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

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***Abstract*—Advanced antenna technologies and algorithms have been developed during the last years. But until today, advanced antenna algorithms of the physical layer and the modes of operation of medium access layers have not been integrated in modern wireless systems. This paper outlines the support of space division multiple access techniques by the wireless metropolitan area network IEEE 802.16a. New concepts are introduced that allow and further optimize the use of SDMA techniques brought by intelligent antennas, i.e. the possibility to enable SDMA in the current IEEE 802.16a MAC is investigated in detail. To overcome current limitations, an enhanced control structure is introduced that masters a concurrent transmission and reception of data to/from several different subscriber stations. The approach is further enhanced to facilitate a more flexible structure that significantly improves the system capacity.**

***Keywords*—SDMA, IEEE 802.16a, MAC, Beamforming, OFDM, Performance Evaluation, Simulation**

I. Introduction

Two wireless metropolitan area networks (MAN), i.e. IEEE 802.16a and ETSI High PERformance Metropolitan Area Network (HiperMAN) working below 11 GHz have been jointly standardized in recent years. One of the next evolutionary steps will be the integration of adaptive antenna techniques into the existing systems. These techniques are expected to have significant impact on the capacity and service quality provided by wireless links and the efficient use of the available spectrum. An initial approach to support space division multiple access techniques in wireless ATM systems has been presented in [1]. Pre-equalization (beamforming) maximizes the Signal-to-Noise Ratio (SNR) by focusing the transmitted energy into the desired direction. At the same time it minimizes the emitted energy towards (all) other directions. This technique, together with the linear nature of the antenna element, enables an antenna array to transmit a signal into one direction while it simultaneously transmits another signal 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 [2]. The simultaneous reception of different signals is known as joint detection techniques. The concurrent transmission/reception of data to/from different spatially separated channels is called space division multiple access (SDMA). It provides another degree of freedom to the MAC layer. Besides the decision which station is allowed to transmit for which duration, the MAC can also schedule more than one station to send/receive their data simultaneously.

Following this introduction, the standard-compliant IEEE 802.16a MAC frame is described in section II. The different downlink (DL) and uplink (UL) transmission phases of the frame are outlined. Section III introduces the event-driven simulation environment and the scenario description used to gain the simulation results shown in the paper. Section IV investigates how the standard compliant MAC frame is able to support SDMA. It figures out that only the DL can transmit data in parallel, but not the UL. This leads to section V where possible enhancements are introduced and discussed, which enable the MAC frame structure to support SDMA. Firstly an extension to the UL-map is discussed. Afterwards an enhanced DL-map is additionally considered. Both extensions allow the MAC protocol to fully support SDMA techniques. Both sections present performance results that evaluate the different approaches to support SDMA.

II. IEEE 802.16a MAC Frame

IEEE 802.16a standardises three different physical (PHY) layers, whereof only the orthogonal frequency division multiplex (OFDM) layer is considered in this paper. Its medium access control (MAC) layer relies on a frame-based transmission, in which the MAC frame has a variable length [3]. 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. Each subframe itself is composed of one or several bursts. 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 to specify the modulation/coding (PHY mode) 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 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 the received MAC packet data unit (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. In contrast to that 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 it must use and (3) the duration of the UL-burst. Thus the SSs, which have been scheduled to transmit data in UL direction, know the duration and the PHY mode of their 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 and simulation results were presented in [4].

III. Simulation Environment

A software-based simulator with a prototypical implementation of the IEEE 802.16a protocol has been developed at 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 event-driven simulator is shown in Figure 1.

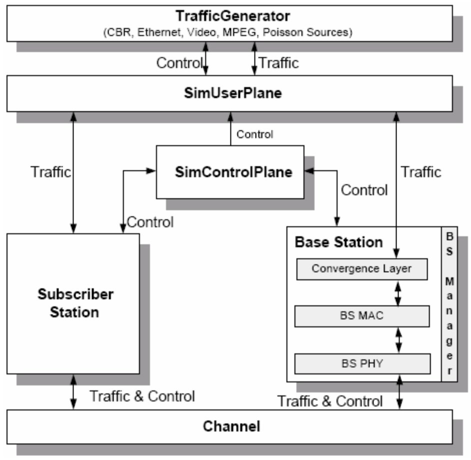

Figure 1: Structure of SDL-based simulator

The protocol stacks of the SS and the base station (BS) are implemented. Stochastic traffic models generate a well defined traffic load which is characteristical for several different applications like MPEG, Ethernet or constant bit rate (CBR). A physical channel transmits the bursts between the SS and the BS and calculates the propagation delay, interference and noise. Based on the calculated signal to interference plus noise ratio (SINR) look up tables are used to map the SINR to the corresponding bit error ratio. These tables introduce the specific behaviour of the PHY layer and the wireless channel. Several control blocks manage the simulation, configure the scenarios and evaluate the transmitted packets.

An exemplary system with 20 MHz bandwidth operating in TDD mode in licensed spectrum bands 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. Simulation results have been obtained without transmission errors, so that they can be seen as an upper limit of the MAC capacity.

The simulation scenario supports multiple SSs with different modulation schemes. To decide the number of SSs per modulation / coding scheme, the surface area of each modulation scheme has been considered. To calculate the surface area of each modulation scheme, the maximal distance between BS and SSs depending on the modulation schemes must be known. This distance can be counted up through the maximal SNR a SS should receive to avoid data loss. [3] proposes 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. A BS is assumed to have a transmission power of P_t = 200 mW which equals 23 dBm. In a real system the noise depends on the used bandwidth of the system. The noise N can be calculated by the formula [5]:

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

where f_Δ is the bandwidth of the system. The outcome of N is $8 * 10^{-14}$ Watt = -100.9691 dBm. According to [6] the path loss between transmitter and receiver in a free space without any obstacle interfering the radio wave can be calculated by:

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

and 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 of its signal power and its noise can be calculated:

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

The calculated SNR can be seen in Figure 2. Each switching point between two different PHY modes results in a certain radius. The corresponding surface area of the cell belonging to a specific PHY mode is a segment of a circle. The surface area can be calculated based on the radius. The areas are certain fractions of the whole cell area.

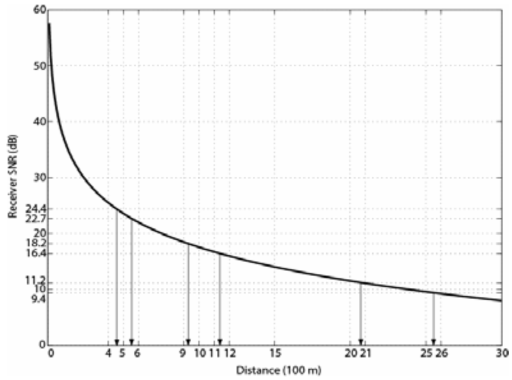

Figure 2: Receiver SNR vs. distance

Based on constant density of SSs, the surface area can be converted to a percentage of SSs using a certain modulation and coding scheme. Assuming 9 active SS per BS, the simulated scenario is made up of different numbers of SSs using a certain combination/coding scheme. The number of SSs corresponding to the percentage of PHY mode utilization can be seen in Table 1.

Modulation	Coding Rate	Number of SS
QPSK	1/2	2
	3/4	3
16-QAM	1/2	1
	3/4	1
64-QAM	2/3	0
	3/4	2

Table 1: Usage of PHY modes

Each SS of the multi-user scenario has a data rate (CBR) of 1/9 of the overall data rate. Having for example 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.

IV. Standard-compliant 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 paper will concentrate 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 3 illustrates how the standard-compliant MAC frame is able to support SDMA. The antenna characteristics are drawn above the frame. Different

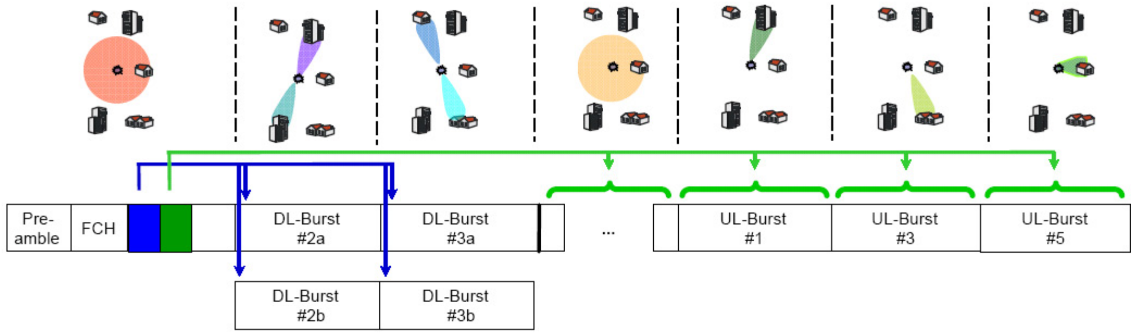

Figure 3: Use of standard-compliant MAC frame to support SDMA (*frametype 1*)

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 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 that 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. #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.

Following 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.

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.

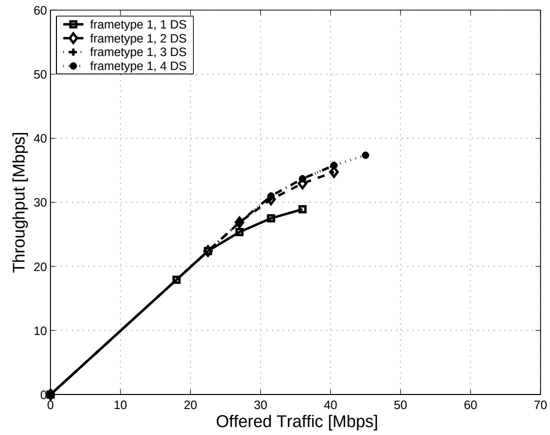

Figure 4: System throughput (*frametype 1*)

Figure 4 shows the overall system throughput gained by means of the simulation environment described in section III. Throughput is plotted with respect to the offered traffic. The parameter *frametype 1* indicates that the standard-compliant frame type is evaluated. The parameter which is varying within the graph is the maximum number of parallel data streams (DS). Taking the graph with only 1 DS, only omni-directional transmission is possible, i.e. no SDMA is performed at all. Having 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.

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 packet data units (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 29 Mbps. This is far below the maximum level of the single 64-QAM ¾ user scenario which is 55 Mbps but it is significantly higher than the 12 Mbps for the single QPSK ½ user scenario [7]. Since the scenario is a mixture of different SSs using different PHY modes, the evaluated 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 35 Mbps. This is an improvement by 20%. In the

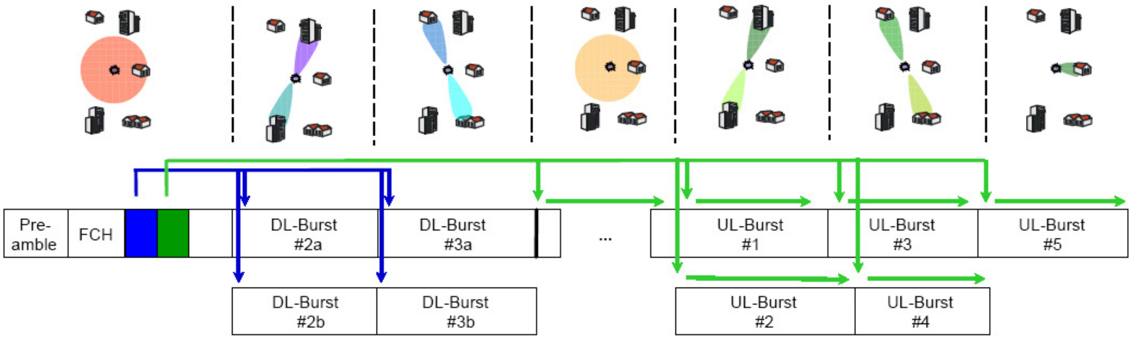

Figure 5: SDMA support of extended UL map (*frametype 2*)

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 does not affect the system throughput that much. Although the BS has got the possibility to schedule three DL-bursts in parallel, this can only be done with the three SSs using QPSK ¾. All other PHY modes are only used by 1 or 2 SSs (refer to Table 1). There is no third SS to be scheduled in parallel. Thus, the level of saturation increases only by 2 Mbps up to 37 Mbps. Since there is no PHY mode used by 4 SSs, the upgrade to 4 concurrent data streams does not bring any benefit within the scenario. Both curves, 3 DS and 4 DS, match each other exactly.

V. Enhanced SDMA concepts

The constraint of the IEEE 802.16a standard to support only parallel DL leads to the approach where possible enhancements to the MAC frame are introduced. With minor modifications to the standard, the support of a parallel UL- and a more flexible DL data transmission is discussed.

A. Extension of the UL map information element

To be able to introduce a parallel reception of different data streams at the BS, the UL-map IE has to be extended. Figure 5 shows the enhanced MAC frame. 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. The first part of the frame, the DL-preamble, the FCH and the burst #1, is again sent omni-directionally. The DL-map and its IEs have not been changed.

But the UL transmission bursts are now arranged differently. 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. Unlike the parallel DL-bursts, the duration of parallel UL transmission bursts and even their PHY modes might be different. The UL is more flexible but also more complex to schedule than the DL.

The overall system throughput of the scenario is shown in Figure 6. The parameter *frametype 2* indicates the standard-compliant frame type enhanced by SDMA capability in UL. Again the lowest curve represents the omni-directional case (1 DS). Because this case can be seen as a non-SDMA case, there is no difference between *frametype 1* and *frametype 2*. Figure 6 shows a maximum system throughput for 1 DS of approximately 29 Mbps which is the same level as for *frametype 1*.

Having an intelligent antenna at the BS which supports 2 DS the system throughput increases to 45 Mbps. In contrast to *frametype 1*, bursts can not only be transmitted but they can also be received in parallel so that the saturation level is much higher. This scenario benefits a lot from the SDMA capability. The system throughput increases by 55% even if only 2 DS can be applied.

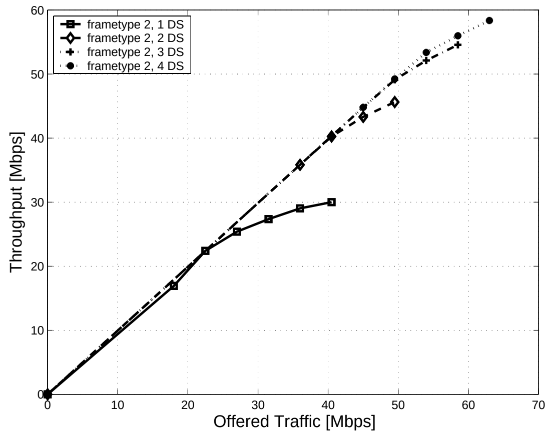

Figure 6: System throughput (*frametype 2*)

The possibility to support 3 concurrent data streams further increases the system throughput to a saturation level of 54 Mbps. With *frametype 1* the impact of a higher number of DS decreased because only equal PHY modes could be scheduled in parallel, but with *frametype 2* this restriction has been partly overcome. Due to the enhanced UL map IE, 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 nearly doubled referred to the non-SDMA case (1 DS). The level of saturation is close to 60 Mbps.

B. MAC frame with enhanced uplink and downlink capability

To enable a fully flexible DL transmission with simultaneous DL bursts, the DL map IE has to be extended. In Figure 7 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 duration of each DL burst. This is indicated by the arrows above the frame. Now, the duration of parallel DL bursts and even their PHY modes might be different. Since the UL-map and its IEs have not been changed referred to the previous section, the reception of parallel UL-bursts equals the one outlined in section V.A. To allow for a better channel estimation at the SS receiver, short preambles are 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 8 shows the overall system throughput of this scenario. The parameter *frametype 3* indicates the newly proposed MAC frame which has SDMA capability in UL and DL. Like in the previous scenarios the lowest curve with only 1 DS represents the omni-directional case. Having an antenna array at the BS simultaneous data streams might be supported. The curves for 2, 3 4 parallel data streams give their simulation results. Note that due

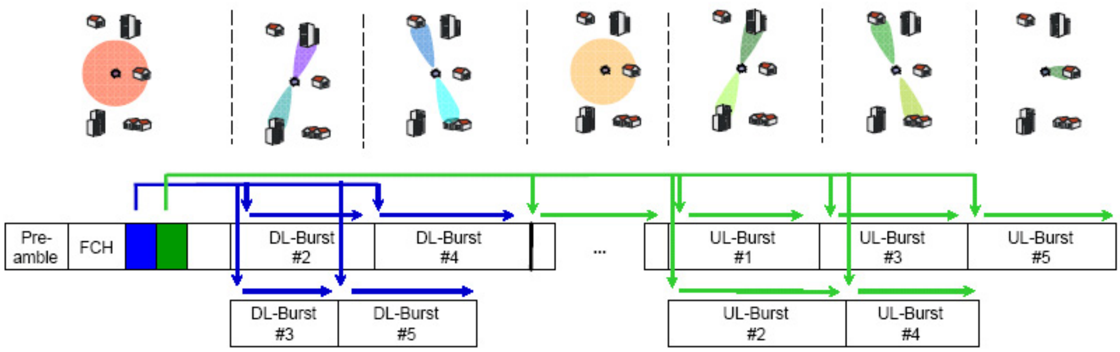

Figure 7: SDMA support of extended UL and DL map (*frametype 3*)

to higher system capacity the scale of the graph differs from the previous ones.

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. Thus, the system capacity scales nearly linearly with the number of antenna elements or number of data streams respectively

Having a BS which supports 2 DS the system throughput increases to approximately 55 Mbps. This is nearly twice the non-SDMA capacity of 29 Mbps. Compared to *frametype 1* and *2* the additional overhead is the larger DL-MAP and the short preambles which have been 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 81 Mbps. With *frametype 2* the impact of a higher number of DS decreased because in DL direction only equal PHY modes could be scheduled in parallel. 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 nearly 110 Mbps, which is 3.79 times the non-SDMA capacity.

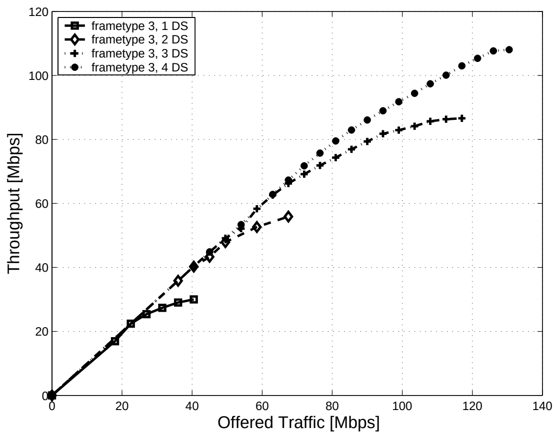

Figure 8: System throughput (*frametype 3*)

Another approach leverages standard-compliant DL- and UL-maps which are transmitted omni-directionally, but whose addresses in the MAC header are not set to broadcast 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. A detailed description can be found in [8].

VI. Conclusions

It was outlined that the standard-compliant IEEE 802.16a system has got a limited capability to support SDMA techniques. A simultaneous data transmission in DL direction is possible, but parallel DL-bursts must have the same start time and PHY mode. Parallel reception of data in the UL direction is not possible with this standard. The concept of extending the UL-map information element with the start time of the UL-burst enables the system to support SDMA in the UL subframe. But the restriction in DL still exists. The introduction of an extended DL-MAP information element enables the system to fully support SDMA in DL and in UL direction according to Figure 7. The MAC frame can be build up flexibly and efficiently. It was shown that the system capacity scales nearly linearly with the number of parallel data streams.

This paper proposes required changes to the IEEE 802.16a standard [3]. During the development of these SDMA concepts the standard itself had been further enhanced. The requirements to enable SDMA in UL direction (refer to section V) had already been introduced during the development of the standard revision process. The requirements to enable SDMA in DL direction have been successfully contributed to the IEEE LAN MAN Standards Committee based on the presented work by the authors of this paper. Thus, the latest version of the standard (802.16-2004) fulfills all necessary requirements to fully support SDMA.

Acknowledgements

We would like to thank Prof. B. Walke of ComNets for his support and all partners involved in the IST-STRIKE project.

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