MAC Protocol Requirements for WLAN's with Beamforming

Emilija Miletić and Klaus Tittelbach-Helmrich

Abstract — **In this paper we are discussing the specific problems that occur in the MAC layer for WLAN's with beamforming, such as hidden nodes, neighbor discovery, setting beamforming coefficients in MIMO systems and training sequences. We compare the solutions in MAC protocols based on different extensions of the IEEE 802.11 standard, on HIPERLAN/2 and in the MIMAX project.**

Keywords — **Beamforming, MAC layer, IEEE 802.11, MIMAX.**

I. INTRODUCTION

BEAMFORMING is a method of intensifying radio frequency (RF) energy at desired places, such as the receiver position, in order to improve the signal to noise ratio (SNR) there. Beamforming may increase system capacity and performance, suppress interference and noise, improve signal quality, and it may save power.

Beamforming techniques have been used for decades in a static manner for point-to-point connections. Recently, adaptive beamforming techniques have become very popular for wireless local area networks (WLAN). They allow changing the shape and/or directions of the beam during WLAN operation. Devices usually possess several antennas (MIMO = multiple input, multiple output), forming an antenna array. The interconnection between the elements, called the feed network, can transfer the signals with fixed phase to each element or can form a phased array. In optimum and adaptive beamforming, the phases of the feed network are tuned to optimize the received or transmitted signal. The geometry of the array and pattern, orientation and polarization of the elements influence the performance of the array.

When beamforming is being used in a WLAN network, adaptations of the Medium Access Control (MAC) protocol are required [1]–[3], since usually not all stations can be reached with the same form of the beam. Some problems to be expected and existing solutions will be discussed in this paper.

II. HOW TO FORM A BEAM

A. Parabolic Antennas

The classical static beamforming antenna is the parabolic antenna. Another classical solution is the Yagi antenna, consisting of one dipole, a reflector and a few directors. More advanced variants are the log-periodic dipole array, the horn antenna, and the Vivaldi antenna [4]. All those are suited for fixed stations having only one operating direction, i.e. for point-to-point links.

B. Sector Antennas

A sectored antenna consists of a number of directed antennas, oriented in different ways, which leads to a sector-shaped radiation pattern. Sector antennas are suitable for networks with several stations at different places, which is the typical setup of a WLAN. They may also be used for removing delayed signal originating from multi-path propagation by reflection or diffraction, and to reduce delay spreading [5].

C. MIMO Systems

In the MIMO approach the transmitter distributes its signal over multiple transmit antennas using a vector modulator. The receiver, reversely, combines the signal from its multiple receiving antennas using a vector de-modulator. This unit amplifies (attenuates) and phase-shifts the individual antenna signals in a controlled way before combining them, in order to achieve a stronger signal and better signal-to-noise ratio by constructive interference.

The gain and phase shift undertaken in the vector (de-)modulator of each antenna can be programmed by setting so-called beamforming or weight coefficients via software. In this way, the shape and direction of the beam can be modified while the WLAN system is operating.

There are other MIMO architectures, where *multiple* symbol streams are coded and multiplied by different coefficients at each antenna before transmission. Those architectures provide enhanced data throughput. However, they are outside the scope of this paper.

III. SPECIFIC PROBLEMS IN WLANs WITH BEAMFORMING

A. Hidden nodes

The hidden node problem emerges in WLAN networks, when terminals, which cannot directly hear each other, communicate with a third station. In Figure 1 (right), suppose B is sending a packet to A. E also wants to send to A, but it does not hear B and hence does not recognize that the channel is busy. When it starts to transmit, a collision occurs at A, which will receive neither of the two frames.

The same problem arises at C in Figure 1 (left), when it receives data from D and a communication between A and B begins.

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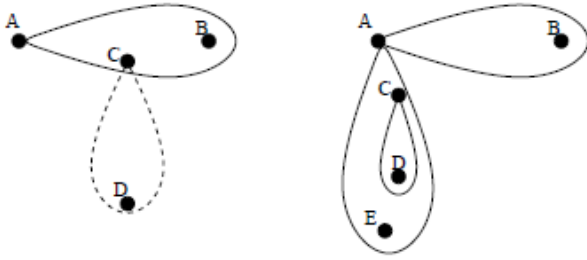
Figure 1 Hidden nodes in beamforming networks

The common solution for this problem, in particular in IEEE 802.11, is the RTS / CTS protocol. Both partners involved in a frame transfer exchange short frames RTS (Request To Send) and CTS (Clear To Send), which announce to every terminal, which can hear either one or the other partner, how long the channel will be busy. The RTS/CTS protocol does not completely prevent collisions, but only the short RTS frames should collide. The usually much longer data frames should be transferred undisturbed and without retransmissions.

Since beamforming improves the signal strength at some places, whereas degrading it at other places at the same time, the hidden node problem is aggravated in such systems.

B. Neighbors Discovery

In networks with sector antennas, upon association of a new terminal, the access point and perhaps also the terminal have to discover the optimum sector for communication. Usually, there is some scanning through the sectors. The proper antenna configuration shall be stored in some data base. In case of migrating terminals, a sector handover protocol is desirable. It should be carried out when the signal-to-noise ratio becomes too bad. A handover may also be advantageous for load balancing.

In MIMO systems, neighbor discovery is often much more complex, since MIMO usually provides much more tunable parameters than selecting one out of several antennas, and since it is a two-sided problem. Both, receiver and transmitter, have to scan. They will find each other only when both have (nearly) optimal antenna settings *at the same time*. The 60 GHz IEEE 802.11ad draft defines a sophisticated two-step algorithm for this.

C. Setting Right Antenna Configuration

In MIMO WLAN it is important to set optimal beamforming coefficients before every frame transfer. The transmitter may easily get those from an entry in its data base and the destination MAC address. For the receiver, setting the optimal beamforming coefficients *in time* may be more problematic, when it does not know the arrival time and transmitter's address in advance. This is for example the case in WLANs based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), which is the basic access protocol in IEEE 802.11 under Distributed Coordination Function (DCF). For non-AP stations in infrastructure networks this is not an issue because stations generally communicate only with the access point (AP).

D. Training Frames

Training frames are sent in MIMO systems before data exchange in order to find the best beamforming coefficients for each particular link. Training frames are exchanged when a station joins the network or in case when the channel deteriorates. The receiver evaluates the training frame and stores the beamforming coefficients for every station in a table, to reuse them before any future data transfer.

Instead of exchanging special training frames, it is also possible to include MIMO training sequences as part of the preamble in *every* frame. This procedure is applied in IEEE 802.11n MIMO WLANs.

IV. MAC SOLUTIONS FOR WLANS WITH BEAMFORMING

A. HIPERLAN/2

HIPERLAN/2 is an early European standard (developed in the late 1990th) for a WLAN-like communication network [6]. It has several very interesting features. One of them is MAC support for QoS (quality of service), another one is the option for sectored antennas. Unfortunately, this standard was not commercially successful.

The medium access in HIPERLAN/2 is based on an almost contention-free TDMA scheme. A scheduler in the central controller defines time slots for every link. Only a short contention-based phase may be used for associations and other unpredictable operations. Stations must strictly adhere to the time slot specifications, which are broadcasted in every beacon. This way, the problems of hidden nodes and of setting the right antenna configuration at the receiver (section III A. and B.) are circumvented. The receiver knows in advance, when and from which peer station it will receive something.

In case of sectored antennas (at the central controller), the MAC superframe is divided into parts, one for each sector. The central controller maintains a data base, in which sector a particular mobile terminal can be reached, and assigns the time slots for it accordingly. For moveable stations the MAC protocol defines a sector handover.

B. IEEE 802.11e

The basic method for channel access in the conventional IEEE 802.11 MAC protocol [7], [8], called Distributed Coordination Function (DCF), is a contention based random procedure. The disadvantage of this method with respect to beamforming is that the receiver does not know in advance, when and from which station it will receive the next frame. Thus, it cannot set optimal beamformer or weight coefficients in time.

The IEEE 802.11e standard (introduced in 2003) improves the original IEEE 802.11 MAC sublayer by introducing the hybrid coordination function (HCF), which includes two medium access methods: enhanced distributed channel access (EDCA) and HCF controlled channel access (HCCA). The EDCA is distributed and can be used in ad hoc networks while the HCCA is centralized and manages access to the medium using a QoS (Quality of Service) access point (QAP). Two new features introduced

in the HCF are the concepts of access category (AC) and transmission opportunity (TXOP). The AC allows for QoS support by assigning different priorities to different data streams. The TXOP is an interval of time when a station has the right to initiate one or more frame transmissions. This helps to reduce overhead due to backoff procedures for contention resolution.

For MIMO systems, the TXOP has the advantage that it also defines a period in time when the transmitter of data packets is known. All potential receivers can set their receiver weight coefficients accordingly.

Also the contention-free Hybrid Coordination Function (HCF) is ideally suited for beamforming, since it is completely controlled by the QAP. Stations only send upon request. They (normally) receive only from the QAP. There is no hidden node problem, and the MIMO antenna weights may be set in a well defined manner. However, HCF hasn't been implemented widely because of the tight frame timing requirements.

C. IEEE 802.11n

802.11n is an extension to the IEEE 802.11 standard introduced in 2007. It supports a longer range and higher wireless transfer rates by introducing MIMO schemes with up to 4 spatial streams. Within a 40 MHz band width channel in either the 2.4 or 5 GHz frequency band, the highest data rate is 600 Mbit/s.

802.11n can operate in three modes, see Figure 2: High Throughput (HT) greenfield Format in which only 802.11n clients are allowed in the network, High Throughput Mixed Format in which the AP listens out for legacy clients and defaults to low data rates for the time that the legacy devices want to transmit, and Non High Throughput Format that effectively treats 802.11n as if it were a 802.11a/g format frame allowing all Wi-Fi traffic to co-exist, but at the data rates of the lowest format (802.11a/g).

802.11n has defined the frame preamble in that way that reduces the need for training frames. Optimal beamforming coefficients may be set in the receiver with every frame transfer for the channel conditions at that time, based on the evaluation of the preamble.

The transmitter's beamformer needs to have an accurate estimate of the channel that it is transmitting over in order to calculate an appropriate steering matrix for transmit spatial processing when transmitting to a specific beamformee. The 802.11n standard defines two methods for this, using implicit or explicit feedback from the receiver [7].
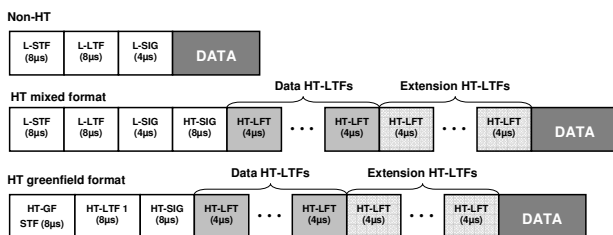

Figure 2 PPDU frame format in IEEE 802.11n
HT-STF: High Throughput Short Training Field
HT-LTF: High Throughput Long Training Field

D. IEEE 802.11 ad

This emerging standard is an amendment to the 802.11 standard that enables multi gigabit wireless communications in the 60 GHz frequency band. Since there are no widespread legacy systems operating in the 60 GHz band, backward compatibility is not an issue, in contrast to 802.11n.

To overcome the large free space propagation loss at 60 GHz, beamforming is used to increase the signal strength in a certain direction. Antenna arrays with a large number of antenna elements are easily possible due to the small radio wave length of about 5 mm. The peak beamforming gain increases along with the number of antenna elements. For example, 16 elements antenna array can provide approximately 12 dB of peak beamforming gain. If used at both the transmitter and the receiver, the additional 20 dB loss at 60 GHz (compared to 5 GHz), can be easily compensated. Such a patch antenna occupies only about 1 cm^2 in area when adjacent antenna elements are separated by half a wavelength. This is a very positive aspect when considering small form factor devices [9].

The draft 802.11ad MAC protocol [10] provides functionality to support neighbour detection and beamforming with two independent phases: sector level sweep (SLS, finding the appropriate antenna configuration for a communication link by double sided TX + RX sweep) and beam refinement protocol (BRP, fine tuning of antenna weights by exchange of training frames). For migrating stations, also a beam tracking procedure during data communication is intended to be implemented.

E. MIMAX

MIMAX [11] is an 802.11a compliant MIMO WLAN system at 5 GHz where signal combining is performed in the analog part of the transceiver, avoiding the need for multiple digital baseband processors. The aim is to reduce system complexity and size. In order to deal with the problems listed in section III, the following proprietary MAC layer extensions have been implemented:

- Determination of the optimal antenna Weight Coefficients (WC) for each connection by transmission and reception of training frames. Storing those optimal weights for each connection in a database.
- Exchanging a short frame sequence RTS/CTS (Request to send / Clear to send) before *any* data frame transfer to allow the receiver to set optimal weights.

A single RTS frame is sent before each multicast frame.
An RTS/CTS pair is generated before each unicast frame.

Figure 3 shows the normal MIMAX data frame sequence (RTS+CTS+DATA+ACK). The transmitter sets the optimal WC's from the data base in the MAC processor before starting the transmission of the RTS frame. The receiver has to receive the RTS with some default or "idle" WCs. It can set the optimal weights when it has identified the transmitting station from the source MAC address in the RTS frame. After the final ACK frame (horizontal line), both stations automatically return to the "idle" weights to be prepared to receive the next RTS.
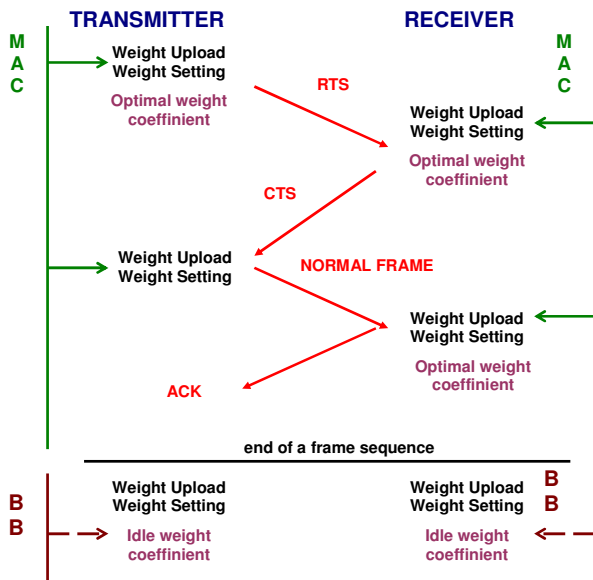
Figure 3: MIMAX normal unicast frame sequence

The frame sequence for training frames is very similar, except for the omitted ACK (Figure 4). From the received training frame, the receiver extracts new optimal weight coefficients and transfers them to the MAC (weight update). There, the WC's are stored in a table that contains the peer station's MAC address and the appropriate coefficient. For transmitting, the same weights are used as for receiving.
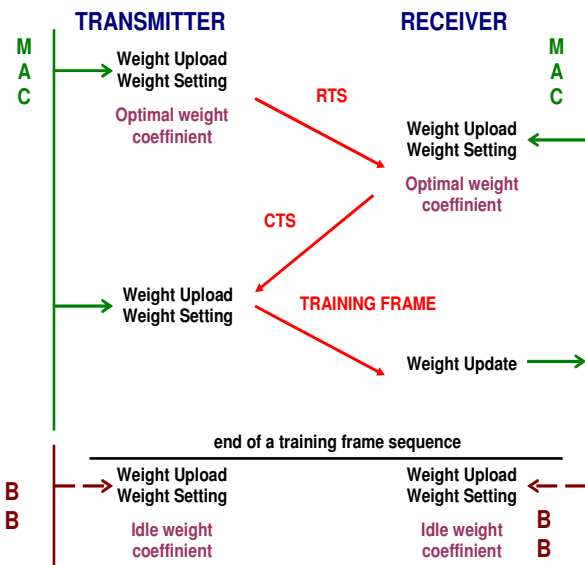

Figure 4: MIMAX unicast training frame sequence

The RTS / CTS pair imposes an undesired overhead on each MAC frame transfer. For 802.11a at 6 Mbit/s it is about 125 µs (RTS + CTS frame durations + two SIFS times). This is rather large, compared with the roughly 10 – 30 µs training symbols duration in 802.11n. For larger data frames, the loss is over-compensated by the higher data rate, which can be used to transfer the long data frame when optimal weight coefficients have been set.

When becoming a member of a WLAN network, a new station needs to find out the optimal WCs for each link with another existing station. After joining the BSS, the new station sends a training frame to the broadcast MAC address. Every other station receiving this frame shall respond with a unicast training frame to the originator of the broadcast training frame, see Figure 5. In this way, one pair of training frames is exchanged between the new and any old stations. The new station can make a complete table of all existing stations in the BSS with appropriate WC's. The other stations may update their tables with the data for the new station.
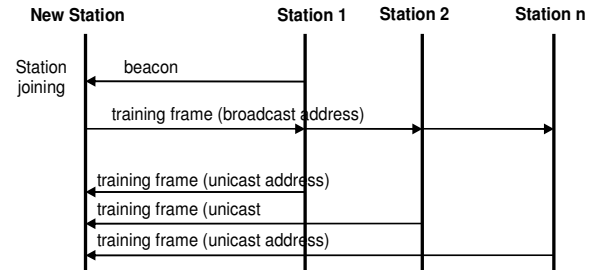

Figure 5: Training frame transfers when
a new station joins to a MIMAX network.

There are more situations when sending of a training frame is desirable. Some of them are in case when a transmission finally fails after a couple of retries (CRC check is wrong) or when the channel became very bad.

REFERENCES

[1] Khalil Fakih, Jean-Francois Diouris, and Guillaume Andrieux, "Beamforming in Ad Hoc Networks: MAC Design and Performance Modelling", *EURASIP Journal on Wireless Communications and Networking Volume 2009, Article ID 83942*

[2] Harkirat Singh and Suresh Singh, "A MAC protocol based on Adaptive Beamforming for Ad Hoc Networks", *Personal, Indoor and Mobile Radio Communications, 2003. PIMRC 2003*

[3] Ram Ramanathan, „Antenna Beamforming and Power Control for Ad Hoc Networks", *BBN Technologies Cambridge, Massachusetts*

[4] Dirk Plettemeier; Michael Jenning; Ting-Jung Liang, "Multilayer Vivaldi antenna for 60 GHz applications," *Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP), 2010* , pp.1-5, 12-16 April 2010

[5] Kohei Mori, "Study of Smart Antennas for High Speed Wireless Communications", *Doctoral Dissertation, Division of Electrical and Computer Engineering, Yokohama National University.*

[6] Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; System Overview, ETSI Standard TR 101 683, www.etsi.org

[7] Standard for Information Technology, Telecommunications and information exchange between systems, Local and metropolitan area networks, Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications.

[8] Oliver Hoffmann, "Tutorial on radio communications: From the basics to future developments Part 3: Advances in wireless LANs", *MobiLight 2010, 12 May 2010, Barcelona.*

[9] Eldad Perahia, Carlos Cordeiro, Minyoung Park, and L. Lily Yang "IEEE 802.11ad: Defining the Next Generation Multi-Gbps Wi-Fi", *IEEE CCNC 2010*

[10] IEEE document 802.11-10/0432r0, https://mentor.ieee.org/802.11/

[11] ICT MIMAX project, http://www.ict-mimax.eu/