WIRELESS WORLD
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MAC Frame Concepts to Support Multihop Communication in IEEE 802.16 Networks

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***Abstract*— The introduction of relay stations into metropolitan area networks allows providing ubiquitous broadband access economically to everyone, even to subscribers in remote places. IEEE 802.16, also known as WiMAX, is one of the most promising technologies that currently integrate relays for multihop communication. Such a relay enhanced IEEE 802.16 network can provide ubiquitous radio coverage, achieve high QoS requirements, and it can be economically deployed and operated. This paper presents two concepts to integrate multihop communication into the IEEE 802.16 system. The first concept follows a centralized approach where the base station has full control over the relay-enhanced cell. The second concept follows a semi-distributed approach where a relay station controls the associated subscriber itself. Both concepts are standard-compliant so that legacy subscriber stations can participate without modification.**

***Index Terms*— IEEE 802.16, multihop MAC frame**

INTRODUCTION

ONE of the major challenges for the telecommunication community is to provide diverse broadband services everywhere. IEEE 802.16 provides broadband access with performances similar to wired xDSL systems, which surpass current 3G mobile data rates. The IEEE standard 802.16 forms the basis of the WiMAX certified technology. [1] [2] [3]

Every wireless system suffers if the radio propagation characteristics become challenging, so does WiMAX. The achievable signal-to-noise ratio (SNR) and therewith the data rate decreases with an increasing link distance. This results in low SNRs at the cell border. Shadowing, which leads to non line-of-sight (NLOS) communication, further reduces the perceived signal quality. The introduction of relay stations may significantly enhance the link quality leading to throughput enhancements and coverage extensions [4]. Thus, relays allow providing ubiquitous broadband access economically to everyone, even to subscribers in remote places. Such a relay enhanced IEEE 802.16 network can provide ubiquitous radio coverage under challenging environmental conditions, achieve high QoS requirements, and it allows for efficient frequency re-use. Furthermore, an economic and scalable deployment and operation is possible, since the network can be flexibly adapted to changing users' behavior or environmental conditions.

Several multihop concepts for frame-based MAC protocols have been developed so far. The wireless LAN standard HiperLAN/2 (H/2) contains a direct mode that allows terminals to communicate directly. The H/2 access point (AP) is coordinating the access, so all terminals that transmits and receives packets via multiple hops must be in the coverage area of the AP's broadcast channel [7]. This excludes a coverage extension by means of relays. Another concept, called the beacon concept, relies on the H/2 option for sector antennas, where an AP transmits the broadcast messages and the following MAC frame through each sector antenna sequentially [6]. Although WiMAX does not foresee such an option for sector antennas, the frame buildup of this concept is similar to the centrally controlled MAC frame proposed in this paper. The third proposal, the subframe concept, realizes multihop communication without special standard options [5]. The AP allo-

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cates periods within its MAC frame for relay stations. The relay station can use these periods to act as an AP, thus generating an individual MAC frame (subframe) for the terminals that are associated to the relay. This promising concept inspired the design of the multihop subframe presented in this paper.

The IEEE 802.16 mesh mode is an optional feature of the standard. As in the H/2 direct mode, traffic can be routed directly between subscriber stations (SSs). The mesh mode replaces the point to multipoint (PMP) frame structure [1]. Thus, legacy 802.16 stations are not able to communicate with such a mesh network. The Task Group IEEE 802.16j wants to overcome these limitations. It aims at specifying enhancements for a mobile multihop operation without further modifications to SSs. Thus, the frame structure shall be PMP compatible and the MAC management procedures, such as association or handover, shall not be modified. Unlike the 802.16 mesh mode, the task group aims at a tree-based deployment only.

According to the requirements of the IEEE 802.16j task group, this paper presents two concepts to support multihop communication in 802.16 networks. Both follow the forwarding principle decode and forward, in which a relay decodes the received data packets and forwards them on the next hop. This paper considers layer 2 forwarding, i.e., packets are processed up to the MAC layer only. The concepts utilize time domain forwarding, where packets are forwarded on the same frequency channel. Thus, the relays have to be equipped with only one transceiver. Although the concepts are based on OFDM, they can be extended to OFDMA, which is the target PHY layer in the 802.16j task group. The control elements, for instance the DL- and UL-MAP, which specify the current MAC frame realization, have to be adapted. The principle frame structure remains valid.

IEEE Std 802.16 MAC Frame

IEEE 802.16 supports a frame-based transmission. Figure 1 illustrates the frame structure of the OFDM PHY layer operating in TDD mode. Each frame consists of a DL subframe and an UL subframe. Subframes are separated by gaps, which overcome the round-trip delay and which allow stations to switch their PHY processors between transmit and receive states and vice versa. The partitioning between DL and UL may vary dynamically to efficiently handle an asymmetric traffic load.

DL subframes start with the periodic broadcast of control information. This phase is composed of the DL preamble, the frame control header (FCH) and the first DL burst. SSs use the periodic DL preamble for synchronization and they perceive the current frame duration as the time interval between two consecutive DL preambles. The frame duration, which may be chosen between 2.5 and 20 ms, is fixed during normal operation. The FCH and the MAC management messages included in the first DL burst define the access to the DL and UL channel, respectively. These messages are composed of Information Elements (IEs). Each IE specifies one corresponding burst. The arrows in Figure 1 indicate the references of IEs within the relevant messages (FCH, DL- and UL-MAP) to the corresponding DL- and UL bursts. The following DL bursts are made up of MAC packet data units (PDUs) scheduled for DL transmission.

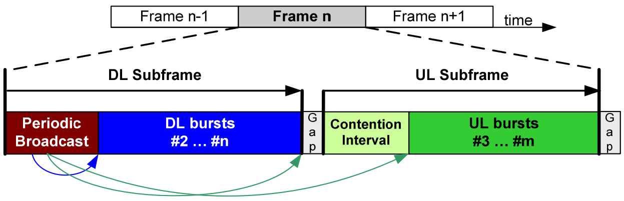

Figure 1: MAC frame structure

The UL subframe consists of contention intervals and one or multiple UL bursts. The base station (BS) schedules slotted contention intervals for initial ranging and for bandwidth request purposes. Initial ranging slots allow SSs to enter the system. UL bursts contain PDUs transmitted by SSs that are scheduled for UL transmission. Since the system is not intended to be highly dynamic and since sophisticated UL bandwidth request mechanisms exist, the BS is not obliged to schedule contention intervals every frame. In order to reduce the MAC overhead, they might be scheduled only occasionally. A more detailed description of the 802.16 frame structure can be found in [1] [3].

The concepts proposed in this paper follow the goals of the task group 802.16j that targets a PMP compatible frame structure and unmodified MAC management procedures. Thus, the minimal requirements are as follows:

- Strictly periodic DL preambles
- Broadcast information (FCH, MAPs) di-

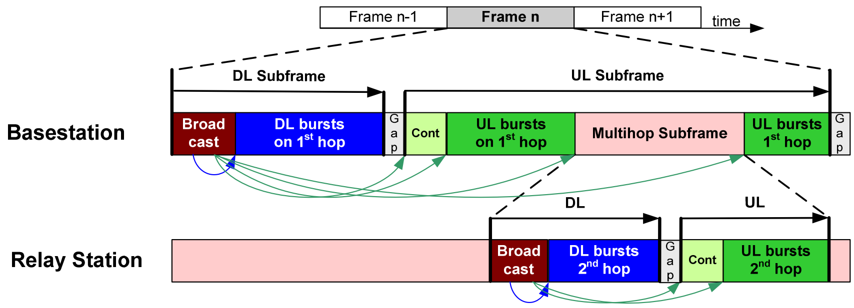

Figure 2: Multihop Subframe Embedded in an 802.16 MAC Frame

rectly following the DL preamble

- Frame description by means of standard-compliant management messages
- Partition of MAC frame in subsequent DL and UL subframe
- Contention intervals provided occasionally

Decentrally Controlled Relays

This chapter presents a decentrally controlled relaying approach. Decentrally controlled means that the relay has full control over the SSs that are associated to it. For the BS, such a relay appears like an ordinary SS. For SSs this relay appears to be a regular BS. The next sections outline the frame structure and the connection management.

Multihop Subframe

The decentralized concept extends the H/2 subframe concept [5] and applies it to the 802.16 system. During the multihop subframe interval, the BS does schedule neither DL nor UL traffic. Instead, it dedicates the interval to the control of the relay station. The relay itself builds an entire frame. This multihop subframe is a standard compliant 802.16 MAC frame.

Figure 2 shows the modified 802.16 frame with the embedded multihop subframe. The frame starts with the DL subframe composed of the broadcast phase and DL bursts. The DL bursts contain PDUs transmitted to SSs that are associated to the BS directly. For the BS, the relay appears to be a regular SS to which data packets are transmitted. All DL bursts of the regular frame are specified by means of the DL MAP. Thus, DL bursts serve SSs and relays on the first hop. Note that the regular DL MAP does not contain IEs that specify burst of the multihop subframe.

The UL subframe starts with a contention interval followed by UL bursts. SSs, which are close to the BS, use these contention slots for network entry or bandwidth requests. The following UL bursts are scheduled for UL transmission. Some bursts contain UL traffic of associated SSs. Other UL bursts are scheduled for the first-hop transmission between the BS and relay stations. Within these bursts, relays can transmit its UL traffic to the BS. Another UL burst is not addressed to UL transmission at all, but it is reserved for the multihop subframe. The BS's broadcast phase specifies this burst by means of a regular IE inside an UL MAP. An arrow in Figure 2 indicates the reference of the IE to the burst.

In order to be standard compliant, the frame structure of the multihop subframe is again divided into a DL and an UL subframe. The DL part starts with the broadcast of control information. The corresponding management messages are only relevant for the multihop subframe. As the arrows in Figure 2 indicate, the DL MAP defines access to the second hop DL channel and the UL MAP schedules UL bursts on the second hop. The relay's management messages only contain IEs that specify bursts of the multihop subframe. The following DL bursts of the multihop subframe contain PDUs for SSs on the second hop. UL bursts are scheduled for UL data on the second hop. A gap divides the DL and the UL part of the multihop subframe. SSs close to the relay can access the contention slots, which are occasionally scheduled at the beginning of the UL part of the multihop subframe to enter the network or to request bandwidth.

The broadcast phase must occur periodically, so that the BS has to schedule the multihop subframe at fixed time intervals. This interval can be as long as the BS's frame duration so that the multihop subframe occurs every frame. Alternatively, the relay's frame duration can be integer multiples of the BS's frame duration so that the multihop subframe occurs only every second or third frame. Anyway, it must not exceed the maximum frame duration (20 ms for OFDM). The periodic scheduling of the multihop subframe can be accomplished since 802.16 provides scheduling services that have been designed to support real-time data streams that generate data packets on a periodic basis. These services, e.g., Unsolicited Grant Service or real-time Polling Service, assign UL bursts at periodic intervals. A relay can use such a periodic UL burst to establish its multihop subframe. The size and the duration of the burst is specified by the QoS parameter set associated to the corresponding UL connection.

SSs close to the BS only notice the BS's frame, whereas SSs near the relay observe the relay station's (sub)frame as if it was a regular frame. SSs that perceive both broadcast control phases believe that they are between two neighboring cells. Therefore, they will associate to the cell that they receive most loudly. The association of SSs to the relay is handled by means of the standard compliant initial ranging procedure.

If the BS is enhanced by more than one relay station, several multihop subframes have to be scheduled in the MAC frame of the BS. If the relay's subcell is enhanced by another relay, a second multihop sub-subframe can be embedded in the subframe of the relay. In this manner, a three-hop communication is provided hierarchically.

Connection Masquerading

The introduction of relay stations demands for a special connection management at the relay station. The relay has to route traversing packets in DL (away from the BS) and in UL (towards the BS) direction from hop to hop. It has to maintain a control connection to exchange signaling information with the BS and it possibly receives and transmits data packets on its own.

The presented Connection Masquerading follows the decentrally controlled relaying approach. For the associated SSs the relay provides all necessary procedures to setup transport and management connections so that the relay acts as a regular BS. For the BS, the relay appears to be an ordinary SS, thus it can setup and release transport connections by means of the standard procedures. Beside the transport connections, the relay maintains its management connections.

Figure 3 shows the connection setup of the masqueraded connection management. The relay station (RS) itself establishes the control connections to the BS. It uses these connections to exchange signaling information, such as connection management or periodic measurement reports. The relay in Figure 3 has also set up transport connections to receive and transmit data packets. These packets include data that is generated, e.g., by a customer that uses the relaying device as a regular SS.

On the right side of the relay, the associated SSs have established management and transport connections to the relay station. The synchronization to the relay's periodic broadcast phase, the contention-based network entry process, and the registration of a SS is handled by the relay. The backbone network assists the process of authentication and authorization. The relay accesses the backbone via its transport connections.

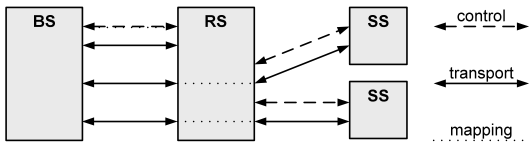

Figure 3: Connection Masquerading

For each transport connection that a SS sets up, the relay opens an associated connection to the BS. Both connections have the same level of QoS. The BS is not aware that the connection corresponds to a SS that is connected by means of a relay. The relay masquerades the transport connection. It maintains a table to map the connection identifier (CID) of one hop to the CID of the other and vice versa. This mapping is indicated in Figure 3.

All protocol functionality that maintains a proper packet transmission, such as ARQ, segmentation and reassembly (SAR), or burst profile management, is performed a link basis. Thus, one link does not affect the subsequent one.

Centrally Controlled Relays

This chapter presents a centrally controlled relaying approach. The BS has full control over the entire relay enhanced cell. The BS directly controls all SSs and all relay stations that are associated to the BS. The relay just forwards packets from hop to hop.

Centralized Multihop Frame

The BS schedules all transmissions, both on the first hop and on subsequent hops. The relay forwards the relevant subset of the control information to the SSs in its subcell. The relay behaves according to the BS's schedule, i.e., it receives, and transmits during bursts scheduled for the corresponding hop.

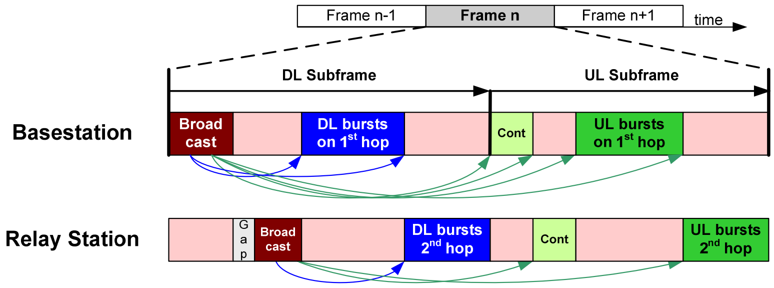

Figure 4: Centralized Multihop MAC Frame

Figure 4 shows the centralized multihop frame. The BS periodically transmits broadcast control information. The DL preamble indicates the frame start and the following management messages, i.e., FCH and MAPs, specify the entire MAC frame including the bursts scheduled on the second and on any subsequent hop. Hence, the BSs' MAPs are larger compared to the BSs' MAPs of the subframe concept. In order to calculate an appropriate schedule, the BS needs to know which connections of the entire relay enhanced cell are active, which QoS requirements do they have, and which connections request UL bandwidth. Having received the broadcast information, the relay filters it and forwards only the relevant subset of information to its subcell. A gap needs to be included in between the BS's broadcast and the relay's broadcast. This gap takes the relay's round-trip delay, the transceiver switching as well as the MAP filtering into account. Figure 4 shows that the forwarded MAPs only specify the bursts that are scheduled for data transmission on the second hop. The size of the MAPs forwarded by the relay stations equals the one from the subframe concept. Before the relay starts transmitting the management messages, it sends the periodic DL preamble. Like in the subframe concept, the relay's frame start time has to be strictly periodic.

DL bursts for data transmission follow the broadcast phase. The BS schedules bursts for any hop. The UL subframe succeeds the DL subframe. Again, phases for data transmission on any hop are scheduled alternately. This ordering of transmission phases assures that all SSs that are associated either to the BS or to the relay do experience a regular, standard compliant MAC frame. They can associate, open connections, and they can receive and transmit data according to the 802.16 protocol.

Connection Mapping

The centrally controlled relay neither manages the SSs' connections nor does it masquerades the transport connections. It just forwards all packets to the BS and SSs, respectively. Figure 5 shows the schematic connection management at the relay station. The relay station itself has control and transport connections to the BS. They carry signaling and data traffic of the relay.

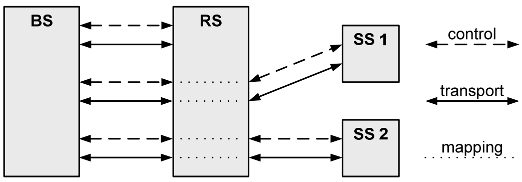

Figure 5: 1-to-1 Mapping of Connections

Furthermore, each connection between the relay and the SS corresponds to a connection between the BS and the relay station. Every time a SS establishes a management connection to the relay, the relay establishes a corresponding management connections to the BS. Each setup of a SS's transport connection results in a new transport connection of the relay. The mapping is realized by mapping tables.

After the synchronization of a new SS to the relay, it starts the ranging process by sending the ranging request during the relay's contention interval. The relay forwards this message to the BS. The BS processes the request and responds to the SS via the relay. The BS entirely handles the following network entry. However, the standard compliant association procedure has to be extended. Using the 1-to-1 mapping two management CIDs have to be assigned during the association procedure instead of one. One CID is required to identify the connection on the first hop and the other for the second hop. Since the BS schedules both hops, it needs to be aware which CID corresponds to which hop. Setting up transport connections follows the same principle. The relay just forwards the request and the BS assigns two transport CIDs.

Signaling messages, such as UL bandwidth requests and measurement reports have to be transmitted from the SSs to the

BS by means of the relay station. Thus, the BS gathers all necessary information to schedule DL and UL bursts for the relays and for the SSs. It periodically broadcasts the FCH and the MAPs and all nodes behave accordingly. This simple forwarding of management messages exclude any link-based control. Since the relay neither receives nor processes any control information, no link-based ARQ or SAR functionality could be performed. These mechanisms have to be performed by the BS on an end-to-end basis. This decreases their performance.

Conclusion

This paper presents two approaches to integrate relay-based multihop communication in the 802.16 standard. Both concepts configure a standard-compliant MAC frame so that legacy subscriber stations can participate without modification.

The first concept follows a decentrally-controlled approach where a relay station controls the associated subscriber itself. No changes to the standard are necessary, but the relays require a full featured MAC protocol whose complexity is comparable to that of a BS.

The second concept follows a centralized approach where the base station has full control over the relay-enhanced cell. The relay stations can be very simple. They only forward packets from one hop to another without processing them. This excludes any link control at the relay but an end-to-end link control is required. However, this approach requires modifications to the MAC management procedures of the BS and the relay station.

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