concurrent data streams. This is due to the implemented scheduling algorithm which always schedules bursts in parallel not taking into account the spatial separability of stations. Even in low load situations bursts are transmitted and received simultaneously. SSs are randomly scheduled in parallel. Thus, even if SSs are co-located and the beamformer cannot sufficiently separate them, they might be scheduled for simultaneous transmission or reception of data.

In high load situations the capacity of systems with multiple data streams exceeds the omni-directional case. The capacity increase of the MAC frame overcomes the decrease due to interference. But the resulting system throughput is far from the potential MAC capacity seen in Figure 16.

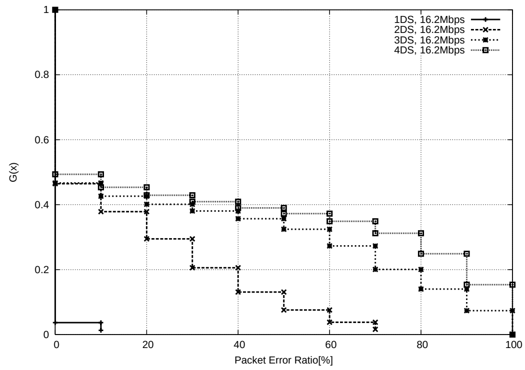

Figure 18: CDF of packet error ratio

Figure 18 shows the complementary cumulative distribution function (CDF) of the packet error ratio. It can be seen that in the omni-directional case nearly no errors occur. The subscriber stations chose their PHY modes based on their receiver SINRs. The PHY modes are sufficiently robust to receive regular bursts. Concurrent transmissions introduce interference which results in packet losses. Having two parallel data streams, only 53 % of all packets are received error-free, i.e. the packet loss ratio equals zero. For the remaining packets loss ratios of up to 70% can be measured. If all four concurrent streams are scheduled, 50 % of the PDUs are received without errors, the rest perceive a loss ratio of up to 100 %.

Smart scheduling strategies are necessary to fully benefit from the capacity of the MAC frame in the presence of interference. The strategy has to take the estimated interference situation into account. It should not schedule stations in parallel that are not sufficiently separable by the beamforming algorithm. Stations interfering each other heavily should be arranged in TDMA mode. The intelligent scheduler needs to acquire information about the current interference situation and about the spatial separability of SSs. Therefore the estimated SINR seems to be a good measure [14]. It can be directly converted into a desired PHY mode and thus into the throughput of the link. Additionally the provided SINR estimates can be used without further knowledge about the exactly applied antenna algorithm.

A. *Max Throughput SDMA Scheduler*

Based on the estimated SINR as scheduling input from the PHY layer a Max Throughput SDMA scheduler is introduced in the following. The scheduler maximizes the throughput of the current MAC frame. It tests all possible combinations of parallel SSs. Having estimated all SINR values of each SS in every combination, the scheduler chooses the combinations that result in the highest system throughput.

Figure 19 plots the throughput of an 802.16 system that utilizes the Max Throughput SDMA scheduler under consideration of transmission errors. It can be seen that the interference-aware scheduler is able to fully exploit the SDMA enhanced MAC capacity. It schedules SSs so that the interference between simultaneous transmissions is minimized. Having reached the saturation of the MAC capability (refer to Figure 16), the scheduler even further increases the throughput. This results from the unfair preference of SSs using higher order PHY modes by the scheduler.

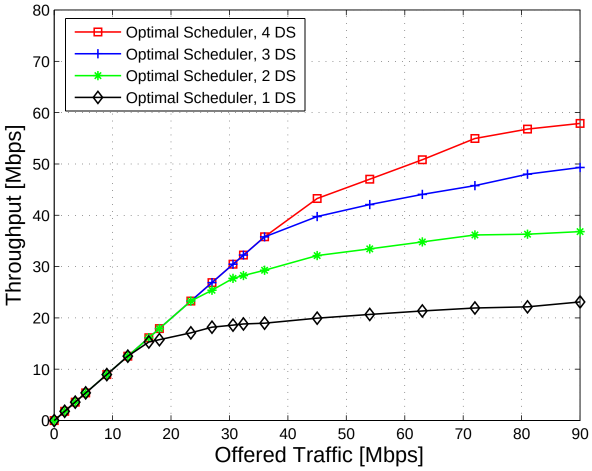

Figure 19: System throughput utilizing the Max Throughput scheduler considering transmission errors

The calculation of an SINR estimate of a single SS within a given combination needs an inversion of the array correlation matrix (refer to chapter V). Since the Max Throughput SDMA scheduler estimates the SINR for every SS of every possible combination, the algorithm becomes rather complex, especially when the number of active SSs in the system increases.

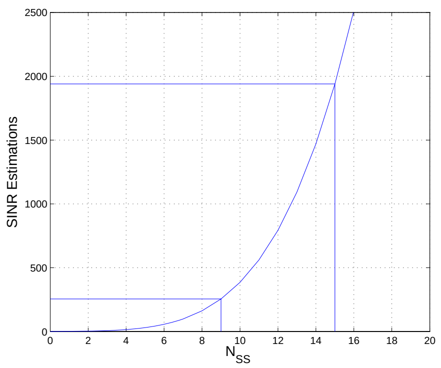

Figure 20: Computational complexity of the Max Throughput SDMA scheduler

Figure 20 shows that the number of necessary SINR estimations is increasing with the faculty of the number of active SSs (N_{SS}). For the example scenario which is composed of 9 SSs 255 SINR estimations are necessary. If the number of active SSs increases, the complexity will no longer be manageable. Within a fixed deployment concept, the characteristics of the wireless channel do not change frequently. Thus, the SINR estimation does not need to be re-calculated every MAC frame and the complexity might be handled by the system. But with the upcoming standard amendment IEEE 802.16e SSs will become mobile [15]. Hence, the propagation conditions vary quickly and the Max Throughput SDMA scheduler might not be applicable at all.

B. Simplified SDMA scheduler

To overcome the computational complexity of the Max Throughput SDMA scheduler, a simplified SDMA scheduler is outlined in this section. The simplified scheduler is not looking for the optimal solution, but for an acceptable one.

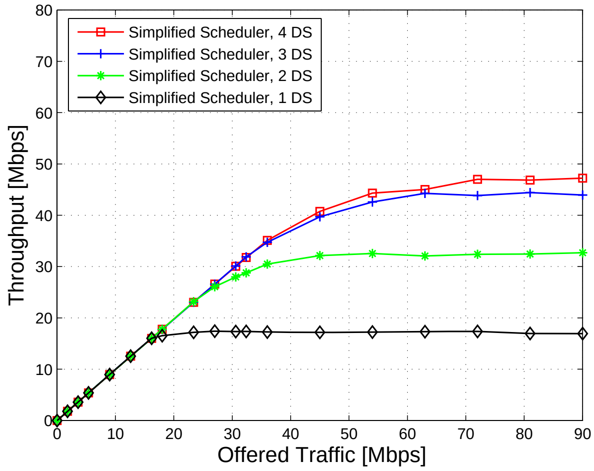

Figure 21: System throughput utilizing the simplified SDMA scheduler considering transmission errors

The scheduler is allocating the first data stream without considering any SDMA specific attribute. If there is still offered traffic left after the first data stream is filled up, the scheduler starts to allocate a second, concurrent data stream. In the second stream, simultaneous bursts are scheduled only if the additional interference does not affect the already scheduled burst, i.e., if the SINR estimation of the already scheduled burst results in an unmodified PHY mode. Otherwise the following burst is tested for concurrent transmission. If, in the end, it is not possible to schedule a particular burst in parallel, it is postponed to the proximate MAC frame.

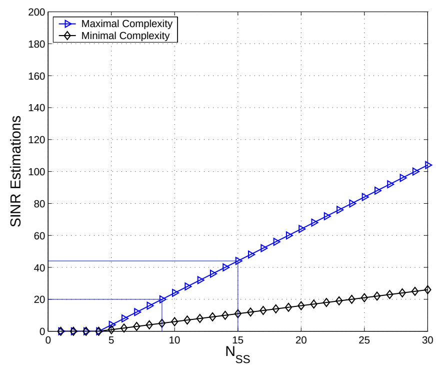

Figure 22: Computational complexity of the simplified SDMA scheduler

Figure 21 shows the throughput of an 802.16 system that utilizes the simplified SDMA scheduler. Taking the omni-directional case (1 DS), the saturation level of the throughput is equal to the one in Figure 19. Having reached the saturation level at 16.5 Mbps, the throughput of the simplified scheduler stays constant due to its fairness. For 2 and 3 parallel data streams, the simplified scheduler is performing similar to the Max Throughput SDMA scheduler. It is able to exploit the SDMA enhanced MAC capacity which is increased by a factor of 2.5 compared to the omni-directional case. If all degrees of freedom given by the 4-element antenna array are leveraged, 4 DS can be supported in parallel. In this case, there is a slight improvement compared to 3 DS, but the simplified scheduler is not able to fully exploit the potential capacity.

The performance of the Max Throughput scheduler cannot be reached.

The number of SINR estimations needed by the simplified scheduler is given in Figure 22. The graphs assume that 4 SS can be scheduled in the first data stream without the need of SINR estimation. The minimum number of estimations is needed when each burst finds a parallel burst right at the beginning. The maximum number is necessary, when the scheduler needs to test all bursts of the first data stream until it finds an appropriate concurrent burst. Thus, the complexity of the algorithm increases only linearly with the number of SSs. For the example scenario between 5 and 20 SINR estimations are necessary.

IX. Conclusions

It was outlined that the former IEEE 802.16a-2003 system had a limited capability to support SDMA techniques. The standard revision, resulting in IEEE 802.16-2004, enhances the DL- and UL-MAP information element. Thus, the MAC protocol allows arranging concurrent bursts which are transmitted or received in SDMA mode. Additionally, optional DL preambles and UL midambles have been included and a possible cyclic shift of preambles and/or midambles further supports the robustness of SDMA. All these enhancements enable the system to fully support SDMA in DL as well as in UL direction. It was shown that the system capacity scales with the number of parallel data streams. To fully exploit the MAC frame capacity under realistic channel conditions, smart scheduling strategies are necessary that do consider the current interference situation and the smart antenna algorithm's capability to separate SSs in space. Thus, leveraging multiple parallel data streams provided by a 4 element antenna array with a simplified scheduler, the system capacity can be more than doubled.

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