Adaptive Space-Time Sectorization for Interference Reduction in Smart Antenna Enhanced Cellular WiMAX Networks

Christian Hoymann, Benedikt Wolz
Chair of Communication Networks
RWTH Aachen University, Faculty 6, Germany
christian.hoymann@comnets.rwth-aachen.de

Abstract— **Adaptive antennas are currently being integrated into wireless systems. As one of the first standards the wireless metropolitan area network IEEE 802.16 provides means to support smart antenna techniques. By means of adaptive antenna patterns smart antennas allow steering the transmit/receive power into certain directions while suppressing undesired power, i.e. interference. This paper introduces an adaptive space-time sectorization scheme that reduces interference by grouping subscriber stations into space-time sectors. The realization of space-time sectors is achieved only by reorganizing transmit and receive bursts within the MAC frame. The proposed scheme results in the same interference reduction as conventional sectorization, but it avoids major disadvantages. Additionally, the sectorization scheme offers various benefits being combined with SDMA. Finally, a MAC frame structure has been designed to allow for space-time sectorization. The frame design is standard compliant to the promising radio access technology IEEE 802.16.**

IEEE 802.16, cellular WiMAX, sectorization, smart antennas, SDMA

I. Introduction

Advanced antenna technologies and algorithms that 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 [1]. Comparable approaches are currently being standardized by the 3GPP for UMTS or by the IEEE for 802.11n. IEEE 802.16 is supported by the WiMAX Forum, which is an industry-led, non-profit corporation formed to promote and certify compatibility and interoperability. Hence, the 802.16 system is often called WiMAX.

Advanced antenna techniques that are using multiple antennas either at the transmitter, at the receiver or at both sides are expected to have a significant impact on the capacity and service quality provided by wireless links and the efficient use and re-use of the available spectrum. Applying an antenna array at a transmitter, beamforming algorithms allow to focus the transmit power into certain directions. Furthermore it is possible to steer nulls in order to reduce the transmit power in other directions. Additional to specific directions, the power transmitted through all side lobes can be minimized. Thus, the desired output power is increased while the undesired output power is minimized [2]. Advanced antennas can improve the capacity of cellular radio systems in various ways. Switched beam antennas, which have a fixed antenna pattern, can be used for sectorization. The capacity increase due to switched beam sectorization has been shown [3]. Later, the ideas were adapted to CDMA systems [4] [5].

This paper investigates the influence of adaptive smart antennas on the level of interference in a multi-cellular network. Since WiMAX was one of the first standards to support smart antennas, the WiMAX system has been chosen as an example system to develop the concept in the following.

First, the capability of smart antennas to focus the transmitted energy into certain directions is leveraged to decrease the interference of a cellular WiMAX system. However, adaptive antenna patterns can only be used during the data transmission phase. Still, control messages have to be broadcasted using an omni-directional pattern. Although the interference can be reduced, the coverage area of a base station (BS) can not be increased.

Second, an adaptive space-time sectorization scheme is developed that further reduces the level of interference by grouping subscriber stations (SS) into space-time sectors. Now, the reduced level of interference can be leveraged by both, the data as well as the control phase. The realization of space-time sectors is achieved only by re-organizing transmit and receive bursts of SSs within the WiMAX MAC frame. Theoretically, this method results in the same interference reduction as conventional sectorization. But it avoids major disadvantages such as frequency channel allocation to sectors, the deployment of several sector antennas at each site, the operation of different MAC entities for each sector, and thus the necessity for a SS to handover between sectors. It is described how space-time sectorization leads to higher throughput values as well as to a more efficient frequency re-use, reflected by larger cluster sizes. Additionally, the proposed space-time sectorization offers various benefits being combining with SDMA.

II. WiMAX System

The IEEE 802.16 MAC layer provides convergence to various higher layer protocols, system access, bandwidth allocation, connection establishment, connection maintenance and security. Since the standard supports four different PHY layers, parts of the MAC are PHY layer independent while others are PHY-specific. In the following orthogonal frequency division multiplex (OFDM) PHY layer with a 256 point transform is assumed. It was designed for non line of sight operation in frequency bands below 11 GHz [1].

The MAC protocol supports a frame-based transmission. The MAC frame consists of a DL subframe and a UL subframe (refer to Figure 1.). Operating in TDD mode, the subframes occur subsequently on the same channel, while they are on separate frequency channels in FDD. 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 DL bursts following the FCH. The FCH is followed by one or multiple DL bursts. The very first DL burst contains broadcast MAC control messages: the DL-MAP defines access to the DL subframe and the UL-MAP allocates access to the UL subframe. Each DL burst is made up of PDUs scheduled for DL transmission. Optionally a DL burst might start with a preamble to allow for an enhanced synchronization and channel estimation of SSs. MAC PDUs transmitted within a DL burst are encoded and modulated by using the same PHY mode. Preamble, FCH, and, bursts containing control messages have to be broadcasted. DL burst containing unicast data PDUs can be transmitted applying an adaptive antenna pattern.

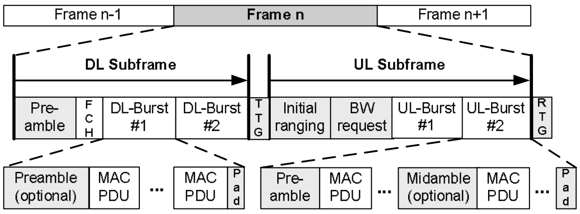


Figure 1. 802.16 MAC frame

The UL subframe consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple UL bursts for data transmission. The initial ranging slots allow a SS to enter the system. The bandwidth request slots are used to transmit bandwidth requests. 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. For better synchronization and channel estimation optional midambles might be periodically included in the UL burst. During the contention phase for initial ranging and bandwidth request, the BS has to receive omni-directionally. UL-bursts scheduled for unicast transmission can be received by the BS through an adaptive antenna pattern. For SDMA operation, the 802.16 standard foresees the allocation of concurrent DL and UL bursts [7]. More information about the IEEE 802.16 MAC can be found in [1] and [6].

III. INTERFERENCE REDUCTION OF SMART ANTENNAS

Beamforming algorithms allow to focus the transmit power of an antenna array into certain directions to increase the transmitted signal strength. Furthermore it is possible to steer nulls in order to reduce the transmit power in other directions. Additional to specific directions, the power transmitted through all side lobes can be minimized. Thus, the desired signal strength is increased while the undesired interference is minimized. Since an antenna is a reciprocal element, the same principle can be applied during the reception of signals. Signals coming from certain directions can be amplified while other directions or regions can be suppressed [2].

The resulting transmit or receive characteristic of such an array can be presented by antenna patterns. Figure 2. shows the antenna pattern of a circular 7-element antenna array that tries to focus its power into the direction of SS1 at 55° while it steers a null to the interfering SS2 at 25°. Furthermore, it can be seen that all side lobes are suppressed. Additional to the characteristic of the antenna, the power can be adapted. On the one hand, the power of the antenna can be adapted to meet the equivalent isotropic radiated power (EIRP) valid for the frequency band in use. Thus, the carrier signal in the desired direction is as powerful as with an ideal point source, but the interference in undesired directions is minimized. On the other hand the radiated power of the antenna array can be maximized so that the desired carrier signal is maximized.

Thus, smart antennas maximize the signal to noise plus interference ratio (SINR) by focusing the transmitted/received energy to/from the desired direction while they minimize the interference towards/from all other directions.

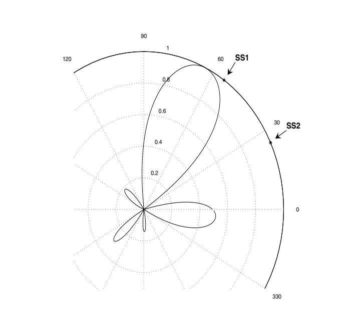


Figure 2. Example antenna pattern [antenna gain as amplitude factor]

The linear nature of the antenna elements enables an antenna array to apply two patterns to two signals simultaneously. Thus it can transmit one signal into one direction while it transmits another signal at the same time into another direction. Both receivers do experience a sufficient SINR. In general, this concurrent transmission / reception of data to / from different spatially separated channels is called space division multiple access (SDMA).

However, adaptive antenna patterns can only be used during the unicast (data) transmission phase. Still, broadcast (control) messages have to be transmitted using an omni-directional pattern. In systems relying on a broadcast phase, such as WiMAX, the interference during the data phase can be reduced by smart antennas and the throughput can be increased. But the interference perceived during the broadcast phase remains unchanged. Thus, the maximum coverage of a BS can not be increased. Even a smart antenna system is limited by the range of the broadcast and contention phase.

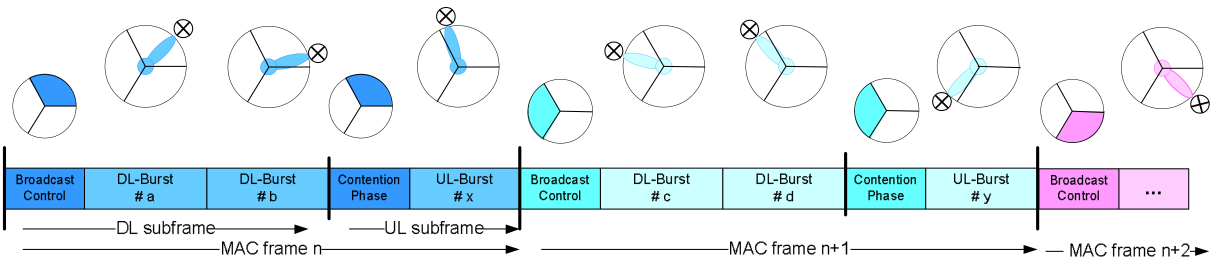


Figure 4. MAC frame and corresponding antenna pattern of space-time sectorization scheme

IV. Sectorization & Clustering

A. Clustering

In order to avoid interference in cellular networks, frequency channels used within one cell can only be reused after a sufficient reuse distance. Hence, cells are combined into clusters in which frequency channels are uniquely assigned to cells. The frequency usage pattern of the entire cluster is regularly repeated throughout the network. Like this the distance to co-channel cells can be increased. Figure 3. a) shows a network with cluster order three. Applying a cluster order k, the distance to co-channel cells D is only a function of the cell radius R [8]:

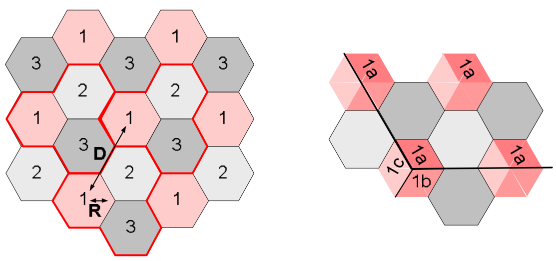
$$D = R * \sqrt{3 * k}$$

With the increasing co-channel distance the carrier-to-interference ratio C/I at a central BS receiving a signal from a SS at the cell border in an idealized network is increasing according to [9]. With γ as the path loss component the C/I can be calculated to:

$$\frac{C}{I} = \frac{1}{6}\left(\frac{D}{R}\right)^{\gamma}$$

B. Conventional Sectorization

Dividing cells into sectors is an established technique for reducing the interference level in conventional cellular wireless networks. The cell is subdivided into several sectors. Each sector is covered by a sector antenna. An individual frequency channel is assigned to each sector and an individual MAC protocol is controlling the access to the wireless channel. The sectorization of cells and the frequency assignment is periodically repeated all over the network.



a) cell cluster order 3 b) 3-sectored cells

Figure 3. Cell clustering & sectorization

Because the power that is emitted backwards from the sector antenna is minimized, the number of interfering co-channel cells can be reduced. Figure 3. b) shows a 3-sectored cell. It is illustrated that only three co-channel cells are visible for the sector antenna instead of six in Figure 3. a). Analog to the previous equation, the expected C/I in a sectorized and clustered cell is given by the following equation in which M is the number of co-channel cells depending on the sector size [9]:

$$\frac{C}{I} = \frac{1}{M}\left(\frac{D}{R}\right)^{\gamma}$$

For the example illustrated in Figure 3. sectorization increases the C/I by a factor of two. The draw-back of sectorization is that the number of channels and the number of users per sector is decreasing. This results in a lower trunking gain.

V. Adaptive Space-Time Sectorization

The new approach of space-time sectorization also divides the cell into sectors. But each sector is not covered by an individual sector antenna but by the smart antenna that is forming an adapted pattern. Furthermore, the sectors are not separated in frequency, but in time. Thus, all sectors are operating on the same band but in different time slots. In the regarded WiMAX system, these time slots are MAC frames.

Figure 4. shows a cell that is divided in three 120°sectors. In conventional sectorization one third of the spectrum is allocated to each sector constantly. The new space-time scheme allocates the entire spectrum to each sector for one third of the time. Thus the sectors are alternately served in the sequence of MAC frames. This alternating frame assignment to sectors can be arranged simply by scheduling the bursts of users located in the first sector within the corresponding numbered MAC frames, while bursts of users from the second sector are scheduled during their appropriate frames. After three subsequent MAC frames all sectors are served.

Even though sectors do have a specific shape, which is reflected by conventional sector antennas, the antenna pattern that is applied during reception or transmission must not have the shape of the sector permanently. Figure 4. illustrates that only during broadcast and contention phases the antenna pattern must be shaped according to the shape of the sector. During unicast transmission periods the antenna array is optimized to point to the proper SS.

By employing adaptive beams instead of sector antennas, a sector becomes a logically connected area, i.e., one sector refers to a group of SSs which are served within a distinctive time. No sector-specific hardware is deployed, such as sector antennas that predefine the shape of the sector. Furthermore only one MAC entity serves all sectors. Hence, the number and shape of sectors can be changed adaptively during the operation simply by updating the MAC protocol at the BS. Like this it is possible to adapt the shape of the sectors, for instance, to a varying traffic load of a network, even if the load follows the cycle of busy hours of a workday. It is also possible to re-shape the sectors of a cell to adapt the network to environmental and topology changes in the coverage area. A newly build office building might cause a re-optimization of the network sectorization, resulting in an adaptive re-shaping of the sectors [4].

Some shapes promise to improve a potential SDMA operation, as SSs can be served in parallel which have a greater angular width between them. Figure 5. shows two exemplary shapes of a two-sector cell. The first shape allows a separation between three SSs that is limited to 60°, whereas the second shape allows for a separation of 120° when three SSs are served in parallel.

Figure 5. Reshaped space-time sectors

The geometrical shape of the sector is limited only by the capability of the smart antenna. The angular width of the sector must be larger than the angular width of a single beam formed by the smart antenna. Otherwise transmit power is radiated to adjacent sectors where it causes interference. Other factors might affect the system performance, e.g., in order to benefit from multi-user diversity, the sectors must contain a considerable amount of users. Like in conventional sectorization, a reduced number of channels per sector results in a reduced trunking gain. If the sector should be served in SDMA, the angular width of a sector must be large enough to exploit the spatial separability of users within one sector. Thus, the shape of a sector should take these trade-offs into account.

While operating the network in SDMA mode, the SDMA scheduler has to find groups of users that are spatially separable. This is done by grouping algorithms whose complexity growth with the number of SSs [10]. If, e.g., a cellular WiMAX network is operating in SDMA mode, the proposed space-time sectorization does not only reduce the interference but it also significantly narrows down the solution space of grouping algorithms. The grouping algorithm as well as the SDMA scheduler has to look for an optimized solution only for the subset of users belonging to the same sector. Thereby, it allows a more efficient SDMA scheduling.

VI. WiMAX MAC Frame Structure to Support Space-Time Sectorization

Operating in space-time sectorization, transmissions have to be organized according to the scheme. In this chapter potential WiMAX MAC frame structures are proposed that allow for space-time sectorization.

The intended frame structure must be standard compliant. In IEEE 802.16 a SS periodically expects a preamble for time- and frequency synchronization followed by the FCH. The period between subsequent preambles is expected to be the frame duration, which is occasionally signaled in a MAC management message, i.e., the DL Channel Descriptor (DCD). At the beginning of the first DL burst, a UL- and a DL-MAP is required that specifies access to the DL- and UL subframe respectively. With respect to the proposed scheme, two fundamental types of phases can be distinguished within the MAC frame: the broadcast and contention phases and the unicast DL and UL transmission phases. Thus each SS expects to receive the following sequence periodically: broadcast, unicast DL, contention, unicast UL. Figure 6. outlines two potential WiMAX MAC frame structures that are organized to support space-time sectorization. The same example cell with three space-time sectors, shown in Figure 4. is assumed. The colors of the phases indicate which sector is currently served.

The upper frame in Figure 6. is an arrangement of three smaller MAC frames. Each MAC frame is an entire standard-compliant WiMAX frame including all necessary phases. Since the broadcast messages are transmitted, by means of the proper antenna pattern, in the corresponding sector only, SSs receive only every third preamble. Thus, the frame duration experienced by the SS, i.e., the difference between two consecutively received preambles, is three times the length of a single frame. This frame duration has to be signaled by the DCD so that SSs do not get confused. The MAPs received during the broadcast phase specify only the small MAC frame of the sector. The time interval meanwhile the other sectors are served, i.e., two frames, is left blank in the MAP. It seems to be unused.

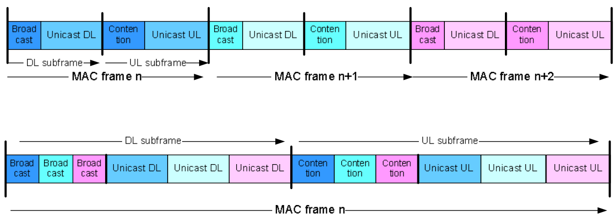


Figure 6. MAC frame structures

The lower frame structure in Figure 6. is a rearrangement of the first. It can be seen that the same phases occur but in a different order. Here all broadcast phases are grouped together and transmitted subsequently. All other phases, such as the DL and UL unicast as well as the contention phase are subsequently arranged, too. Now the frame duration experienced by the SSs is the length of the large frame. But, the perceived frame start times are shifted by the duration of one or two broadcast phases. Note that the preamble is assumed to be transmitted strictly periodical. Thus, the variable sized broadcast phase becomes fixed size in this structure. The frame is experienced as follows: it starts with the preamble/FCH combination followed by one burst containing other signaling messages such as MAPs. After an interval that is not scheduled for DL transmission, the DL bursts containing unicast PDUs are transmitted. Again the other sectors are served during the interval that seems to be unused. Then, another silent interval occurs followed by the contention phase. The unicast UL transmissions are scheduled again surrounded by two periods of silence.

Since the first proposed MAC frame structure (upper frame in Figure 6.) requires fewer modifications to existing MAC protocol implementations, the authors recommend this structure.

Compared to a regular non-sectorized WiMAX system with the same frame duration, the upper frame structure introduced slightly higher delay values since the perceived frame duration is three times the nominal one. A TDD system, that leverages the reciprocity of the channel, estimates the wireless channel in UL and uses the gathered channel state information for the DL. Such a system, e.g., a SDMA system, might suffer from the higher distance between the UL and the DL transmissions. The lower structure introduces more overhead compared to a regular frame of equal length, because the preamble and the FCH have to be transmitted three times instead of once. The MAPs can be shorter, but they have to be transmitted three times as well.

VII. Challenges of Space-Time Sectorization

Applying sectors in space-time domain requires synchronization of BSs in such a manner that the frame start and the switching point between DL and UL subframe has to be fixed and synchronized throughout the network. If otherwise co-channel cells are unsynchronized, i.e., different sectors are simultaneously active, the number of co-channel sectors that are generating interference increases and the impact of interference reduction due to space-time sectorization vanishes.

Imperfections in the antenna pattern applied during the broadcast and contention phases might decreases the benefit of the proposed scheme. It was mentioned that during these phases the antenna pattern has to be shaped so that the entire sector is covered but signals from/to neighboring sectors are suppressed. Imperfect patterns result in an increased level of interference.

VIII. Conclusions

The paper outlines that the capability of smart antennas to focus the transmitted energy into certain directions can be leveraged to decrease the interference of a cellular system during the unicast transmission phase. In order to reduce the interference during the critical broadcast and contention phase an adaptive space-time sectorization scheme is developed. By re-organizing transmit and receive bursts within the MAC frame, space-time sectors can be realized. The bursts are served by means of smart antennas. This scheme results in the same interference reduction as conventional sectorization, while avoiding major disadvantages. Both, the unicast as well as the broadcast phase benefit from this reduction. The reduced interference leads to higher throughput values as well as to a more efficient frequency re-use. Additionally, the proposed space-time sectorization offers various benefits being combining with SDMA. Finally, two potential WiMAX MAC frame structures were introduced that allow for space-time sectorization. The proposed frame structures are standard-compliant and can be easily configured without major changes to existing MAC protocol implementations. Only the allocation of unicast DL and UL bursts within subsequent MAC frames has to be re-organized.

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