Influence of SDMA-Specific MAC Scheduling on the Performance of IEEE 802.16 Networks

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Abstract - **Advanced antenna technologies and algorithms, which have been developed during the last decades, are currently being integrated into modern wireless systems. As one of the first standards the wireless metropolitan area network IEEE 802.16 provides means to support smart antenna techniques. This paper outlines the support of space division multiple access (SDMA) techniques by IEEE 802.16. It shows the influence of intra-cell interference generated by concurrent SDMA transmissions. Finally, the authors present two SDMA-specific scheduling algorithms that are able to cope with the additional interference.**

1. Introduction

The IEEE standard 802.16 for wireless metropolitan area networks has been published in October 2004 [1]. The technology is supported by the WiMAX Forum, an industry-led, non-profit corporation formed to promote and certify compatibility and interoperability of broadband wireless products. As one of the first standards 802.16 includes means to integrate adaptive antenna techniques. Comparable approaches are currently being standardized by the 3GPP for UMTS or by the IEEE for 802.11n. These advanced antenna techniques have a significant impact on the capacity and service quality provided by wireless links and the efficient use of the available spectrum [4]. The simultaneous transmission can be accomplished by pre-distortion or beamforming techniques. The concurrent reception is known as joint detection. In general, 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 conventional TDMA, FDMA or CDMA based medium access.

Following this section, an introduction to smart antenna techniques that enable SDMA is given in section 2. Sections 3 and 4 describe the enhanced MAC and the physical (PHY) layer of IEEE 802.16. Section 5 introduces the event-driven simulation environment and the scenario description used to gain the simulation results shown in this paper. Section 6 explains the SDMA support of the MAC frame. It presents performance results that evaluate the SDMA support of the IEEE 802.16 MAC layer. Furthermore, it investigates the influence of intra-cell interference on the system capacity. It outlines why intelligent scheduling strategies are necessary. Finally, section 7 introduces two scheduling algorithms that are able to efficiently support the special needs of SDMA systems.

2. Space Division Multiple Access

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. An antenna pattern is steered by applying a weight, i.e., a complex number to each antenna element. Thus, a pattern is represented by a weight vector w_i which contains one weight per antenna element (see Figure 1). If multiple patterns are applied, one weight vector per pattern has to be calculated ($w_0 \ldots w_{K-1}$). Beamforming 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. The linear nature of the antenna elements enables an antenna array to apply two patterns simultaneously. It can transmit one signal into one direction while it transmits another signal at the same time into another direction. Thereby, both receivers do experience a sufficient SNR. Since an antenna is a reciprocal element, the same principle is valid during the reception of signals [2]. Here, joint detection techniques allow an antenna array to receive different signals simultaneously. Both signals can be separated and the bit streams can be recovered individually.

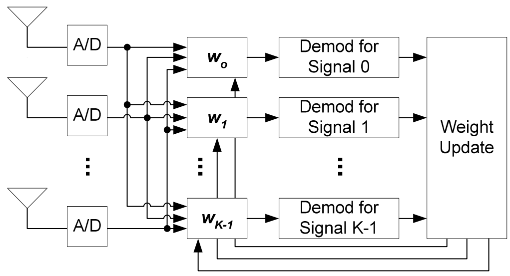

Figure 1: Beamformer for multiple signals [3]

Figure 2 shows an example configuration. 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 to user 2, assuming the different users can be separated well enough by the applied algorithm. At the same time 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 towards user 1. The resulting amplitude factors α_{11} and α_{21} pointing at user 1 are shown in Figure 2 where a 4-element linear antenna array is utilized in a two-user scenario. This principle can be applied in downlink (DL) as well as in uplink (UL).

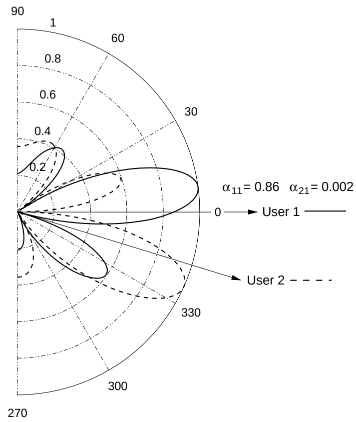

Figure 2: Two optimized beam patterns and corresponding amplitude factors (α)

3. Medium Access Control

The IEEE 802.16 MAC layer provides convergence to various higher layer protocols, system access, bandwidth allocation, connection establishment, connection maintenance and security. QoS is provided for the transmissions of packet data units (PDU) over the PHY layer. Parts of the MAC are PHY layer independent while others are PHY-specific [1].

The MAC protocol supports a frame-based transmission. The frame of an OFDM-based MAC operating in time division duplex (TDD) mode consists of a DL subframe and a UL subframe. The DL subframe starts with a preamble used for synchronization. The following frame control header (FCH) specifies the location as well as the modulation and coding scheme (PHY mode) of up to four DL bursts. The FCH is followed by one or multiple DL bursts. The very first DL burst contains 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. An IE in the DL-MAP specifies a DL burst and an IE in the UL-MAP specifies a UL burst. Each DL burst is made up of PDUs scheduled for DL transmission. MAC PDUs transmitted within the same DL burst are encoded and modulated by using the same PHY mode. The UL subframe consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple UL bursts. The initial ranging slots allow a subscriber station (SS) to enter the system. Each of the following UL bursts contains MAC PDUs transmitted by a single SS with the corresponding PHY mode. Each UL burst starts with a preamble. More information about the IEEE 802.16 MAC can be found in [1] and [9].

4. Physical Layer

The investigated IEEE 802.16 PHY layer uses orthogonal frequency division multiplex (OFDM) with a 256 point transform, designed for non line of sight operation in frequency bands below 11 GHz. The forward error correction scheme consists of the concatenation of a Reed-Solomon outer code and a convolutional inner code. The concatenation of both codes is made rate-compatible by means of puncturing. The different code rates are paired with the available modulation schemes to form PHY modes of varying robustness and efficiency [1].

In order to model the antenna characteristics of the array the optimized weight vectors have to be calculated. The algorithm in use (Minimum Variance Distortionless Receiver) is an optimal beamformer such that it does not only steer nulls to interfering stations but it maximizes the SNR at the required station [2].

The services of the PHY layer, which are extended by SDMA-specific services, are provided to the MAC layer at the PHY service access point. By means of service primitives, the MAC layer can control the PHY. To allow for SDMA, the channel quality needs to be estimated, optimized antenna patterns have to be calculated and PDUs are transmitted or received via different antenna patterns. As it will be outlined in section 6.2 one of the most important services for an SDMA MAC scheduler is the estimation of signal-to-interference-plus-noise ratios (SINR). The scheduler needs this knowledge to optimally separate SSs in the spatial domain.

4.1. SINR Estimation

In order to estimate the correct SINR, the transmit and the receive cases have to be differentiated. Figure 3 illustrates all relevant signals during concurrent reception of data from spatially separated stations. It can be seen that an optimized antenna pattern is applied at the base station (BS). It maximizes the wanted signal S from SS A and minimizes the intra-cell interference I_{intra} from SS B that is concurrently transmitting. If more than one station is scheduled to transmit in SDMA, all intra-cell interferences have to be counted as well. The third fraction of the received signal strength is generated by neighboring cells that are operating on the same frequency. By minimizing the side lobes of the pattern the beamforming algorithms tries to minimize the inter-cell interference I_{inter}^{BS} received at the BS. The estimation of the SINR during SDMA reception has to consider all above mentioned signals and filters them through the optimized antenna pattern, thus the signals in the following equation get the index ^{opt}. Finally, receiver noise N_{Rx}^{BS} has to be considered. The SINR at the BS during the reception of one SS, which is spatially separated from other SSs can be calculated as:

$$SINR\_Rx_{estimated} = \frac{S^{opt}}{N_{Rx}^{BS} + I_{\text{inter}}^{BS\ opt} + \sum_{\substack{\text{SDMA} \\ \text{stations}}} I_{\text{intra}}^{opt}}$$

Figure 4 illustrates the relevant signals during SDMA transmission. An optimized antenna pattern is applied at the BS that maximizes the wanted signal S to SS A. All other patterns, which are optimized for concurrent transmissions to other SSs, minimize the intra-cell interference I_{intra} to SS A. Again, neighboring cells generate inter-cell interference I_{inter}^{SS} at the receiver. In the transmit case the side lobes of the transmit pattern do not affect the SINR at the SS, but they are responsible for inter-cell interference at neighboring cells. During SDMA transmission the wanted signal S and the intra-cell interference I_{intra} is filtered through their corresponding optimized antenna patterns. Since it is assumed that SSs are receiving omni-directionally, the inter-cell interference is not filtered. Again receiver noise N_{Rx}^{SS} has to be considered. This results in the following equation:

$$SINR\_Tx_{estimated} = \frac{S^{opt}}{N_{Rx}^{SS} + I_{\text{inter}}^{SS} + \sum_{\substack{antenna\\patterns}} I_{\text{intra}}^{opt}}$$

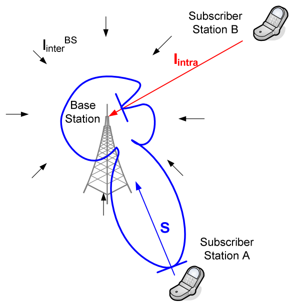

Figure 3: Relevant signals during SDMA reception

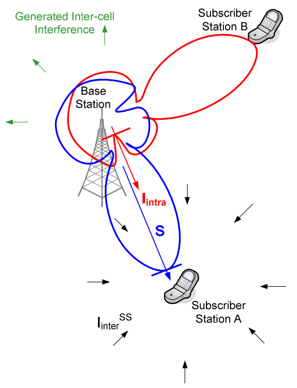

Figure 4: Relevant signals during SDMA transmission

5. Simulation Environment

A software-based simulator with a prototypical implementation of the IEEE 802.16 protocol has been developed at ComNets. The protocol stack is specified formally with the Specification and Description Language (SDL). 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, the MAC and the PHY layer. Stochastic traffic models generate a well defined traffic load. Control blocks manage the simulation, configure the scenarios and evaluate the transmitted packets. A physical channel transmits PDUs between 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 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. Look-up tables are generated by sophisticated link layer simulations [4].

An exemplary IEEE 802.16 system with 20 MHz bandwidth operating in TDD mode is evaluated in the following. The MAC frame length is set to 10 ms and a cyclic prefix of ¼ of the OFDM symbol 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. Second, the consideration of transmission errors shows the influence of intra-cell interference. The scenario is made up of 9 active SSs per BS. The PHY mode used by the SSs is listed in Table 1. SSs are located within an angle of 180° as depicted in Figure 6. The load generator offers constant bit rate traffic. Each SS gets a share of 1/9 of the overall traffic. Having, e.g., an offered traffic of 2 Mbps for each SS (1 Mbps DL, 1 Mbps UL) an overall offered traffic of 18 Mbps is generated.

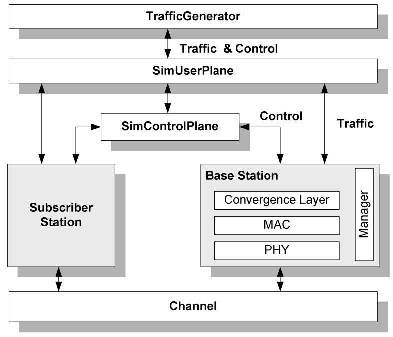

Figure 5: Structure of SDL-based simulator

Modulation	Coding Rate	Receiver SNR (dB)	Number of SS
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

The BS is assumed to have an antenna array which allows for beamforming in DL and joint detection in UL direction. Thus, the BS can send different data streams to different SSs by applying optimized antenna patterns. Assuming reciprocity of the wireless channel in TDD systems, the channel state information is known at the BS. SSs are assumed to have omni-directional antennas.

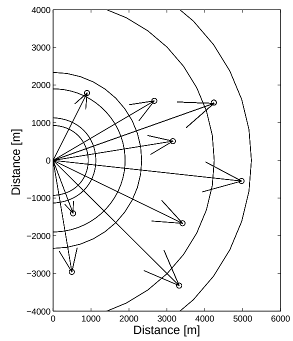

Figure 6: SSs' location within the scenario

6. SDMA Enhanced IEEE 802.16

The standard IEEE 802.16-2004 contains enhanced DL- and UL-MAP information elements. So the MAC protocol allows for arranging concurrent bursts which are transmitted or received in SDMA mode. Additionally, optional DL preambles and UL midambles might be included and a possible cyclic

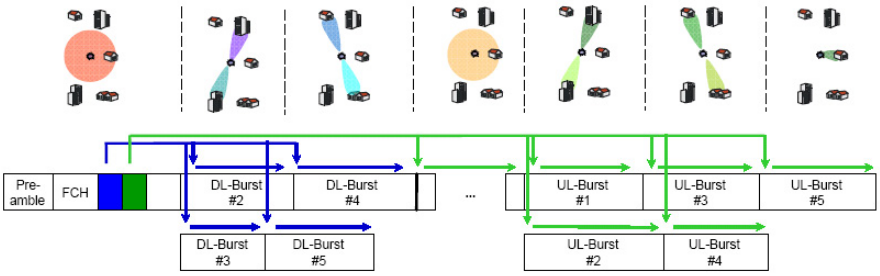

Figure 7: SDMA support of IEEE 802.16-2004 using concurrent transmission DL MAP IEs

shift of preambles and/or midambles further supports channel estimation as well as time and frequency synchronization and therewith the robustness of SDMA. All these enhancements enable the system to fully support SDMA [10]. Figure 7 shows the SDMA enhanced IEEE 802.16 MAC frame. The antenna characteristics are drawn above the frame. Inside the DL burst 1, the DL- and the UL-MAP is highlighted. The arrows show the timing information included in the IEs, i.e., start time and burst duration.

Starting with the DL preamble, the first part of the frame is sent omni-directionally. Preamble, FCH and DL burst 1 are broadcasted as the antenna pattern above the frame indicates. This is necessary because all SSs need to decode the MAPs. At the beginning of the next burst the antenna characteristic is adapted. The BS applies the antenna weight factors to the antenna elements. Thus, the BS can send one data stream containing DL burst 2 in the direction of a SS while at the same time the BS can send a different data stream containing DL burst 3 in the direction of another SS. The number of data streams is limited by the capability of the antenna array to form lobes which sufficiently separate the different signals. To enable a parallel reception of different data streams at the BS, the UL-MAP is specifying the duration and the start time of each UL burst. With the UL-MAP IE it is possible to let different SSs start their UL transmission bursts at the same time only separated in space.

6.1. MAC Frame Capacity

Figure 8 shows the overall system throughput of the IEEE 802.16 MAC frame operating in SDMA mode. It is assumed that all SSs are perfectly separable by the antenna. No transmission errors occur. The throughput is plotted with respect to the offered traffic. The parameter that is varying within the graph is the maximum number of parallel data streams (DS). In a system with 1 DS only TDMA transmission is possible, i.e., no SDMA is performed. Deploying an antenna array at the BS, which allows separating two SSs, two concurrent DSs can be scheduled. Having more elements at the BS's antenna array more parallel antenna beams and therewith more simultaneous DSs can be handled.

Being in low-load situations, the offered traffic can be carried entirely by the system. Reaching a certain level the system runs into saturation. The MAC frame is 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. Since a multi-user multi-PHY-mode scenario is evaluated, the observed throughput is below the maximum level of a single user 64-QAM ¾ scenario (55 Mbps) but higher than in a single user QPSK ½ scenario (12 Mbps) [9]. Supporting 2 DS the throughput increases to approximately 31 Mbps. This is nearly twice the non-SDMA capacity of 16.5 Mbps.

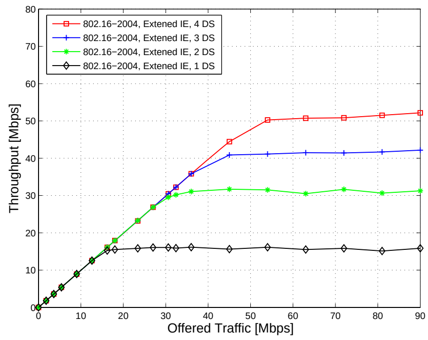

Figure 8: System throughput of IEEE 802.16-2004 using concurrent transmission DL MAP IEs

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 SDMA enhanced MAC frame allows for a flexible and efficient scheduling of bursts. The resulting system capacity nearly scales linearly with the number of parallel data streams

6.2. Influence of Intra-cell Interference

The simulation results shown in the previous section evaluate the maximum capacity of the IEEE 802.16 MAC layer operating in SDMA mode. They assume perfect separability of SSs and thus no transmission errors. This section will outline the effect of intra-cell interference on the system capacity. For that purpose, the same simulations as in section 6.1 have been performed 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 PDUs under certain channel conditions. Receiver noise affects the transmission. Intra-cell interference generated by concurrent transmission and reception of bursts influences the receiver SINR. The reduced signal quality introduces a higher probability of packet errors, which reduce the system capacity.

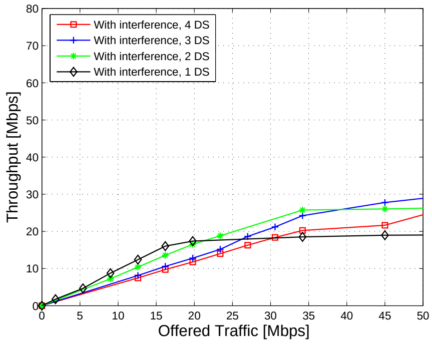

Figure 9: System throughput considering packet errors

Figure 9 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 that is not aware of the intra-cell interference introduced by SDMA. The scheduler just schedules bursts in parallel not taking into account the spatial separability of stations. SSs might be scheduled for simultaneous transmission or reception of data although they are closely co-located and the beamformer cannot sufficiently separate them. Even in low load situations bursts are transmitted and received simultaneously. In high load situations the capacity of systems with multiple data streams exceeds the 1 DS case. The capacity increase of the MAC frame overcomes the decrease due to interference. However, the resulting system throughput is far from the potential MAC capacity seen in Figure 8.

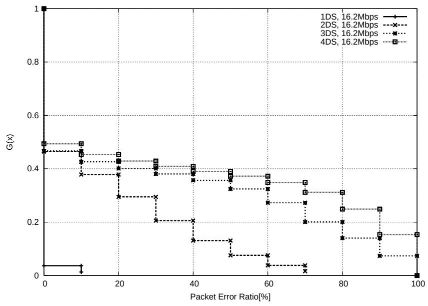

Figure 10: CCDF of packet error ratio

Figure 10 shows the complementary cumulative distribution function (CCDF) of the packet error ratio. It can be seen that in the 1 DS case nearly no errors occur. The chosen PHY modes are sufficiently robust to receive regular bursts. Concurrent transmissions introduce interference which results in packet losses. Having two parallel DSs, only 53 % of all packets are received error-free, i.e., their packet error ratio equals zero. For the remaining packets error ratios of up to 70% can be measured. If four concurrent DSs are scheduled, 50 % of the PDUs are received without errors, the rest perceives a loss ratio of up to 100 %.

Smart scheduling strategies are necessary to fully benefit from the capacity of the SDMA enhanced MAC frame in the presence of interference. The scheduling 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, which do interfere each other heavily, should be arranged in TDMA mode. An intelligent scheduler needs to acquire information about the current interference situation and about the spatial separability of SSs. For this, the estimated SINR seems to be a good measure [5] [6]. It can be directly converted into a desired PHY mode and thus into the throughput of the link. More accurate PHY mode selection algorithms for multicarrier systems take the estimated mean SINR plus an additional indicator such as the variance of the subcarrier SINRs into account [7]. Additionally, the provided SINR estimates can be used without further knowledge about the exactly applied antenna algorithm.

7. SDMA Scheduler

SDMA scheduling algorithms look for groups of users that are spatially separable. Users of the same spatial group will be scheduled in one SDMA slot while users of different groups will be scheduled in different time slots (regular TDMA) [8]. The performance of the spatial grouping directly affects the system performance. On the one hand, grouping algorithms can search through the whole combinatorial set of possible solutions to find the optimal one. On the other hand, computationally less complex heuristics do not try to find the optimal solution, but a sub-optimal one. In order to set the boundaries of the potential performance gains of different algorithms, three grouping strategies have been evaluated in randomly generated scenarios (Monte Carlo simulation). A scenario consists of one central BS with a 5-element circular antenna array and 10 SSs. The SSs' positions are randomly generated following a uniform distribution in each of the 3000 scenarios. Free-space propagation has been assumed and the size of the scenario is aligned with the coverage area of the most robust PHY mode. Lookup tables for the conversion of SINRs to PHY modes and therewith data rates are used from the 802.16 standard. Figure 11 shows the CCDF of the throughput gains of three spatial grouping algorithms applied to the randomly generated scenarios. The gain is defined as the mean throughput of the SDMA schedule normalized to the mean throughput of the non-SDMA, i.e., pure TDMA schedule of the given scenario.

The upper bound is marked by an optimal grouper. For each scenario the algorithm exhaustively searches for the optimal partition of SSs. A partition of the SSs is a set of nonempty spatial groups of SSs such that every SS is in exactly one of these groups. More formally, the spatial groups are both collectively exhaustive and mutually exclusive with respect to the set of SSs being partitioned. The optimal partition has the maximum mean group throughput. The schedule that results from a given partition is composed of several time slots in which the SSs of the corresponding spatial group are scheduled in SDMA. Thus, the optimal grouper has to estimate the throughput of all possible partitions. Having an antenna array that is able to provide five concurrent data streams, at least two groups with five SSs each are necessary to serve all SSs in two time slots. If in this case all SSs are perfectly separable, the mean throughput of the SDMA schedule is five times higher than the mean throughput of the TDMA schedule, thus the gain is five. This is the maximum gain visible in Figure 11. The mean gain of the optimal grouper is 3.22.

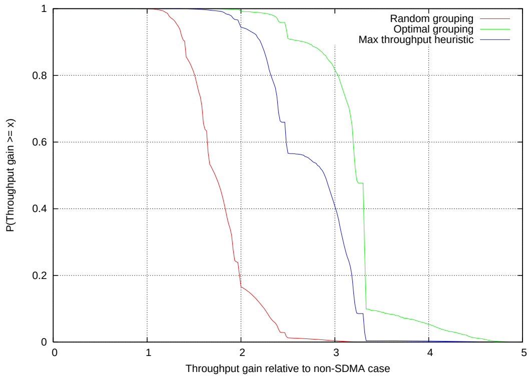

Figure 11: Throughput gain of spatial grouper

The lower bound is marked by the random grouper. The scheme randomly selects a partition. Due to the random nature the SDMA performance of the resulting schedule is sometimes worse than the TDMA one. This is reflected by the minimum gain of the random grouper, which is 0.69. Gains smaller than one occur so rarely during the simulation that their probability is not visible in Figure 11. Its mean gain compared to the non-SDMA schedule is 1.79.

The results of the max throughput grouper resides in between the boundaries. The algorithm first selects the spatial group that results in the highest throughput. This group is scheduled in the first time slot. Taking the set of unserved SSs, the next group is chosen that again results in the highest throughput. The next slot is scheduled for that group. As long as there are unserved SSs left, slots are scheduled. The result is again a partition of the set of SSs into spatial groups. The computational complexity of the max throughput grouper is far below the optimal grouper since it does not search through the whole combinatorial set of possible partitions. Its mean gain is 2.76, which is a promising result.

7.1. Max Throughput Scheduler

Based on the max throughput grouper introduced in the previous section, an 802.16 scheduler has been developed for the simulator. It takes the estimated SINR as scheduling input and maximizes the throughput of the current burst. For this purpose, it tests all possible spatial groups. Having estimated the SSs' SINRs in every group, the scheduler chooses the group that result in the highest throughput. Figure 12 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 exploit the SDMA enhanced MAC capacity shown in Figure 8. Having reached the saturation level, the throughput does not stay constant but it further increases. This results from the unfair preference of SSs using higher order PHY modes by the scheduler.

The calculation of the SINR estimates of one spatial group needs an inversion of the array correlation matrix [2]. Since the scheduler estimates the SINRs for every possible spatial group, the algorithm is still rather complex, especially when the number of active SSs in the system increases. Figure 13 plots the number of necessary SINR estimations in case of 4 DS: $\sum_{i=1}^{4}\binom{N_{SS}}{i}$

This SINR estimation algorithm has $O(N_{SS}^{4})$ complexity. For the example scenario, which is composed of 9 SSs, 255 SINR estimations are necessary. Within a fixed deployment concept, the characteristic of the wireless channel does 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 standard amendment IEEE 802.16e SSs become mobile. Hence, the propagation conditions vary quickly and the max throughput SDMA scheduler might not be applicable.

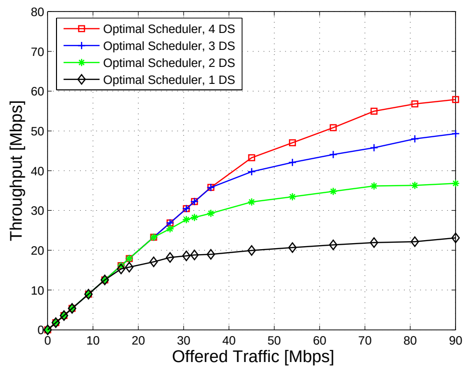

Figure 12: System throughput utilizing the max throughput scheduler

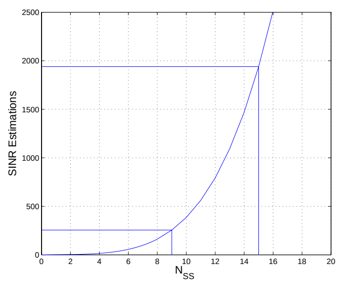

Figure 13: Computational complexity of the max throughput scheduler (4 DS)

7.2. Simplified SDMA scheduler

To further reduce the computational complexity, a simplified SDMA scheduler is outlined in this section. The scheduler is motivated by the promising results of the random grouper in Figure 11. The simplified scheduler is not looking for any optimized solution, but for an acceptable one. It just assures that the performance does not drop below the TDMA one. The scheduler is allocating the first data stream in TDMA 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 SDMA bursts are scheduled 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, another TDMA burst is tested for concurrent SDMA transmission. If it is not possible to schedule a particular burst in parallel, it is postponed to the proximate MAC frame.

Figure 14 shows the throughput of an 802.16 system that utilizes the simplified SDMA scheduler. Taking the TDMA case (1 DS), the saturation level is equal to the one in Figure 12. 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 DSs, the simplified scheduler is performing similar to the max throughput scheduler. It is able to exploit the SDMA enhanced MAC capacity which is increased by a factor of 2.5 compared to the TDMA case. If four degrees of freedom are provided by the antenna array, up to 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.

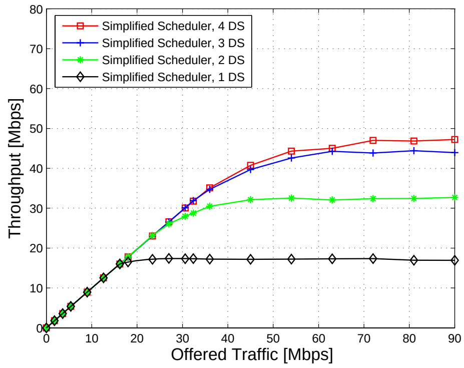

Figure 14: System throughput utilizing the simplified SDMA scheduler

The number of SINR estimations needed by the simplified scheduler is given in Figure 15. The graphs assume that 4 SS can be scheduled in the first data stream without the need of any SINR estimation. The minimum number of estimations is needed when each newly scheduled burst finds an appropriate parallel burst at the first try. 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.

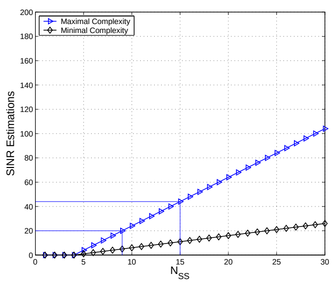

Figure 15: Complexity of the simplified scheduler (4DS and 4 bursts in the first stream)

8. Conclusions

IEEE 802.16 fully supports SDMA. The MAC protocol allows arranging concurrent bursts which are transmitted or received concurrently. To fully exploit the MAC frame capacity, smart scheduling strategies are necessary that do consider the current interference situation and the smart antenna algorithm's capability to spatially separate SSs. But the computational complexity has to be taken into account. The introduced max throughput heuristic nearly exploits the full capacity of the SDMA MAC frame but it is still computationally complex. A simplified scheduler can reduce the complexity. It schedules SSs in parallel when this is feasible. The performance of both schedulers is comparable in situations with three or less parallel data streams. If more than three streams can be provided by the physical layer, the max throughput scheduler outperforms the simplified one.

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