MAC Layer Concepts to Support Space Division Multiple Access in Wireless Metropolitan Area Networks (IEEE 802.16a)

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***Abstract*— Wireless last mile technology, e.g. IEEE 802.16a or ETSI HiperMAN, is becoming a challenging competitor to conventional wired last mile access systems like DSL and cable modems or even fiber-optic cables. High data rates, low delay values and even quality of service can be provided by such systems.**

Advanced antenna algorithms have been developed years ago, e.g. beamforming came up some decades ago, spatial multiplexing algorithms, e.g. BLAST, were developed in 1996 and space time coding was first published in 1998. Since then, their fundamentals have been investigated and their improvements regarding the wireless link capacity have been proved. But till 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. The system can simultaneously transmit data to different stations in downlink direction, a parallel reception of data is not possible. A new concept is introduced that additionally enables a simultaneous data reception from several different subscriber stations. Another approach further enhances the system by introducing a new idea to control the medium access control frame. The build up of the frame is signaled to the different stations separately by means of private control elements. Thus, the frame can be designed individually for every single station and more flexibility and a higher capacity is introduced to the system.

I. Introduction

Lately two wireless metropolitan area networks (MAN), working below 11 GHz, IEEE 802.16a and ETSI High PERformance Metropolitan Area Network (HiperMAN) have been standardized with a close cooperation of both organizations. Both OFDM-based physical layers shall comply with each other and a global OFDM system should emerge [1].

The main advantage of wireless MAN technologies over wired systems like DSL and cable modems results mainly from the high costs of the labor-intensive deployment of cables. ”A 200-square-kilometer service area costs a DSL provider over $11 million. The same area can be served wirelessly for about $450000” [2]. Apart from being wireless the above mentioned MAN systems IEEE 802.16a and HiperMAN have been designed to fulfill today’s most promising challenges: non-professional installation of terminals, rapidly scalable infrastructure deployment, efficient spectrum usage and quality of service support.

The next evolutionary step will be the integration of adaptive antenna techniques into the wireless systems. These techniques are expected to have a significant impact onto the capacity and service quality provided by wireless links and onto the efficient use of the available spectrum. First approaches to support space division multiple access techniques in wireless ATM systems have been done in [3].

Three categories of advanced antenna algorithms can be outlined. Some techniques, e.g. space time coding, maximize the diversity. More redundancy is added to the signal and it becomes more robust. In general the data rate stays the same [4]. The criteria of other techniques, e.g. spatial multiplexing, is the maximization of the data rate. Several independent data streams are transmitted at once [5]. Both kind of techniques do not essentially affect the medium access control (MAC) layer. The signal to interference ratio (SIR) of a link gets better or the data rate for a connection increases, but both effects can be handled by the MAC.

Beamforming maximizes the SIR by focusing the transmitted energy into the desired direction. At the same time it minimizes the transmitted 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 receiver do experience a normal SIR. Since an antenna is a reciprocal element, the same principle goes for the reception of signals [6]. The simultaneous transmission/reception of data into/from different spatially separated channels is called space division multiple access (SDMA). That gives another degree of freedom to the MAC layer. Besides the decision which station is allowed to transmit for which duration, it can even schedule more than one station to send 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. Chapter III 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 IV where possible enhancements are introduced and discussed, which enable the MAC frame structure to support SDMA. At first an extension to the UL-map is discussed in subsection IV-A. Afterwards private

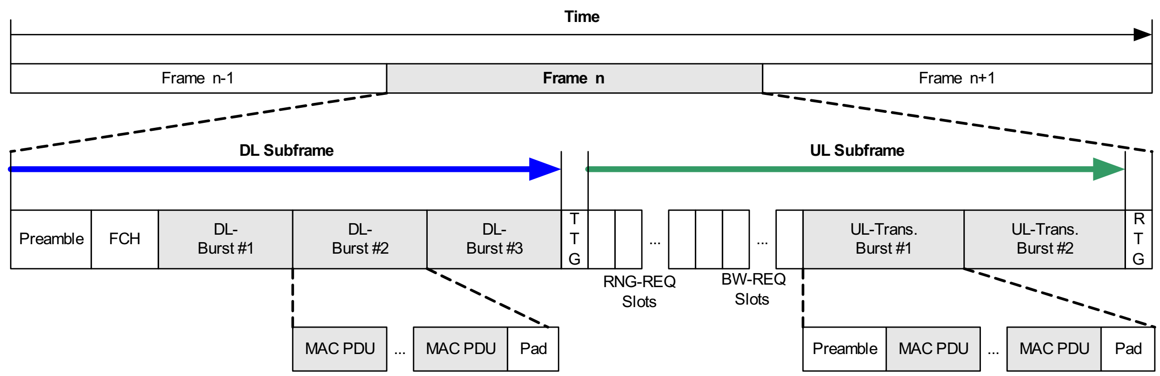

Fig. 1. Standard-compliant MAC frame (IEEE 802.16a, TDD)

maps are introduced in sub chapter IV-B to signal individual frame structures to different stations. To reduce the overhead which comes along with additional control elements, the last subsection IV-C discusses the concept of transmitting signaling information adaptively.

II. IEEE 802.16a MAC frame (TDD)

The wireless MAN standard IEEE 802.16a supports a frame-based transmission, in which the MAC frame has a variable length. The MAC frame structure for the OFDM PHY in time division duplex (TDD) mode is illustrated in Fig. 1. Each frame consists of a DL-subframe and a UL-subframe, with the DL-subframe always preceding the UL-subframe. A DL-subframe consists of only one DL transmission burst starting with a preamble 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. The mandatory PHY mode of the FCH is QPSK 1/2. The FCH and/or the DL-burst #1 contains the broadcast MAC control messages, i.e. DL and UL channel descriptor (DCD, UCD) and the UL- and DL-map. DCD and UCD define the characteristic of the physical channels.

The DL-map defines the access to the DL channel, and the UL-map allocates access to the UL channel. Among other things the maps contain one information element (IE) for each burst. 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 whom 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) the basic SS connection identifier (CID) which is a unique address of the station which is allowed to send, (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 transmission bursts. The start time is simply the addition of all durations of the preceding UL transmission bursts.

The FCH is followed by one or multiple DL-Bursts, which are ordered by their PHY mode. While the most robust one is transmitted first, the last burst has the highest PHY mode. Thus, the whole MAC frame is specified by the FCH and/or the DL-burst #1, as illustrated in Fig. 1. The transmitter receiver turnaround gap (TTG) between the DL- and the UL-subframe is needed by the sending BS modem to switch from transmitting to receiving. The receiving modem of the SSs needs it vice versa. The UL-subframe consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple UL transmission bursts, each transmitted from a different SS. Each UL transmission burst starts with a short preamble. The receiver transmitter turnaround gap (RTG) at the end of the MAC frame is needed by the sending SS modem to switch from transmitting to receiving. It finalizes the frame structure.

A more detailed description of the MAC layer can be found in [7] and [8]. An initial analytical performance evaluation was presented in [9].

III. Standard-compliant support of SDMA

Although the 802.16a MAC frame has originally not been designed to support SDMA techniques, these techniques can be used as introduced in the following.

A. General aspects

The base station (BS) has several receive antennas (antenna array) which allow beamforming in DL and in UL direction. The application of a spatial filter enables the BS to receive several data streams coming from different directions simultaneously. Having a bidirectional link, which is the case in systems running in TDD mode, the channel information is known. Thus the BS can send different data streams to different users by means of spatial filters associated to different SSs (or groups of SSs). Since perfect beamforming is assumed

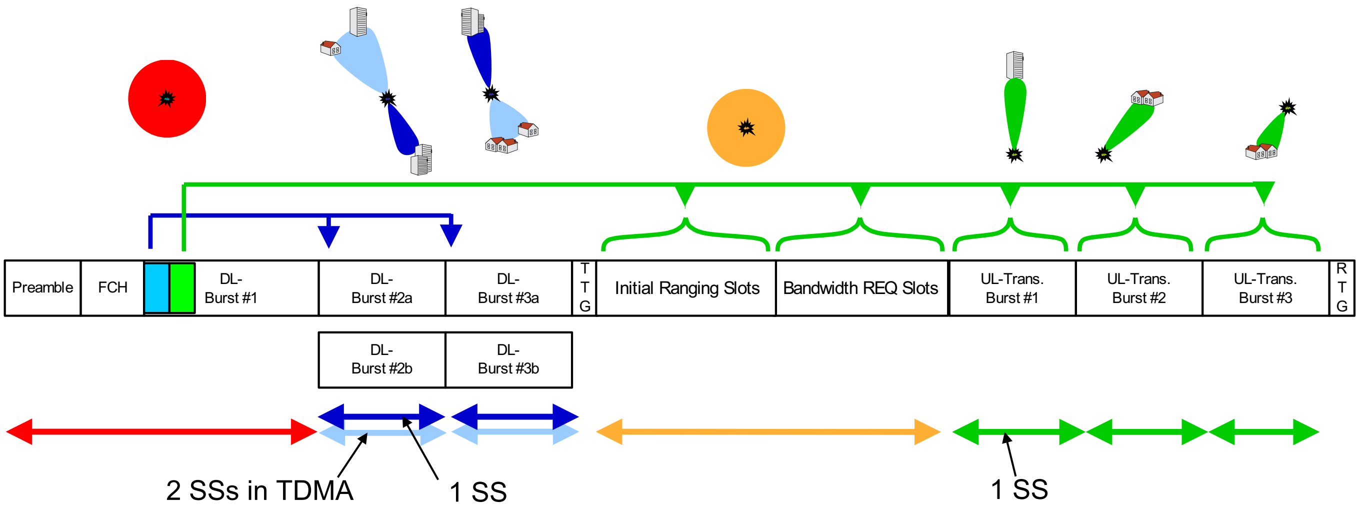

Fig. 2. Use of standard-compliant MAC frame to support SDMA

in the following, this paper will concentrate on the effect of SDMA techniques onto the MAC layer.

The SSs are assumed to have only one antenna element. They are not capable to use advanced antenna techniques like, e.g beamforming. The are always sending and receiving omni-directionally.

The position of two phases of the MAC frame must be known to all stations, especially to stations which are not yet registered at the BS. These phases are the contention slots for initial ranging and bandwidth request. SSs which want to enter the system can register themselves within the initial ranging slots. A SS which needs bandwidth can request it within the bandwidth request slots. In both cases the BS does not know in advance which SS will utilize the contention slots. Since the information about the two phases are specified in the UL-map, the UL-map has to be transmitted omni-directionally.

The preceding phase for DL data transmission (DL-subframe) and the following UL transmission bursts are fully scheduled by the BS. The BS is always aware which SS is receiving and which SS is sending data. Thus the BS can schedule the SS in a way that enables the BS to simultaneously receive data from and send data to different SSs.

B. SDMA enabled MAC frame structure

Fig. 2 illustrates how the standard-compliant MAC frame is able to support SDMA. Above the frame one can see the antenna characteristic which is applied to the BS antenna array for the particular phase. The duration of the phase and the served SSs can be seen below the frame. Inside the DL-burst #1 of the MAC frame, the DL- and the UL-map is highlighted. The arrows coming out of the maps identify the timing information (start time or burst duration) which is included in the maps.

Starting with the DL-preamble, the first part of the frame is sent omni-directionally. Preamble, FCH and DL-burst #1 are sent everywhere as the antenna pattern above the frame indicates. This is necessary because all SSs need to decode the DL- and especially the UL-map like it was outlined in section III-A.

At the beginning of DL-burst #2 the antenna characteristic changes. The BS is able to determine the antenna weight factors it has to apply to each antenna element, because the BS has already received at least the registration (and maybe data) from the SSs. During this initial reception of the registration message, the spatial filter respectively the direction of arrival could be calculated at the BS. This calculation is assumed to be done perfectly during the registration process. Thus, the base station can send one data stream containing DL-burst #2a in the direction of a group of subscriber stations. 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 just 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. So 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. Like this, two different data streams with the same PHY mode can be sent during the same DL-burst to different SSs (or groups of SSs).

After DL-burst #2 the antenna pattern changes again. Within DL-burst #3 other SSs have been scheduled by the BS. So the antenna weight factors have to be changed to send data to these SSs adaptively. Again the start time and the PHY mode are known by the SS. The BS sends different data streams,

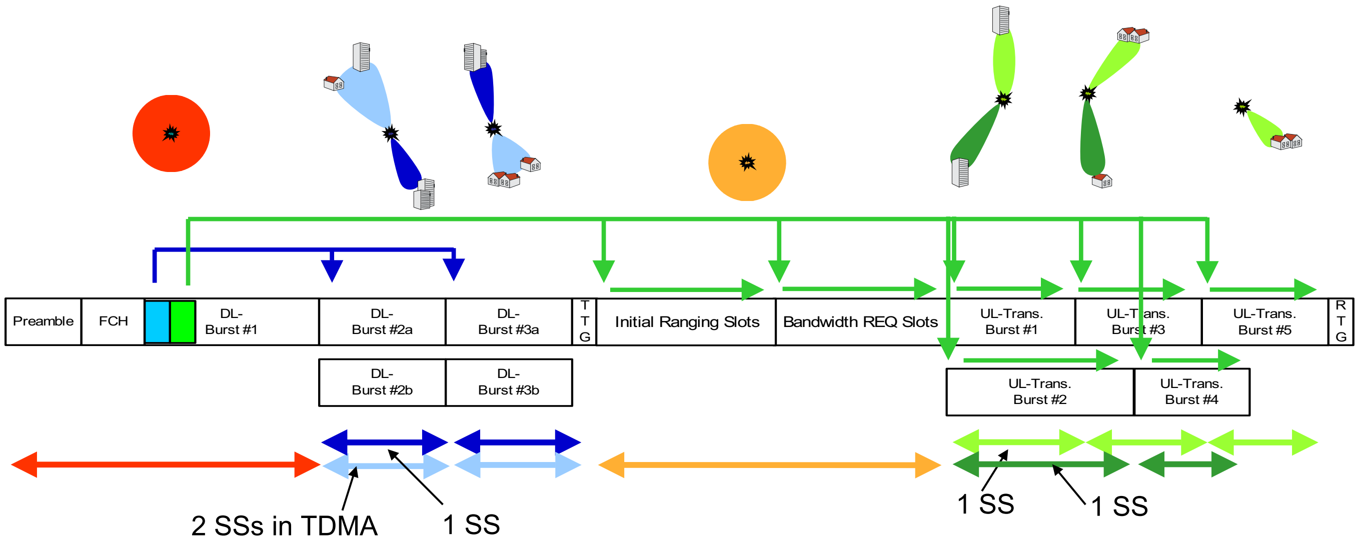

Fig. 3. SDMA use of enhanced MAC frame

i.e. DL-burst #3a and #3b to different SSs (or groups of SSs) simultaneously.

Since the SSs of DL-burst #3 might not receive any signal during the preceding DL-burst #2, they might loose their synchronization. The time synchronization is not critical but the frequency synchronization might cause trouble. But since beamforming can not be perfectly applied (there are side lobes directing in other directions) and due to multipath propagation there should be always a weak signal which is used to keep track of the frequency synchronization. Another solution to re-synchronize might be a preamble at the beginning of each DL-burst.

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, the UL transmission bursts are following. As already mentioned above, the UL map IE only contains the burst duration. The start time is calculated as the addition of all durations of preceding bursts. This behavior leads to a succession of UL transmission bursts. There is no way to communicate a simultaneous transmission of different SSs. Nevertheless the BS can use beamforming to increase the SIR of each single signal at the receiving BS. Like this higher PHY modes can be assigned to the SSs or with a given PHY mode the rest bit error ratio is reduced.

Finally, the parallel transmission of data to different subscriber stations 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.

IV. Enhanced SDMA concepts

The constraint of the IEEE 802.16a standard to support only a limited parallel DL leads to the following 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. A new field is added which is specifying the start time (12 bit) of the UL transmission burst. Like this, the start time is no longer the SS's addition of the durations of all preceding bursts, but it is directly signaled from the BS to the SS. Thus, parallel data transmission is possible in UL direction.

Fig. 3 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. All SSs can decode the DL- and UL-map. Since the DL-map and its IEs have not been changed the sequence of parallel DL-bursts equals the one outlined in chapter III.

But the UL transmission bursts, following the contention phase for initial ranging and bandwidth request, are now arranged differently. With the enhanced UL-map IE it is possible to let two different SSs start their UL transmission burst at the same time. Like in the DL, the antenna array of the BS adapts its weight factors to the received signals in a way that both UL transmission bursts, e.g. #1 and #2, are received simultaneously. The data streams of the SSs can be separated in the BS. The different streams are assigned to the

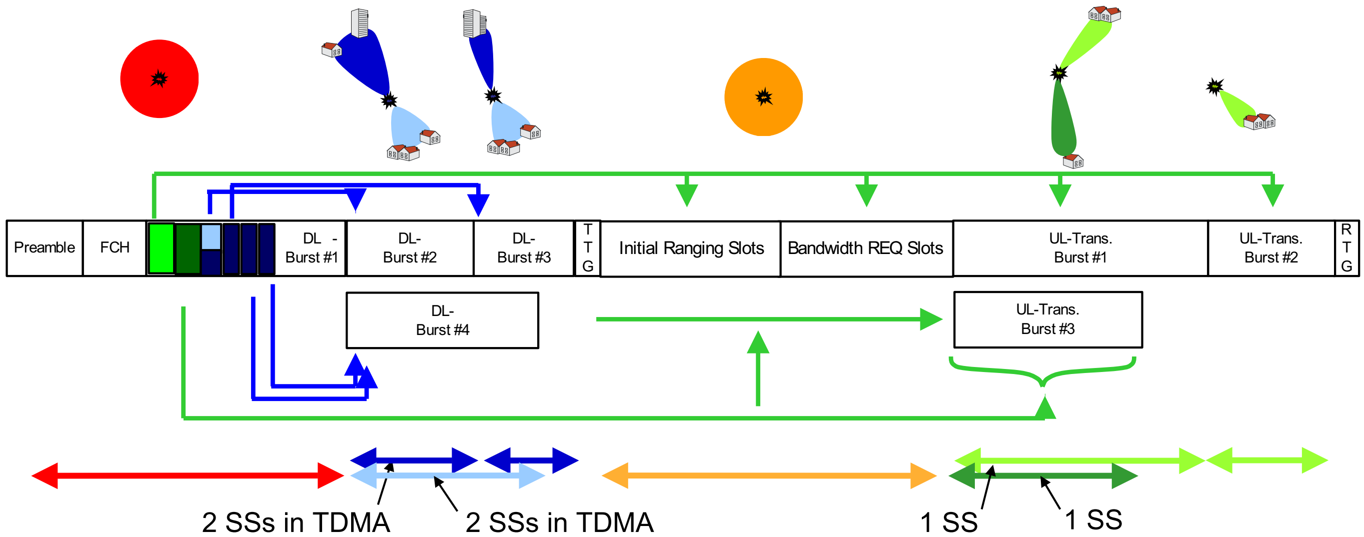

Fig. 4. SDMA support of private maps

corresponding SS and decoded as usual. The number of data streams is again limited by the capability of the antenna array to form lobes that sufficiently separate the received signals.

When a SS has reached the end of its UL transmission burst, indicated by the corresponding duration in the UL-map IE, it stops its transmission. Another SS, which has been scheduled by the BS, starts its transmission, e.g. burst #3, at the time indicated by the start time within the corresponding UL-map IE. The antenna weights of the BS are adapted to the new SS and the reception of the new data stream starts. 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.

Thus, the BS can receive different data streams coming from different SSs at the same time. In addition to the possibility of parallel DL, this concept enables the system to support SDMA techniques.

B. Private DL- and UL-maps

The restriction to use equal start times and lengths as well as to apply identical PHY modes in parallel DL-bursts leads to a concept with both, a flexible UL- and DL transmission. This new approach leverages private maps which are transmitted omni-directionally or adaptively, but whose addresses in the MAC header are not set to the broadcast CID but to the basic SS CID. This basic SS CID is a unique address which identifies a SS. Thus an individual frame structure in UL- and in DL- can be signaled to each SS.

Private maps are originally added to the standard with the advanced antenna system (AAS) option. This option extends the range of the IEEE 802.16a BS. SSs which can only decode the well known preamble, but which are not able to decode the omni-directionally transmitted maps, are referred to as AAS SSs and can use the AAS option. DL- and UL-maps for these AAS-SSs are transmitted adaptively into the corresponding direction. Since the range of the signal is extended while sending in the adaptive mode, the AAS SSs can now decode their private maps. Thus, it is possible for them to join the cell even if they are outside the omni-directional range of the BS [8].

In the AAS option, each SS only receives exactly one map. In contrast, within the new concept, SS might receive two DL- and/or two UL-maps. The required change of the standard would not be the introduction of private maps but the specification of rules how to handle two received maps. The private map, if present, has to overwrite the broadcast map. These private maps enable the BS to signal individual frame structures to the SSs. A flexible sequence of parallel DL-bursts as well as full flexibility in the UL can be achieved. In contrast to the AAS option, the function of private maps in this new concept is not range extension but capacity increase.

Fig. 4 illustrates the enhanced MAC frame behavior. It can be seen that within the DL-burst #1 several maps are transmitted omni-directionally. Some of them are addressed to the broadcast CID (broadcast maps, light color) while others are addressed to basic SS CIDs (private maps, dark color). Only the broadcast UL-map is mandatory since it contains the information regarding the contention slots. In Fig. 4 the broadcast UL-map is sent first and besides the contention slots it further specifies the subsequent UL transmission burst #1 and #2. Following the broadcast UL-map, a private UL-map is transmitted, which is specifying the UL transmission burst #3. This UL burst #3 is scheduled in parallel to UL burst #1 and can therefore not be signaled within the broadcast UL-map. The private UL-map is decoded only by one single SS. This SS should overwrite the broadcast information with the

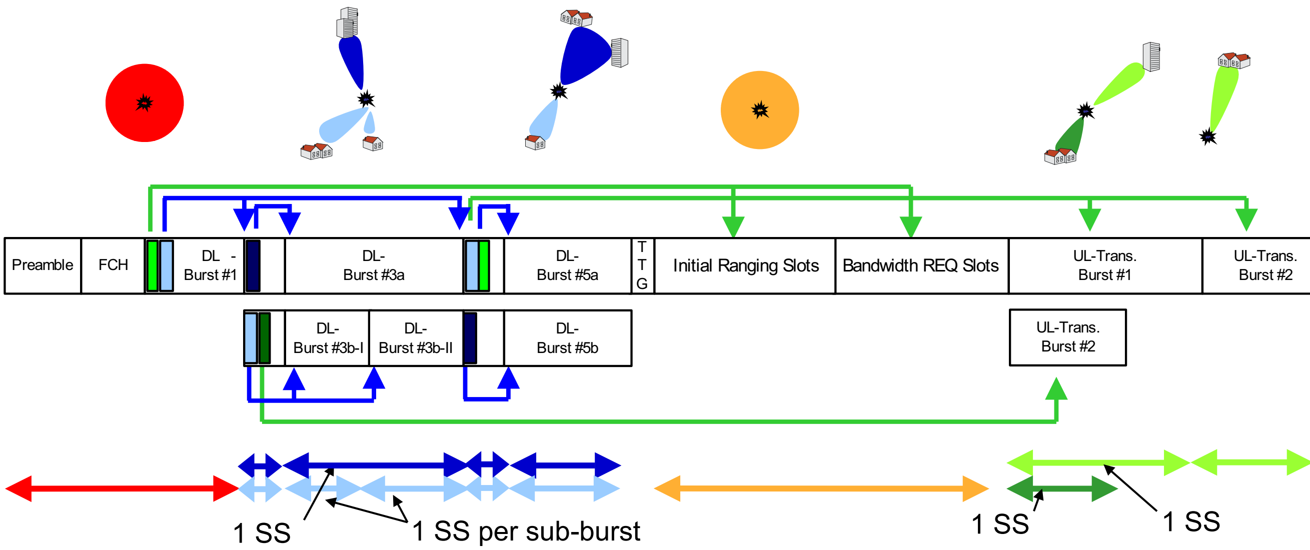

Fig. 5. Adaptive transmission of private maps

private one.

Next to the UL maps, the DL-maps can be seen in DL-burst #1. There might be a broadcast DL-map specifying the subsequent DL-bursts, but it is not required (half dark color, half light color). All SS which have been scheduled to receive data in the DL subframe can be addressed directly. In Fig. 4 the first DL-map refers to DL-burst #2 and it is sent to the broadcast CID. Two SSs will receive data within that DL-burst one after another. A time division multiple access (TDMA) scheme is applied within the burst. These two SS only receive the broadcast DL-map and no private one.

Following the broadcast DL-map a private DL-map is transmitted to the basic SS CID of the terminal which is receiving data in DL-burst #3. The private map is specifying only this burst for only this particular SS. Since there is data for only one SS in the burst #3, no further private map has to be sent for this burst. The last two private maps in the figure both specify the DL-burst #4. The burst itself contains data for two SSs in TDMA mode. To signal this information to both SSs, a private DL-map has to be transmitted to each of them. After the omni-directionally transmitted DL-burst #1 the remaining DL-bursts #2, #3 and #4 are sent adaptively into the direction of the corresponding SSs. All bursts might have their own start times, different durations and individual PHY modes. The DL-subframe now supports a fully flexible data transmission.

With the application of private UL-maps, the possibility of parallel data transmission is added to the UL-subframe. UL transmission burst #3 is received by the BS simultaneously to UL transmission burst #1. Neither the start time or length nor the duration of the burst is limited by the protocol. The number of parallel data streams is only limited by the capability of the adaptive antenna.

C. Signaling information sent in adaptive phase

The usage of private maps to support SDMA introduces overhead. The more flexible the frame structure gets, the more private maps have to be transmitted omni-directionally in DL-burst #1. This leads to the idea of transmitting the private maps in the adaptive phase. Therefore a frame structure has to be developed which is specified roughly by the broadcast maps during the omni-directional transmission of DL-burst #1. Later on, in the adaptive phase, private maps might be send to further specify the parallel data transmission in a more flexible way.

Fig. 5 shows the structure of the MAC frame. Within the DL-burst #1 only the broadcast UL- and broadcast DL-map are omni-directionally transmitted. To reduce the duration of DL-burst #1, they are kept as short as possible. Thus, the UL-map only contains two IEs which specify the contention slots for initial ranging and bandwidth request. The DL-map contains IEs which are specifying only every second DL-burst, i.e. #2, #4 etc..

After the DL-burst #1 the adaptive transmission phase begins. Since this DL-burst #2 is specified within the broadcast DL-map, its start time and the PHY mode is known and processed by every SS. Right at the beginning of that burst, additional DL-maps are sent, which further specify the subsequent burst. The DL-map included in burst #2a is specifying burst #3a and the DL-map in burst #2b is specifying burst #3b. The antenna weight factors, i.e. the spatial filter of the array, is not changed between DL-bursts #2 and #3. The maps and the following data (MAC PDUs) is transmitted only to those SSs which are scheduled by the BS. Thus, the DL-maps can be sent either as broadcast or as private maps, because even if the map is addressed to the broadcast CID, it can only be received by the SSs which are within the range of the antenna array. Only these SSs will receive data during the following burst and they have to adapt their PHY mode according to the adaptively transmitted DL-map.

Fig. 5 indicates that the DL-map in DL-burst #2a is a private map (dark color), because there is data for only one SS in the following DL-burst #3a. In contrast to that, the DL-map in DL-burst #2b must be addressed to the broadcast CID (light color), because two different SS will receive data in DL-burst #3b. One of the SSs is able to decode a higher PHY mode than the other, so the DL-burst #3b is split up into two parts. Data within DL-burst #3b-I is transmitted with a more robust PHY mode than the data in DL-burst #3b-II. The split of the DL-burst is specified by the corresponding DL-map.

This example shows that the proposed structure can adapt the DL-subframe very flexibly. The basic structure of DL-maps transmitted adaptively (in even numbered bursts) which further specifies the following (odd numbered) DL-burst, is repeated for different groups of SSs as often as needed to serve all users. The required change to the standard is the specification of the handling of two different broadcast maps. There is always one broadcast map for UL and DL. But SSs might receive another broadcast and/or private map which has to overwrite the earlier received maps.

To signal the current MAC frame structure of the UL-subframe, additional UL-maps have to be sent. These UL-maps are transmitted adaptively. The scheduler has to take care that the additional UL-maps are sent in the correct data stream which the corresponding SSs are able to decode. In Fig. 5 a broadcast UL-map is transmitted adaptively in DL-burst #4a, because the SSs that are scheduled in the UL transmission bursts #1 and #2 are also within the receiver range of DL-burst #4a. They are able to receive and decode the second UL-map addressed to the broadcast CID. The UL transmission burst #3, which is scheduled in parallel to UL transmission burst #1 has to be signaled individually. The corresponding SS is within the range of DL-burst #2b and therefore the UL-map can be transmitted there. Since the addressee is only one SS, the UL-map is addressed to the basic SS CID of this particular station.

It was outlined that the proposed concept is fully flexible in DL- and in UL direction. There are no restrictions concerning PHY modes, start times or burst durations. The omni-directional phase is kept as short as possible to save time for the data transmission phase. The additional private and/or broadcast UL- and DL-maps are all transmitted adaptively to reduce the introduced overhead. But the intelligence to schedule the data, the broadcast and the private maps all in the right positions and with the right spatial antenna filter, has to be implemented in the base station scheduler. The more flexible the MAC frame structure becomes, the more complex is the BS scheduler.

V. Conclusion

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 the current standard.

The concept of extending the UL-map information element with the start time of the UL transmission burst enables the system to fully support SDMA in the UL subframe, but the restriction in DL still exists.

The introduction of private DL- and UL-maps which are sent additionally to broadcast maps enables the support of SDMA both in UL- and DL direction. In contrast to the existing approach which extends the cell range, in the presented concept, private maps are leveraged to increase the cell capacity by means of simultaneous transmission and reception of data. This concept only introduces minor changes to the standard, because private maps are already existing in IEEE802.16a.

The overhead, introduced by private maps, can be reduced by the presented concept, that even signaling information is sent out adaptively. Only the basic frame structure is signaled during the omni-directional phase, while further information is transmitted adaptively via private and/or broadcast maps. This approach increases the complexity of the base station scheduler, but the overhead due to omni-directionally sent private maps can be significantly reduced.

VI. Acknowledgments

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References

[1] Koffman and Roman, “Broadband Wireless Access Solutions Based on OFDM Access in IEEE 802.16,” *IEEE Communications Magazine*, April 2002.

[2] Cherry, “The wireless last mile,” *IEEE Spectrum*, pp. 18–22, September 2003.

[3] U. Vornefeld, C. Walke, and B. Walke, “SDMA-Techniques for Wireless ATM,” *IEEE Communications Magazine*, pp. 2–7, November 1999.

[4] Siavash M. Alamouti, “A Simple Transmit Diversity Technique for Wireless Communications,” *IEEE Journal on selected areas in communications*, vol. 16, no. 8, pp. 1451–1458, October 1998.

[5] G.J. Forschini and M.J. Gans, “On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas,” *Wireless Personal Communications*, vol. 6, pp. 311–335, 1998.

[6] L. Godara, “Application of Antenna Arrays to Mobile Communications, Part II: Beamforming and Direction-of-Arrival Considerations,” *Proceedings of the IEEE*, vol. 85, no. 8, pp. 1195–1245, August 1997.

[7] IEEE, “802.16: Air Interface for Fixed Broadband Wireless Access Systems,” Tech. Rep., Institute of Electrical and Electronics Engineers, 2002, IEEE standard for local and metropolitan area networks.

[8] IEEE, “802.16a: Air Interface for Fixed Broadband Wireless Access Systems – Amendment 2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2–11GHz,” Tech. Rep., Institute of Electrical and Electronics Engineers, 2003, IEEE standard for local and metropolitan area networks.

[9] C. Hoymann, M. Püttner, and I. Forkel, “The HIPERMAN Standard – a Performance Analysis,” in *IST Mobile and Wireless Communications Summit*, Aveiro, Portugal, June 2003, pp. 827–831.