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Computer Networks 49 (2005) 341–363
Computer Networks
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Analysis and performance evaluation of the OFDM-based metropolitan area network IEEE 802.16

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Available online 22 June 2005

Abstract

Wireless last mile technology is becoming a challenging competitor to conventional wired last mile access systems like DSL and cable modems or even fiber-optic cables. The Institute of Electrical and Electronics Engineers has developed a standard for fixed broadband wireless access systems namely IEEE 802.16. Its OFDM mode targets frequency bands below 11 GHz.

This paper gives an overview of the OFDM-based transmission mode of the IEEE 802.16 standard. The medium access control (MAC) and the physical layer are described in detail. Especially the MAC frame structure is elaborated. An analytical performance evaluation of an example scenario is performed which results in overall system performance measures. Especially the interaction of fragmentation and padding of OFDM symbols and its effect on the system capacity is evaluated. Furthermore, different MAC layer configurations with different levels of robustness are analyzed. Optional features to resist challenging channel conditions are outlined. Their trade off, i.e., a reduced MAC layer capacity is pointed out. It is shown that the system can be optimized while maintaining the necessary robustness against environmental challenges. A prototypical IEEE 802.16 protocol stack including a sophisticated channel model has been implemented. By means of this stochastic event-driven computer simulator, downlink and uplink delay as well as throughput evaluation is performed. Thus, performance results based on meaningful MAC configuration examples are provided. Simulative and analytical results are compared.

Keywords: IEEE 802.16; WiMAX; MAC; PHY; OFDM; Performance evaluation; Analysis; Simulation

1. Introduction

The wireless metropolitan area networks (MAN) IEEE 802.16-2001 and its amendment for frequencies between 2 and 11 GHz IEEE 802.16a-2003 have been standardized in 2003

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1389-1286/$ - see front matter
doi:10.1016/j.comnet.2005.05.008

[1,2]. They specify four different physical (PHY) layers, whereof only the orthogonal frequency division multiplex (OFDM) layer is considered in the paper. The revision of the standard, including the MAN base document, the amendment for lower frequencies, i.e., below 11 GHz, and the amendment for detailed system profiles was published in October 2004 as IEEE 802.16-2004 [3]. From the date of publication the previous volumes are superseded by the new one.

The OFDM-based transmission mode of the IEEE 802.16 standard has been standardized in close cooperation with the European Telecommunications Standards Institute (ETSI) whose standard is named High PERformance Metropolitan Area Network (HiperMAN) [4,5]. Thus, the HiperMAN standard and the OFDM-based transmission mode of IEEE 802.16 are nearly identical. Both OFDM-based physical layers shall comply with each other and a global OFDM system should emerge [6]. Both standards form a basis for WiMAX certified technology. The WiMAX Forum (Worldwide Interoperability for Microwave Access) is an industry-led, non-profit corporation formed to promote and certify compatibility and interoperability of broadband wireless products such as IEEE 802.16 and HiperMAN [7].

The main advantage of fixed broadband wireless access (FBWA) 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 $450,000" [8].

Apart from being wireless the above-mentioned FBWA systems IEEE 802.16 and HiperMAN have been designed to meet today's most promising challenges: Non-line-of-sight operation capability cuts the deployment costs. Large cells radii allow for rapidly deployable infrastructure networks. This will decrease time to market for new broadband services which will be crucial for the success of new operators. Networks become even more scalable by utilizing the optional Mesh deployment. The system performance enables operators to offer services requiring high peak bit rates. Quality of service (QoS) support for packet-based services is provided by the system.

Following this introduction the OFDM-based transmission mode of the IEEE 802.16-2004 MAC protocol is described in detail in Section 2. Section 3 outlines the OFDM-based PHY layer with its main transceiver modules. A multi-user multi-mode scenario based on a realistic PHY mode distribution is derived in Section 4. A system performance evaluation by means of a mathematical system model follows in Section 5. The PHY and MAC layer capacity of the example scenario is calculated. Moreover, the interaction of fragmentation and padding is evaluated. MAC layer configurations with different levels of robustness are compared. In Section 6 a prototypical implementation of the IEEE 802.16 protocol stack is introduced. By means of the stochastic event-driven computer simulation, packet delay as well as throughput evaluation is performed. The simulation results are compared with analytical results.

2. IEEE 802.16 medium access control protocol

The scope of the IEEE 802.16 standard comprises the MAC and the PHY layer as illustrated in Fig. 1. The MAC includes a service-specific convergence sublayer that interfaces higher layers. The MAC common part sublayer carries the key functions and below resides the security sublayer.

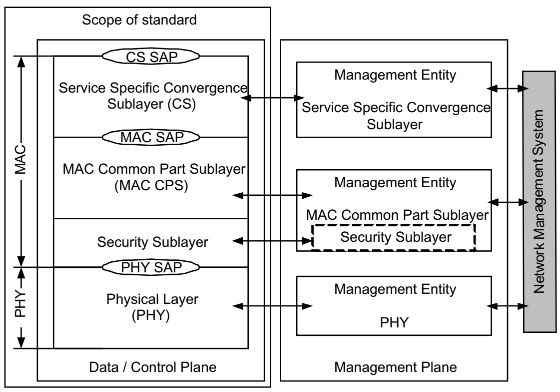

Fig. 1. IEEE 802.16 protocol layering [3].

2.1. Service specific convergence sublayer

The service specific convergence sublayer (CS) provides any transformation or mapping of external network data, received through the CS service access point (SAP). This includes classifying external network service data units (SDU) and associating them with the proper service flow identified by the connection identifier (CID). A service flow is a unidirectional flow of packets that is provided with a particular QoS.

2.2. MAC common part sublayer

The MAC common part sublayer (CPS) provides system access, bandwidth allocation, connection establishment, and connection maintenance. It receives data from various CSs classified to particular CIDs. QoS is applied to transmission and scheduling of data over the PHY layer.

IEEE 802.16 is optimized for point to multipoint (PMP) configurations where several subscriber stations (SSs) are associated with a central base station (BS). As an optional feature it allows for a flexible Mesh deployment where a direct communication between SSs is possible.

The system supports a frame-based transmission, in which the frame can adopt variable lengths. The frame structure of the OFDM PHY layer operating in time division duplex (TDD) mode is illustrated in Fig. 2. Each frame consists of a downlink (DL) subframe and an uplink (UL) subframe, with the DL subframe always preceding the UL subframe. The DL subframe consists of only one DL PHY transmission burst starting with a long preamble (2 OFDM symbols) used for synchronization.

The following frame control header (FCH) contains the DL frame prefix (DLFP) and occupies one OFDM symbol. The DLFP specifies the location as well as the modulation and coding scheme (PHY mode) of up to four DL bursts following the FCH. The mandatory modulation used for the FCH is BPSK with code rate 1/2.

The FCH is followed by one or multiple DL bursts, which are ordered by their PHY mode. While the burst with the most robust PHY mode, e.g., BPSK 1/2 is transmitted first, the last burst is modulated and coded using the highest PHY mode, i.e., 64 QAM 3/4. Each DL burst is made up of MAC packet data units (PDUs) scheduled for DL transmission. Optionally, a DL burst might start with a short preamble (1 OFDM symbol) to allow for an enhanced synchronization and channel estimation of SSs. MAC PDUs transmitted within the same DL burst might be associated with different connections and/or SSs but they are all encoded and modulated using the same PHY mode. In DL as well as in UL direction the burst length is an integer number of the OFDM symbol length so that burst and OFDM symbol boundaries match each other.

The UL subframe consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple UL PHY transmission bursts, each transmitted from a different SS. The initial ranging slots allow a SS to enter the system by requesting the basic management CIDs, by adjusting its power level and frequency offsets and by correcting its timing offset. The bandwidth request slots are used by SSs to transmit the bandwidth request header.

Each UL PHY transmission burst contains only one UL burst and starts with a short preamble

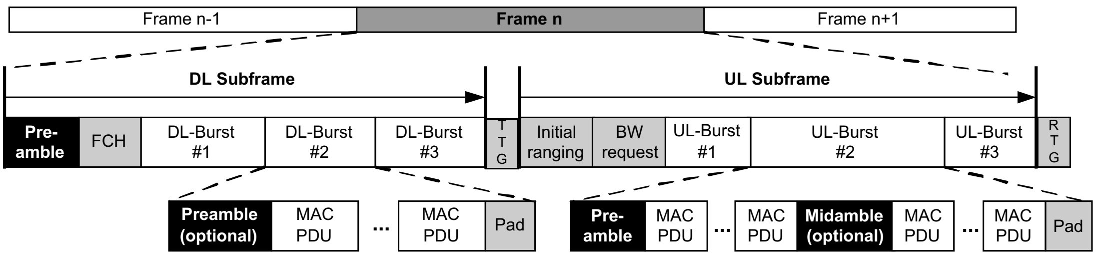

Fig. 2. IEEE 802.16 MAC fracme in TDD mode.

(1 OFDM symbol). For better synchronization and channel estimation optional midambles (1 OFDM symbol) might be periodically included in the UL burst. All MAC PDUs of a UL burst are transmitted by a single SS using the same PHY mode. DL and UL subframes are separated by the receive/transmit transition gap (RTG) and the transmit/receive transition gap (TTG) respectively.

In the following the broadcast MAC management messages are described. Fig. 3 shows the basic MAC management messages used to specify the internal structure of the MAC frame. The time references of the messages to the corresponding elements of the MAC frame are indicated by arrows.

The DLFP contains up to four information elements (IEs). Each IE specifies a DL burst. Thus, the DLFP can specify up to four DL bursts. If the DL subframe is made up of more than four bursts, an additional DL-MAP specifies the remaining ones. If there are less than four bursts present, the DLFP is sufficient and no DL-MAP has to be transmitted. The DLFP IE contains the length and the PHY mode of the corresponding DL burst. The start time of a burst can be calculated as the addition of all burst durations of the preceding bursts. The IE can additionally inform about the optional preamble at the beginning of the DL burst.

DL burst 1 contains the broadcast MAC control messages, i.e., DL and UL channel descriptor (DCD, UCD) as well as the UL- and DL-MAP. DCD and UCD define the characteristic of the physical channels. The DL-MAP defines access to the DL channel and the UL-MAP allocates access to the UL channel. Thus, the whole MAC frame is specified by the MAC messages included in the FCH and the DL burst 1.

Among others, the MAPs contain one IE for each burst of the frame. Each IE in the DL-MAP specifies a DL burst and an IE in the UL MAP specifies one UL transmission burst. The last IE of each MAP indicates the end of the MAP and refers to the end of the subframe. Besides the start time the last IE is empty.

The DL-MAP IE is made up of four values, the CID of the addressee of the burst, the PHY mode, the start time of the burst and a bit to indicate whether an optional preamble is present. If the specified DL burst contains MAC PDUs for several SSs, the CID is set to the broadcast CID and all SSs have to start decoding the burst at the specified start time with the given PHY mode. The information as to which connection the received MAC PDUs belong can be taken from the MAC header of the particular PDUs.

The start time of the following DL-burst is automatically taken as the end of the current one. That means the burst duration is implicitly given by subtracting the burst start time from the start time of the following burst. This calculation strictly relies on a sequential nature of bursts.

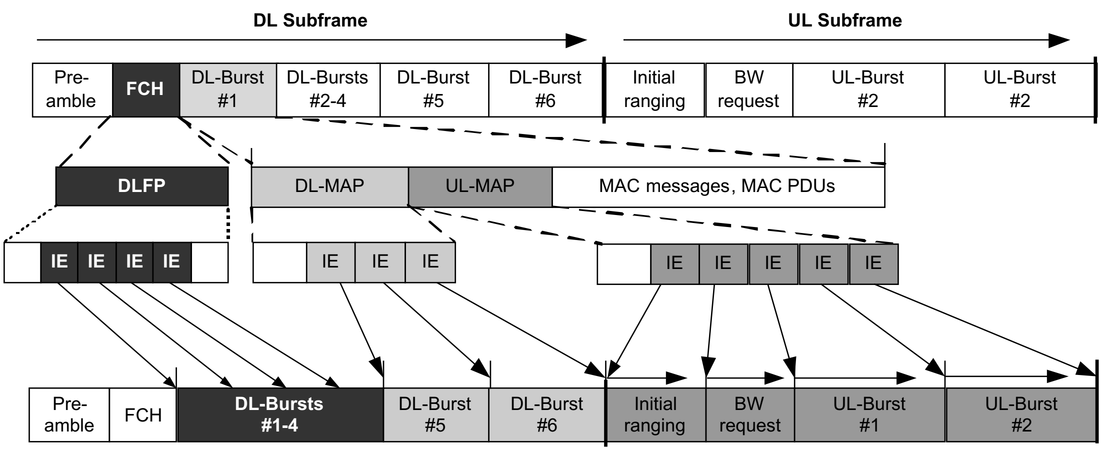

Fig. 3. IEEE 802.16 references of MAC management messages.

Optionally the DL-MAP IE might be extended to contain the duration. Knowing the start time and the duration, the BS is able to flexibly arrange concurrent DL bursts, e.g., for space division multiple access (SDMA) mode. The explicit indication of the duration overcomes the restriction of the sequential nature of bursts. A detailed description of different concepts to enable SDMA in IEEE 802.16 protocols can be found in [9]. If all PDUs of a burst belong to only one SS, the burst is directly addressed to the SS. No other SS has to decode the burst. As mentioned above, a short preamble might be appended to the DL burst additionally to the long preamble at the beginning of the DL subframe. This short preamble is used by the SSs for channel estimation and synchronization purposes. It is indicated by the preamble present bit in the MAP IE.

The UL-map IE is made up of six elements. The CID is the unique address of the station which is scheduled for the particular UL burst. The start time and the duration of the corresponding UL burst are given. Hence, unlike the DL subframe the UL subframe does not rely on a sequential structure of bursts. The PHY mode of the burst specifies the modulation and coding scheme used by the SS. The subchannel index is used to indicate which OFDM subcarriers shall be used. Subchannelization can only be used if the SS is able to transmit on a subchannel basis. This capability has to be negotiated during the network entry. In addition to the mandatory long preambles prepended to each UL burst, midambles might be included in the UL burst on a periodic basis. The use of midambles is indicated by the UL-MAP IE. Together with the preamble the midambles allow for an enhanced synchronization and channel estimation at the BS.

An optional functionality cyclically shifts both preambles and/or midambles in time. The shift allows for a joint detection of SSs by the BS during the UL subframe if the BS is capable of processing SDMA algorithms. In the DL subframe the reception of concurrent bursts sent by the BS in SDMA mode might be enhanced.

MAC PDUs consist of a fixed-length MAC header, a variable-length payload and an optional 32-bit cyclic redundancy check (CRC). Since the size of the payload is variable, the length of the MAC PDUs may vary between 6 and 2051 bytes. This allows the MAC to tunnel various higher layer traffic types without knowledge of the formats of those messages. The structure of a MAC PDU is shown in Fig. 4. The MAC header might be directly followed by one or more subheaders. There are several different subheaders carrying information for various purposes such as Mesh, automatic repeat request (ARQ), packing or fragmentation.

CS data can be encapsulated in a MAC PDU payload either directly, i.e., a single MAC SDU becomes the payload, or packing and/or fragmenting of the SDUs may be optionally enabled. MAC management messages are carried as MAC PDU payload as well. Fragmentation is the process of dividing a MAC SDU into one or more MAC PDUs with the aim to allow efficient use of available bandwidth relative to QoS requirements of a connection's service flow. Packing is the process of packing multiple MAC SDUs into a single MAC PDU. If packing is enabled for a connection, the transmitting side has full discretion whether or not to pack.

The IEEE 802.16 ARQ mechanism is an optional part of the MAC layer and can be enabled on a per-connection basis during connection establishment. It is a bitmap-based ARQ mechanism based on the fragment sequence number of the fragmentation or packing subheader. The mechanism can either work as a cumulative, a selective acknowledge or a combined ARQ mechanism.

The IEEE 802.16 Mesh mode is an optional feature of the standard. In contrast to the mandatory PMP configuration where traffic only occurs between the BS and the SSs, in the Mesh mode traffic can be routed through other SSs and can occur directly between SSs. Depending on the transmission protocol algorithm used, this can be done on the basis of distributed scheduling, on the basis of centralized scheduling, or on a combination of both.

Fig. 4. MAC PDU.

Using distributed scheduling, all nodes including the Mesh BS coordinate their transmissions in their two-hop neighborhood and broadcast their schedules (available resources, requests and grants) to all neighbors. All nodes ensure that the resulting transmissions do not cause collisions with the data and control traffic scheduled by any other node in their two-hop neighborhood. Using centralized scheduling, the Mesh BS gathers resource requests from all Mesh SSs within a certain hop range. The BS determines the amount of granted resources for each link in the network both in downlink and uplink, and communicates these grants to all Mesh SSs within the hop range.

All Mesh communications are in the context of a link which is established between two nodes. Thus, the PMP frame structure composed of a downlink- and an uplink-subframe is replaced by a structure based on bursts scheduled for the transmission between two nodes. All PDUs, i.e., data and control messages are forwarded in the time domain by the Mesh SSs.

2.3. Security sublayer

The security sublayer provides subscribers with privacy across the FBWA network by encrypting connections between SS and BS. Whether the payload of a PDU is encrypted or not is indicated in the MAC header. The type of encryption and its usage is negotiated during connection setup.

3. IEEE 802.16 OFDM PHY layer

The investigated IEEE 802.16 physical layer uses orthogonal frequency division multiplex (OFDM) with a 256 point transform, designed for both line of sight (LOS) and non-line-of-sight (NLOS) operation in frequency bands below 11 GHz, both licensed and license exempt. TDD and frequency division duplex (FDD) variants are defined. Channel bandwidths vary from 1.25 to 28 MHz. Additional air interfaces based on orthogonal frequency division multiple access (OFDMA) with a 2048-point transform and based on single-carrier (SC) modulation are specified.

Since a single harmonized frequency band is not present, Ref. [10] recommends that the frequency bands 3.4–3.6 GHz, 10.15–10.3 GHz and 10.5–10.65 GHz should be identified as preferred bands for FBWA. Due to the favourable propagation properties, as well as the suitable amount of low-cost spectrum (license exempt) and available cheap radio frequency technology, [11] chose the frequency band 5.725–5.875 GHz. Beside the 5 GHz and the 3.5 GHz bands, WiMAX targets the licensed 2.5 GHz bands which have been allocated in the U.S., Mexico, Brazil and some Southeast Asian countries. New bands of interest are especially in the lower frequencies. The WiMAX Forum announced its intention to advance the allocation of licensed and license-exempt spectrum in lower frequency bands [7].

Link distances, i.e., cell sizes vary strongly based on the frequency bands used, the environment, propagation conditions and antenna gain. The system targets distances between 2 km and 4 km for NLOS and up to 15 km for LOS.

The phenomenon of delay spread is due to multipath scattering. In order to avoid inter-symbol interference and inter-carrier interference a cyclic prefix (CP) is introduced in front of every data part of an OFDM symbol [12]. In the targeted frequency bands, radio communication benefits significantly from the ability to operate under obstructed LOS and NLOS conditions. It is therefore necessary to choose a CP larger than the maximum delay spread. Table 1 lists common maximum delay spread values in different types of environment. These delay spread values remain unchanged for any operating frequency above 30 MHz, since the wavelengths become much

Table 1
Delay spread [12,13]

Type of environment	Maximum delay spread (μs)
In-building (house, office)	<0.1
Large building (factory, malls)	<0.2
Open area	<0.2
Suburban area LOS	0.2–1.0
Suburban area NLOS	0.4–2.0
Urban area	1.0–3.0

smaller than man-made architectural structures. Recent measurements do confirm the values for frequency bands between 800 MHz and 6 GHz [12,13].

In the following, the basic modules of a IEEE 802.16 transmitter respectively receiver are outlined.

A randomizer adds a pseudo-random binary sequence to the DL and UL bit stream to avoid long rows of zeros or ones for better coding performance. It appends a tail byte to bring the convolutional coder in the zero state after each burst.

The forward error correction (FEC) scheme consists of the concatenation of a Reed–Solomon (RS) outer code and a convolutional inner code (CC). The RS coder corrects burst errors at the byte level. It is particularly useful for OFDM links in the presence of multipath propagation. The CC corrects independent bit errors. A CC decoder can benefit from softbit input generated from de-modulation and de-puncturing. The concatenation of both codes is made rate-compatible by the following puncturing functionality. Based on four puncturing patterns bits are removed to realize different code rates. The support of block turbo coding and convolutional turbo coding is an optional mode.

The interleaving is composed of a block and a bit interleaver. The block interleaver maps adjacent coded bits onto non-adjacent subcarriers to overcome burst errors. The bit interleaver maps adjacent coded bits alternately onto less and more significant bits of the constellation to avoid long runs of unreliable bits.

BPSK, QPSK, 16-QAM and 64-QAM are the modulation schemes to modulate bits to the complex constellation points. The FEC options are paired with the modulation schemes to form burst profiles, i.e., PHY modes of varying robustness and efficiency. The possible PHY modes are listed in Table 3. The basic IEEE 802.16 OFDM parameters are outlined in the second column of Table 2.

Table 2
Basic OFDM parameters

OFDM parameters	Value	Scenario
Bandwidth BW		20 MHz
Sampling rate $F_s = 1/T$	Depends on BW	23.04 MHz
Useful time T_B	$256 \cdot T$	11.11 μs
T_G/T_B	1/4, 1/8, 1/16, 1/32	1/4
CP time T_G		2.78 μs
Symbol time T_{sym}	$T_G + T_B$	13.89 μs
Carriers N_{FFT}	256	
Data carriers	192	

Table 3
Usage of PHY modes

Modulation	Coding rate	Receiver SNR (dB)	Surface [%]	Number of SS
PSK	1/2	6.4	39.40	6
QPSK	1/2	9.4	20.56	3
	3/4	11.2	27.95	4
16 QAM	1/2	16.4	4.10	1
	3/4	18.2	5.15	1
64 QAM	2/3	22.7	0.92	0
	3/4	24.4	1.92	0

4. Multi-user multi-mode scenario

The IEEE 802.16 frame structure and therewith the system capacity depends on the number of SSs and on the number of different PHY modes in use. For each SS an UL burst including preamble, padding and possibly midambles is allocated and an UL-MAP IE is inserted in the UL-MAP. For each PHY mode a DL burst is scheduled that might contain a preamble and padding bytes. A DL-MAP IE is included in the DL-MAP. Thus, the number of active SSs and the number of PHY modes in use should be realistically covered by the scenario. The scenario introduced in the following supports multiple SSs with different modulation and coding schemes.

4.1. PHY layer configuration and PHY mode distribution

The number of SSs using certain modulation/coding schemes has to be derived. Therefore the surface area covered by a specific modulation scheme is considered. To calculate the surface area of each PHY mode, the maximal distance between BS and SSs depending on the modulation schemes must be known. This distance is determined using the maximal signal to noise ratio (SNR) a SS should receive to avoid data loss. Ref. [3] proposes switching points between modulation schemes depending on receiver SNR. With the maximal SNR, the maximal distance a SS should have from its BS can be calculated. The noise depends on the system bandwidth and on the temperature of the receiver. The noise N can be calculated by the formula [14]:

$$N = f_{\Delta} \frac{4.0\ \text{pW}}{\text{GHz}}.$$

f_{Δ} is the bandwidth of the system. According to [15] the path loss (L_F) between transmitter and receiver in a free space without any obstacle interfering the radio wave can be calculated by

$$L_F = 20 * \log_{10} \frac{4\pi d}{\lambda}\ [\text{dB}].$$

The path loss depends on the distance d and on the wavelength λ. For the following calculation no other sources of interference are taken into account and perfect transceivers are assumed. The receiver SNR can be found with

$$P_r\ [\text{dBm}] = P_t\ [\text{dBm}] - L_F\ [\text{dB}],$$
$$\text{SNR}\ [\text{dB}] = P_r\ [\text{dBm}] - N\ [\text{dBm}].$$

P_r denotes the received power and P_t the transmit power. Power values are given in dBm whereas the path loss is measured in dB. With all equations above the distance between BS and SS in dependence on its signal power and its noise can be calculated:

$$d = \frac{\lambda * 10^{\frac{P_t\ [\text{dBm}] - \text{SNR}\ [\text{dB}] - N\ [\text{dBm}]}{20}}}{4\pi}.$$

It is assumed that the scenario system is being operated in the upper 5 GHz band. As an example, this unlicensed band starting at a frequency of 5.47 GHz is restricted to outdoor use in Germany. The typical system bandwidth in this frequency band is 20 MHz. The noise in a 20 MHz band can be calculated to 8×10^{-14} W which equals -100.97 dBm. According to the maximum allowed equivalent isotropic radiated power (EIRP) of 1 W, the transmitters are assumed to have a transmission power P_t of 1 W which equals 30 dBm. In frequency bands licensed for WiMAX the maximum allowed transmit power is assumed to increase up to 3 W for SSs and up to 60 W for BSs. The calculated SNR and the switching points can be seen in Fig. 5.

Each switching point between two different PHY modes results in a certain radius. The radius of the last switching point, i.e., BPSK 1/2 marks the cell boundary. In this example the cell area has a maximum radius of approximately 7.4 km. The parts of the surface area of the cell which are covered by specific PHY modes are regions lying between two concentric circles. The area of the annulus (F_{Annulus}) formed by two circles of radii R_1 and R_2 is

$$F_{\text{Annulus}} = \pi \cdot (R_1^2 - R_2^2).$$

The cell boundary in an ideal cellular deployment is a hexagonal cell so that the area belonging to the last mode, i.e., BPSK 1/2 is not a whole annulus but certain parts of it are cut away. The area covered by BPSK 1/2 can be calculated as

$$F_{\text{BPSK1/2}} = \frac{3}{2}\sqrt{3}R^2_{\text{BPSK1/2}} - \pi R^2_{\text{QPSK1/2}}.$$

The area per PHY mode is a certain fraction of the whole cell area. The proportion of each surface area per PHY mode is listed in Table 3. Note that the distribution of PHY modes in a hexagonal cell neither depends on the frequency band in use nor on the transmission power. One can easily see that the annulus where the most robust PHY mode BPSK 1/2 is in use is represented over proportionately. The sensitive and powerful modes in the inner circles of the cell cannot be utilized very often because their range is limited to a small area.

Assuming a constant density of SSs within the whole cell, the proportion of the annulus of a PHY mode can be converted to a proportion of SSs using this modulation and coding scheme. The example scenario is made up of a total number of 15 active SS per BS. The number of 15 subscribers results from the analysis conducted in Section 5.2 where a maximum of approximately 15 users could be scheduled in one MAC frame assuming a fixed payload size of 381 bytes. Of course more subscribers can be handled by the system, but their payload has to be fragmented into smaller blocks or the corresponding connections have to be

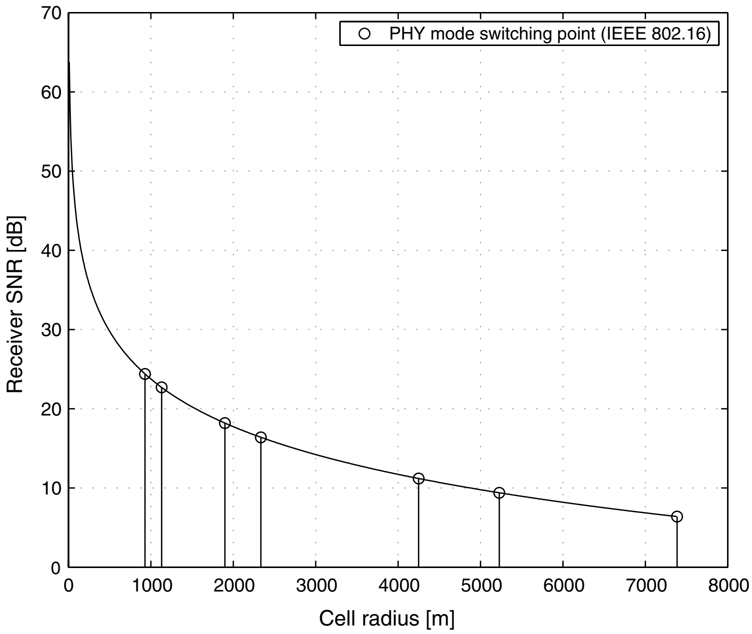

Fig. 5. Receiver SNR vs. distance.

scheduled in subsequent MAC frames. Thus, the overall MAC capacity is distributed to the different SSs.

Now the number of SSs using a certain PHY mode can be calculated as the percentage rate times the total number of users. The resulting number of SSs corresponding to the percentages of PHY mode utilization is listed in Table 3. Each SS of the multi-user scenario has the same data rate, i.e., 1/15 of the overall data rate. Having, for example, a system throughput of 30 Mbps, each SS can offer 2 Mbps (1 Mbps DL, 1 Mbps UL).

4.2. MAC layer configuration and evaluation

The example system with 20 MHz bandwidth operates in the 5 GHz bands in TDD mode. The frame length is set to 10 ms. Fig. 6 illustrates the MAC frame analyzed. The scenario deals with several DL and UL connections. The DL subframe consists of the DL preamble, the FCH and several DL bursts. The optional DL preambles are disabled but the CRC is applied to the PDU. According to the standard, the TTG as well as the RTG should be between 0 and 100 μs, here they are set to 26 μs, i.e., two OFDM symbols.

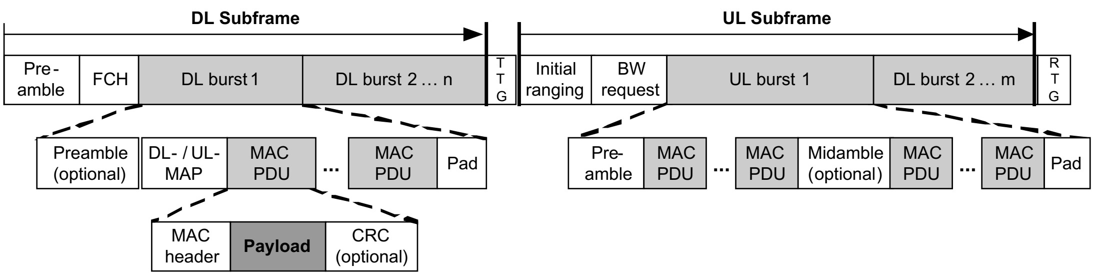

Fig. 6. IEEE 802.16 MAC frame structure of example scenario.

The UL subframe starts with three ranging slots. To allow for the transmission of the long preamble and the ranging request management message (RNG_REQ, 13 byte) and to cope with a round trip delay of stations being up to 8000 m away, 8 OFDM symbols are considered for each ranging slot. Each of the 10 bandwidth request slots containing a short preamble and the BW-REQ management message is considered to be 2 OFDM symbols long. Several UL bursts are scheduled in the UL subframe. The optional midambles are disabled. Packing and fragmentation are initially shut off so that every burst is padded to fill up an integer number of OFDM symbols. The following performance evaluation of the system throughput does not take ARQ into account.

To calculate the resulting static system throughput MAC and PHY overhead is subtracted. Thus, all frame elements which do not contain payload have been removed (white parts of Fig. 6). The payload of the MAC PDUs remains. Now the bit rate on MAC level can be calculated by dividing the payload of the MAC frame by the frame duration.

5. Performance analysis

The IEEE 802.16 MAC frame structure and the PHY layer characteristics have been modeled by an analytic system model implemented in MATLAB. The model takes all the above introduced features into account and calculates various different MAC and PHY layer measures. The scheduling is based on a fair queuing algorithm where all SSs are treated equally. First the DL subframe is filled up and afterwards the UL bursts are allocated. Starting from the highest PHY mode, one PDU of each user is scheduled for transmission. When one PDU of each user has been scheduled, the algorithm restarts as long as there is free capacity in the subframe. If necessary, DL- and UL MAPs are included and updated. Optional preambles are prepended and CRCs are appended if required. In the end each burst is filled up with PDU fragments or bursts are padded up to an integer number of OFDM symbols. Thus, the MAC frame is entirely filled. Characteristics of the wireless channel are not considered in the model. The transmission is assumed to be error-free.

In the following the model is used to evaluate the IEEE 802.16 system performance and the influence of various different MAC and PHY layer configurations.

5.1. Optimal MAC PDU configuration

While efficiently filling the MAC frame with data the optional features packing/fragmentation and ARQ have to be considered. The packet length of incoming traffic may vary significantly between 53 bytes for ATM cells (even less for Voice over IP applications), up to 1518 bytes for Ethernet traffic and up to 65,535 bytes for IPv4 packets (and even more for IPv6). These packets may be fragmented and/or packed into the MAC PDU payload. Encapsulating data in MAC PDUs means adding additional overhead, i.e., header (6 bytes), subheader (2 bytes) and CRC (4 bytes). As the payload increases, the ratio overhead to payload decreases for error-free transmission. The assumption of residual bit errors leads to an optimum size which is different from the result of the error-free case. Residual bit errors introduce additional overhead, since faulty MAC PDUs need to be retransmitted. The larger the MAC PDU, the more data has to be retransmitted when an error occurs. Additionally, the probability that an error occurs during the transmission of the particular PDU increases with the size of the PDU. These two competing effects can be expressed in the following formulas.

$$\mathrm{OH}_{\mathrm{MAC}} = \frac{\text{header} + \text{subheader} + \text{CRC}}{\text{payload}},$$

$$\mathrm{OH}_{\mathrm{ret}} = \sum_{i=1}^{\infty} (1 - (1-p)^{N_{\mathrm{MAC}}})^i \frac{N_{\mathrm{MAC}}}{\text{payload}} = \frac{(1 - (1-p)^{N_{\mathrm{MAC}}})}{(1-p)^{N_{\mathrm{MAC}}}} \frac{N_{\mathrm{MAC}}}{\text{payload}}.$$

The calculation denotes the MAC overhead ($\mathrm{OH}_{\mathrm{MAC}}$) and the retransmission overhead ($\mathrm{OH}_{\mathrm{ret}}$). In 802.16 the ARQ feedback messages can be transported as MAC subheaders within a given MAC PDU so that signaling overhead due to ARQ messages is neglected for the following

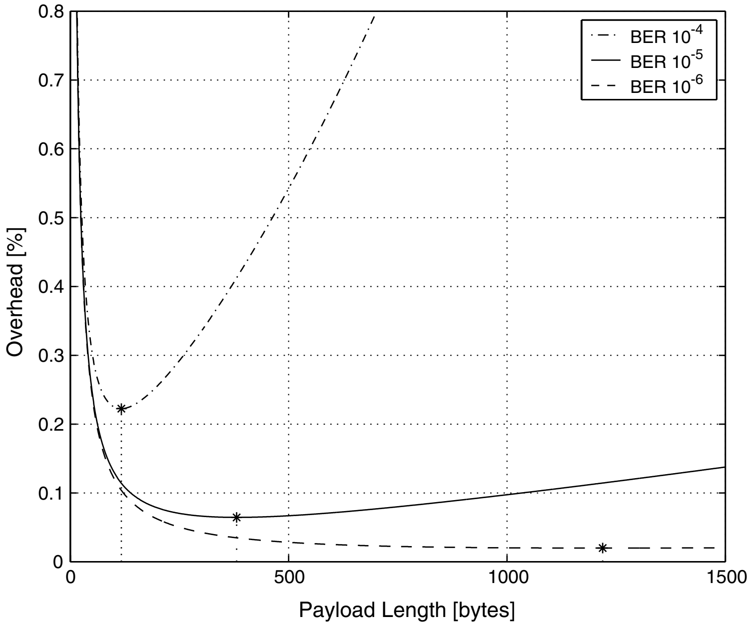

Fig. 7. Optimum packet length with rest bit errors.

calculation. The variable p signifies the residual bit error ratio (BER) and N_{MAC} the total length of the MAC PDU in bits. The variables header, subheader, CRC and payload denote the length of the corresponding PDU elements.

The addition of both equations leads to the overhead in case of residual bit errors in Fig. 7. The overhead measured in percent is plotted vs. the payload length in bytes. It can be seen that there are local minima of the overhead depending on the BER which lead to optimum payload lengths. The optimal MAC PDU payload length and the corresponding BER are given in Table 4.

5.2. System performance of the example scenario

From the basic assumptions of the PHY layer that have been made for the example scenario (20 MHz bandwidth in the upper 5 GHz frequencies using a CP of 1/4) the basic OFDM parameters can be calculated. The resulting values are listed in the last column of Table 2. It can be seen that in the targeted frequency band a CP of 1/4 of the useful symbol duration leads to a guard period of 2.78 μs. This CP has been chosen to deal with delay spreads for NLOS operation in suburban areas (compare Table 1). The OFDM symbol duration is calculated to be 13.89 μs.

Table 4
Optimum payload length

Bit error ratio	Optimum payload length [byte]	Overhead [%]
10^{-4}	117	22.24
10^{-5}	381	6.44
10^{-6}	1219	1.98

Using different PHY modes, a certain amount of data can be carried by a single OFDM symbol. The throughput at the PHY level can be calculated by dividing the amount of data per symbol by the symbol duration. The results vary from 6.91 Mbps for BPSK 1/2 up to 62.21 Mbps for 64 QAM 3/4. All resulting PHY throughput values are listed in Table 5.

To show the corresponding MAC capacity of the different PHY modes a single user scenario is evaluated first. Serving a single user, the MAC frame does only contain one DL- and one UL burst. Since a uniform payload length cannot be derived from the higher layer protocols like TCP/IP, UDP, ATM or Ethernet, the single user scenario assumes a traffic load of constant bit rate

Table 5
PHY modes and corresponding throughput

Modulation	Code rate	PHY throughput [Mbps]	MAC throughput [Mbps]
BPSK	1/2	6.91	6.10
QPSK	1/2	13.82	12.19
	3/4	20.74	18.59
16 QAM	1/2	27.65	24.69
	3/4	41.47	37.19
64 QAM	2/3	55.30	49.68
	3/4	62.21	55.78

(CBR) traffic with a packet size of 381 bytes. This is the optimum payload size assuming a BER of 10^{-5} (refer to Table 4). All other parameters are taken from the example scenario.

The resulting throughput on MAC level ranges from 6.10 Mbps for a single BPSK 1/2 user up to 55.78 Mbps for one 64 QAM 3/4 station. MAC layer throughput results for all PHY modes are listed in Table 5. Approximately 90% of the bit rate at the PHY level is available to higher layers, or in other words the MAC protocol reduces the bit rate by 10% due to overhead.

The IEEE 802.16 system capacity depends on the number of SSs and on the number of different PHY modes represented in the scenario. For the multi-user multi-mode scenario the distribution of users and their corresponding PHY modes have been derived in Section 4. In the following the example scenario will be evaluated.

Fig. 8 plots the MAC throughput of the example scenario vs. the payload length. Transmitting small packets, the throughput is low because the overhead due to the MAC header and the CRC dominates the small MAC payload. Transmitting ATM cells of 53 bytes, the MAC throughput lies at 8.27 Mbps. With increasing payload length the MAC overhead decreases and the throughput reaches a maximum around 11 Mbps (10.67 Mbps at 381 bytes). Since all SSs are scheduled fairly a MAC throughput of approx. 711 kbps can be provided to each SS, whereof 355 kbps is allocated in UL and 355 kbps is scheduled in the DL direction.

Once the packet length exceeds a certain length, one single MAC frame cannot handle all stations. The number of scheduled users in one DL and one UL subframe is also drawn in Fig. 8. It can be seen that for a payload length larger than 350 bytes, one MAC frame does not have enough capacity to handle all stations at once. Instead of the entire 15 only fewer stations can be supported. First the

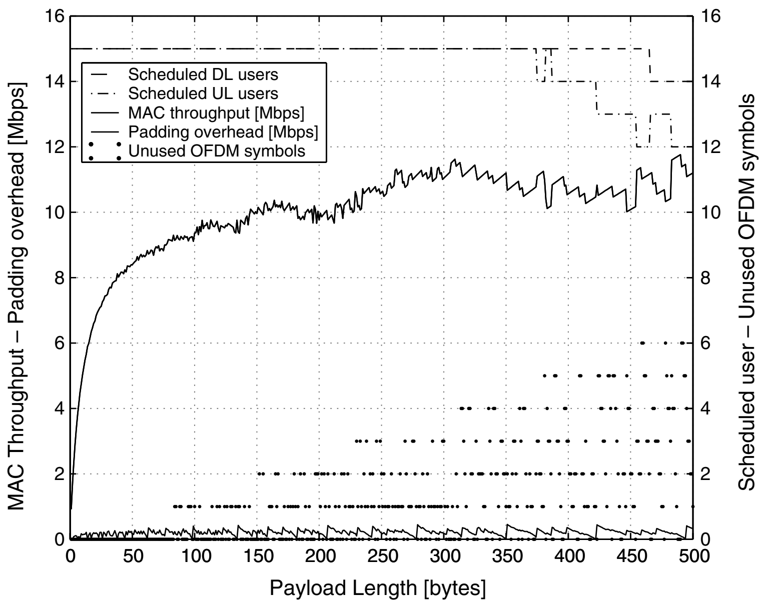

Fig. 8. MAC throughput of example scenario.

UL subframe reaches the limit and shortly afterwards the DL subframe cannot serve all users. From this point on the payload would have to be fragmented or the stations would have to be scheduled in subsequent MAC frames to serve all SSs. Since the partitioning of scheduled users onto PHY modes varies with payload lengths larger than 350 byte, the shape of the curve changes at this point.

Fragmentation is disabled in the example scenario. Thus, bursts are padded to end up on OFDM symbol boundaries. Padding bits cannot be used and count as overhead. The amount of padding bits per frame is divided by the frame duration and the resulting padding overhead is shown in Fig. 8. The padding overhead varies between 0 and 450 kbps. Its mean value for packets between 1 and 500 byte is 265.55 kbps. Since fragmentation is disabled some OFDM symbols might remain unused. In this particular case one OFDM symbol remains to be allocated in the subframe but the MAC PDU is too long to fit into it. Even if the highest PHY mode is used the symbol cannot be filled. The amount of unused OFDM symbols per frame is plotted in Fig. 8. The highest PHY mode used in the scenario is 16 QAM 3/4 in which an OFDM symbol contains 72 bytes. Once the PDU length exceeds this limit, i.e., the payload length exceed 62 bytes, one OFDM symbols might stay unused. If the PDU length exceeds 144 bytes, i.e., a payload length of 134 byte, two OFDM symbols might not be allocated. This stepped behavior can be seen in the graph.

The padding overhead and the unused OFDM symbols can be utilized to transmit MAC PDUs if it is possible to fragment at least the last PDU of each burst. Fig. 9 plots the difference between the MAC throughput without fragmentation and the throughput of a system that allows fragmenting the last payload into PDUs which fill up the bursts. The differential throughput varies between 0 and 420 kbps depending on the payload length. The mean value for a payload between 1 and 500 bytes is 157.1 kbps.

By fragmenting the last payload scheduled in a burst all unused OFDM symbols can be allocated, but the padding overhead can only be reduced, it cannot be eliminated. Due to the size of the MAC header, the fragmentation subheader and the CRC, gaps smaller than 12 bytes still have to be padded. The remaining padding overhead is drawn in Fig. 9. It can be seen that the padding

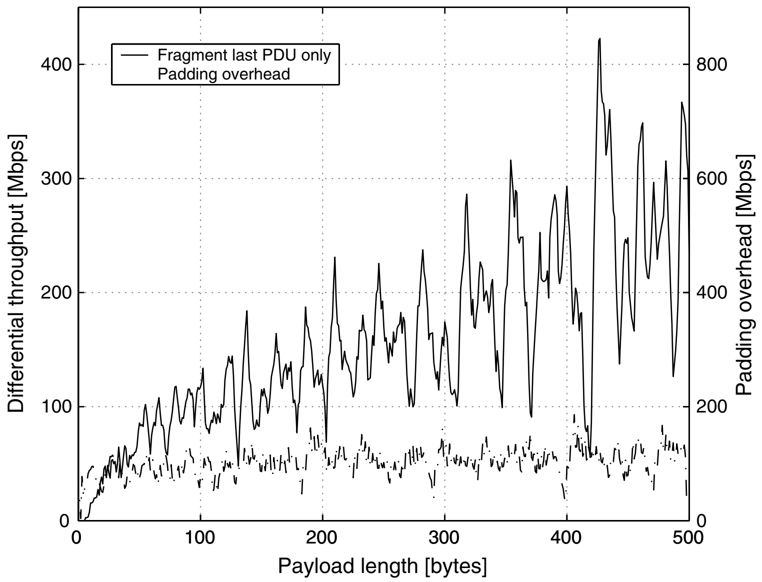

Fig. 9. Capacity gain of fragmenting last PDU.

overhead is significantly reduced compared to the non-fragmentation case. But its mean value remains at 67.79 kbps compared to 265.55 kbps in Fig. 8.

Fragmenting all PDUs introduces more overhead compared to fragmenting only the last PDU. The subheader included after every MAC header reduces the MAC throughput. Compared to the non-fragmentation case a mean gain in MAC throughput of 43.0 kbps can be achieved. Thus, fragmentation of all PDUs does not gain in terms of MAC frame utilization compared to the case of fragmenting the last PDU only. It optimizes the throughput in the presence of residual bit errors as has been outlined in Section 5.1. Further on, fragmentation allows increasing the number of served users per frame like it has been outlined before. Finally fragmentation is necessary to transmit payload that is larger than the maximum payload length of 2041 byte. If the optional ARQ mechanism is enabled for a specific connection the fragmentation or packing subheader is used to sequentially number the transmitted blocks.

By means of optional preambles prepended to DL bursts IEEE 802.16 provides means to enhance the stations' capability to synchronize to the BS and to estimate the channel. Optional midambles included in UL bursts help the BS to improve its channel estimation. The optional CRC is necessary to detect bit errors in the payload of a MAC PDU. If an error occurs the ARQ mechanism can request to retransmit the erroneous PDU. If ARQ is disabled for the particular connection the PDU is simply discarded. These features (optional DL preambles, UL midambles and CRCs) allow for configuring the MAC protocol in a more or less robust way. As a trade off for robustness, the MAC capacity is decreased. In the example scenario the optional preambles and midambles are disabled. CRC is enabled and protects the MAC PDU payload.

Fig. 10 shows the throughput of a sensitive MAC layer configuration and the throughput of a robust MAC layer configuration. As a reference the MAC capacity of the example scenario is plotted. The sensitive configuration disables the CRC as well as all optional DL preambles and UL midambles. By disabling the CRC each MAC PDU is shortened by 4 bytes. Especially in situations where the payload is short, e.g., below 50 bytes, the MAC capacity is increased by more than

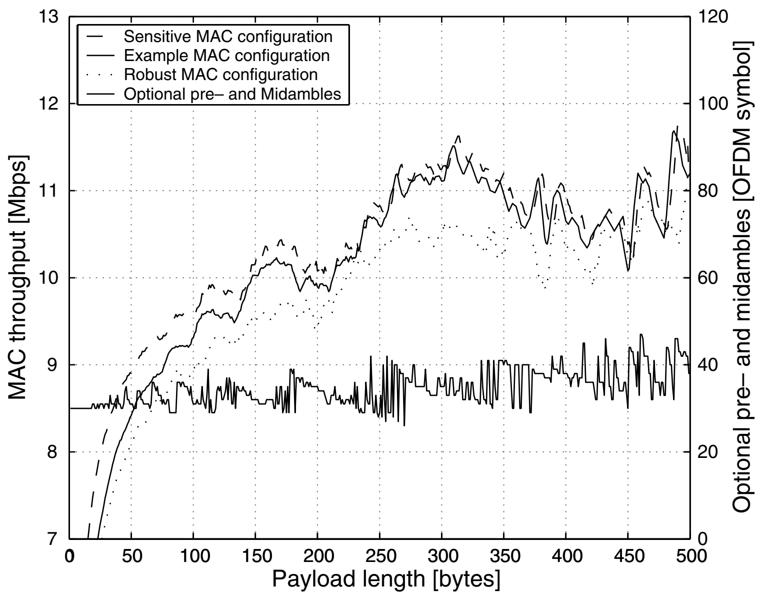

Fig. 10. Capacity of different MAC configurations.

500 kbps. Beyond the payload length of 150 bytes, the influence of the CRC overhead starts to vanish. The MAC capacity of the example scenario and the MAC capacity of the system with a sensitive MAC configuration approach each other. The mean throughput gain for packet between 0 and 500 bytes amounts to 255.6 kbps.

Within the robust MAC layer configuration preambles are prepended to each DL burst and midambles are included after every 8th OFDM symbol of each UL burst. As in the example scenario a 32-bit CRC protects the payload of every PDU. Beside the MAC throughput, Fig. 10 additionally plots the number of OFDM symbols occupied by optional preambles and midambles that have been included in the MAC frame. It can be seen that the overall number of optional pre- and midambles varies around 30. Five preambles are included in the DL bursts of the five different PHY modes of the scenario. The remaining 25 midambles are included in between the OFDM symbols of the UL bursts. Thus, a relatively constant overhead is introduced by this optional feature. A mean capacity loss of 461.9 kbps compared to the example scenario is the trade off for the robustness of the MAC configuration.

To protect the useful part of the OFDM signals against inter-symbol interference and inter-carrier interference, a CP is prepended. The CP is configured to be a certain fraction of the useful time. Values of 1/32, 1/16, 1/8 and 1/4 are foreseen by the standard. The resulting CP length has to be larger than the maximum delay spread of the environment. Due to the increased symbol duration, the SNR and the number of symbols per second that are transmitted decreases [16]. Fig. 11 plots the MAC throughput of 802.16 systems using different cyclic prefixes. It can be seen that the throughput highly depends on the length of the CP. Thus, the CP should not be made longer than strictly necessary. Indoors and in open areas, the maximum delay spread is smaller than 0.2 μs (refer to Table 1). A CP of 1/32 of the useful time results in a guard time of 0.347 μs and is sufficient for the target environment. Fig. 11 shows the significant gain in efficiency when using a shorter CP. A mean throughput gain of 2.28 Mbps can be achieved using a CP of 1/32 compared to the CP of 1/4 of

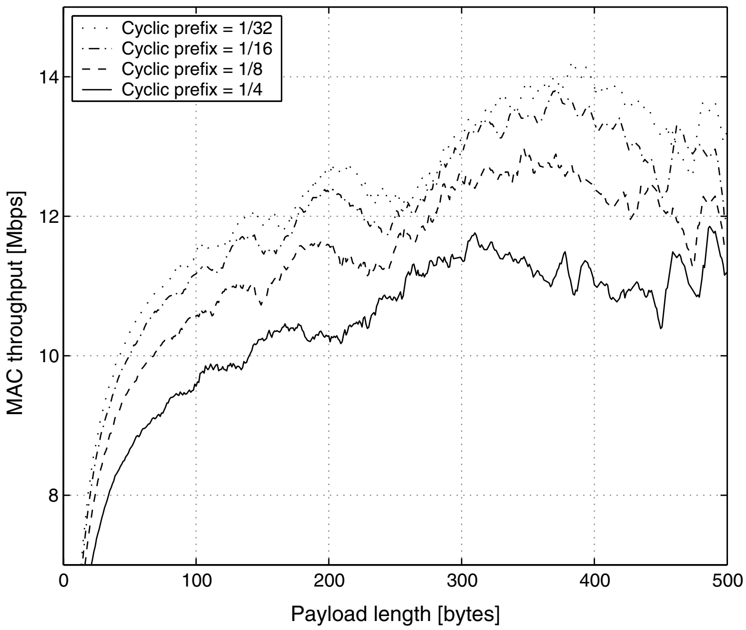

Fig. 11. System capacity with different cyclic prefixes.

the example scenario. In LOS operation in suburban areas the maximum delay spread does not exceed 1.0 μs. A CP of 1/8 of the useful time results in a CP length of 1.389 μs and protects the OFDM symbols sufficiently. A mean throughput gain of 1.14 Mbps is obtained compared to the reference scenario.

The performance analysis has shown that the IEEE 802.16 standard provides several means to adapt the MAC and PHY layer configuration to the system environment and user demands. Using the features efficiently, the system performance can be optimized by maintaining the robustness and operability of the system.

6. Simulative performance evaluation

6.1. IEEE 802.16 simulator

A software-based simulator with a prototype implementation of the IEEE 802.16 protocol has been developed at RWTH Aachen University. The protocol stack is specified formally with the Specification and Description Language (SDL) and is translated to C++ by means of a code generator. The structure of the event-driven simulator is shown in Fig. 12.

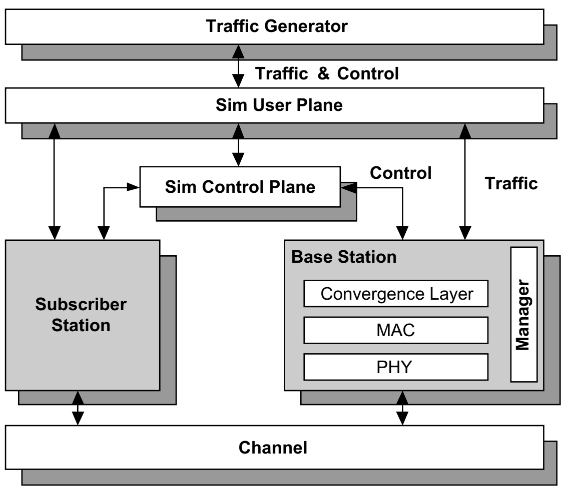

Fig. 12. Structure of SDL-based simulator.

The protocol stacks of SS and BS are implemented. The stack is composed of the convergence layer, the MAC and the PHY layer. Stochastic traffic models generate a well defined traffic load which is characteristic for several different applications like MPEG, Ethernet or CBR. Two control blocks manage the simulation, configure the scenarios and evaluate the transmitted packets.

A physical channel transmits the bursts between the SSs and the BS. Based on the path loss of the carrier, the interference introduced by other stations and the receiver noise, the channel calculates the SNR for the particular packet. The SNR is mapped to the corresponding error ratio look up table. These tables introduce the specific behavior of the PHY layer and the wireless channel. The look-up tables are generated by a sophisticated link layer simulation chain, which has been developed during the IST-STRIKE project [17,18].

The link layer simulation chain models the behavior of transmitters and receivers of 802.16 systems. It implements all relevant transmit and receive blocks such as randomizer, coder, interleaver, etc. Beside the transceivers the simulation chain models the real channel characteristics. Different channel models, e.g., the Stanford University Interim (SUI) models [3] or an additive white Gaussian noise (AWGN) channel model are available.

Fig. 13 plots the coded BER vs. the SNR. The results have been obtained with the link layer simulation chain by using an AWGN channel. Since the packet length in 802.16 systems is not fixed the resulting packet error ratio has to be individually calculated based on smaller units like bits, bytes or OFDM symbols. Due to the concatenated Reed–Solomon and convolutional channel coders the occurrence of bit errors is correlated over time. Using SUI channel models instead of AWGN the frequency-selective fading introduces even more burst errors. Simulations have shown that errors of OFDM symbols are not correlated. Thus the OFDM symbol error ratio is used as the interface to the protocol simulator. The OFDM error ratio can be calculated by the link layer simulation chain. It is shown in Fig. 14.

In the protocol simulation, the resulting packet error ratio of a PDU (p_{PDU}) can be calculated as

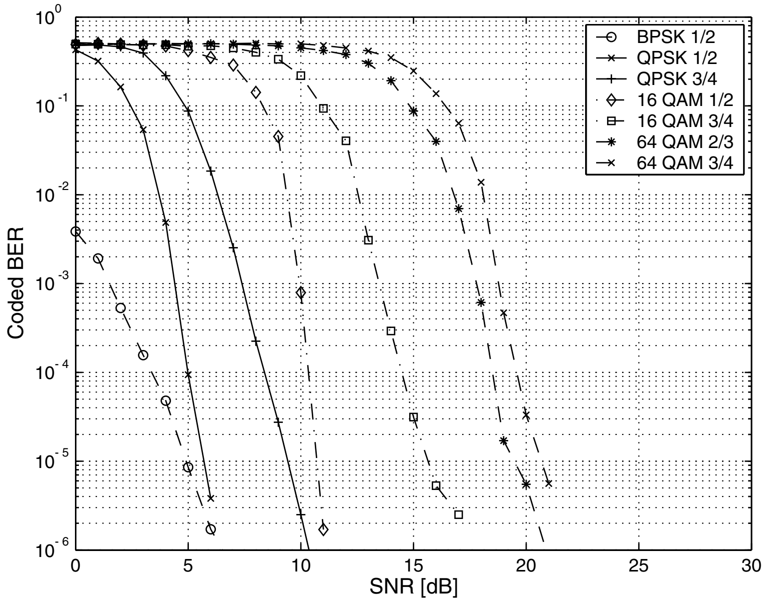

Fig. 13. Coded bit error ratio vs. SNR.

follows. The calculation is based on the PDU size N_{OFDM} measured in OFDM symbols and the OFDM symbol error ratio (p_{OFDM}).

$$p_{\mathrm{PDU}} = 1 - (1 - p_{\mathrm{OFDM}})^{N_{\mathrm{OFDM}}}.$$

6.2. Simulation results

The traffic generator generates CBR traffic with a fixed payload size of 381 bytes (refer to Table 4). The payload is encapsulated into MAC PDUs without being packed or fragmented. ARQ is also disabled. To validate the simulator MAC capacity of the different PHY modes with the MAC throughput values of the analysis, a single user scenario is evaluated first. Therefore packet transmission over the channel is assumed to be error-free.

Fig. 15 illustrates the linear relationship between carried and offered traffic. As long as the offered traffic does not exceed the maximum possible bit rate of the corresponding PHY mode, it is entirely carried. The upper most graph corresponds to the highest PHY mode, i.e., 64 QAM 3/4, and the lowest graph to the lowest modulation and coding scheme, i.e., BPSK 1/2. Having reached the saturation level the MAC throughput stops increasing and remains nearly constant. The saturated MAC capacity of BPSK 1/2 amounts to 5.8 Mbps. The highest PHY mode 64 QAM 3/4 reaches 52.7 Mbps. The maximum throughput values as they were obtained with the IEEE 802.16 simulator for all modulation and coding schemes are presented in Table 6.

The upper limits of these throughput values have been predicted through the theoretical analysis of the previous sections. They do not match exactly with the IEEE 802.16 simulator since the bandwidth request mechanism in the simulator is based on bandwidth requests. Requests are sent during a contention phase. Other functionality like association and the transmission of channel descriptor messages (DCD, UCD) further reduces the capacity slightly.

Figs. 16 and 17 show the complementary cumulative distribution function (CDF) of DL and UL packet delay values for 64 QAM 3/4. The packet delay contains queuing and transmission delay. The discrete Limited Relative Error (LRE) algorithm that measures the local correlation of the stochastic data is used. The following results are within a maximum limited relative error of 5%. The offered throughput varies between 40 Mbps

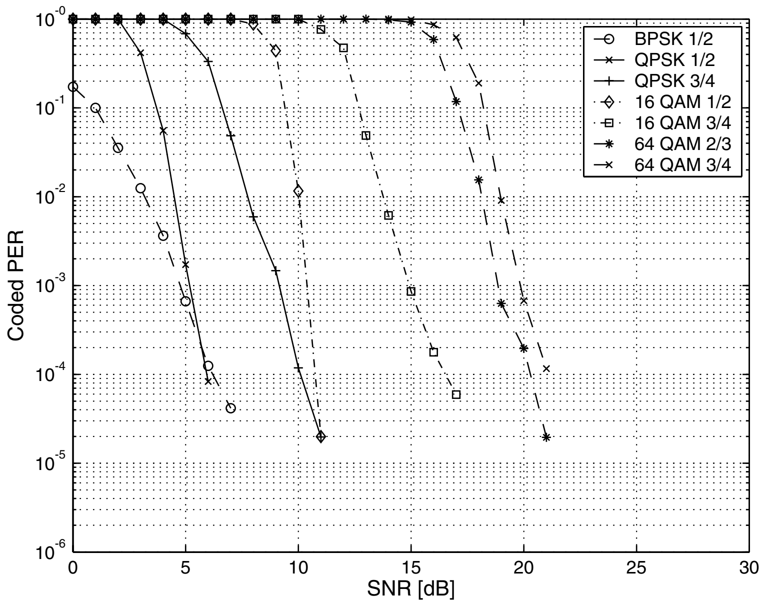

Fig. 14. OFDM error ratio vs. SNR.

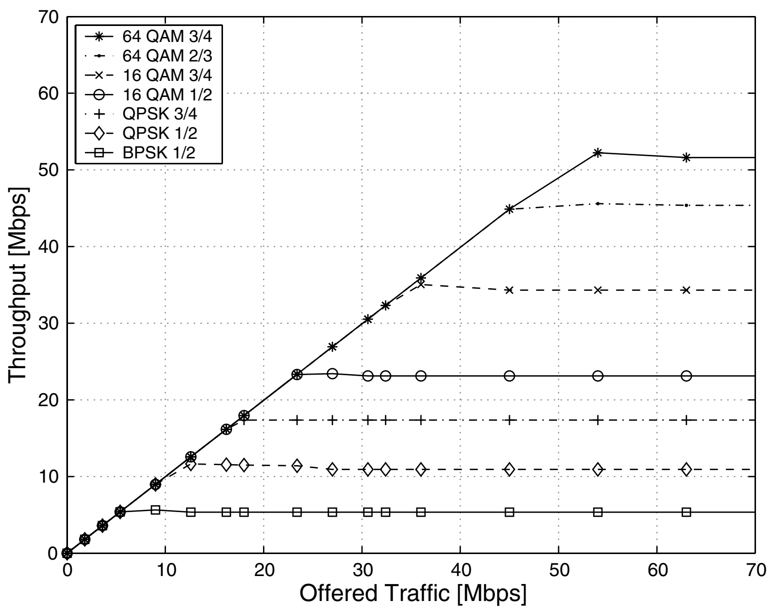

Fig. 15. MAC throughput vs. offered traffic.

and 50 Mbps. The minimum DL delay for an offered traffic of 40 Mbps (approximately 76% of the maximum referred to Table 6) is around 3 ms, which signifies that these packets were sent right after the DL preamble, FCH and the MAPs of the proximate MAC frame. Only 25% of all

Table 6
Maximum MAC throughput per PHY mode

Modulation	Code rate	MAC throughput [Mbps]	
		Simulated	Theoretical
BPSK	1/2	5.8	6.09
QPSK	1/2	11.8	12.19
	3/4	17.6	18.59
16 QAM	1/2	23.8	24.69
	3/4	35.2	37.19
64 QAM	2/3	46.9	49.68
	3/4	52.7	55.78

arriving DL packets needed more than 10 ms (one MAC frame) to be transmitted.

The minimum UL delay for an offered traffic of 40 Mbps is significantly above the minimum DL value. Due to the bandwidth request mechanism of the SSs the minimum delay increased to 20 ms. For the uplink scheduling services best effort (BE) and non-real-time polling service (nrtPS) the SS sends a bandwidth request message to the BS, which allocates UL bandwidth for transmission in the following MAC frames. Other scheduling services like real-time polling service (rtPS) and unsolicited grant service (UGS) which do not rely on accessing contention phases are foreseen for IEEE 802.16 but have not been considered in this simulation. Another reason for the high delay is that the transmission of data takes place in UL bursts that are always scheduled after the DL subframe, initial ranging and bandwidth request periods. These periods are scheduled prior to the UL data transmission bursts. Fifty percent of all arriving UL packets needed more than 30 ms (3 MAC frames) to be transmitted. The delay increases for DL and UL if the offered throughput increases towards its maximum.

Finally a multi-user, multi-mode scenario is evaluated. Transmission errors caused by an AWGN channel have been considered. The same scenario as derived in Section 4 is used. The distribution of users and PHY modes for the scenario is listed in Table 3.

The simulated MAC throughput is plotted in Fig. 18. As long as the offered traffic does not exceed the maximum possible MAC throughput, it can be carried entirely. Reaching the saturation capacity, the MAC throughput remains nearly constant. The saturated MAC capacity of the simulation scenario amounts to approximately 10 Mbps. The MAC throughput of the simulation is confirmed by the calculated throughput shown in Fig. 8.

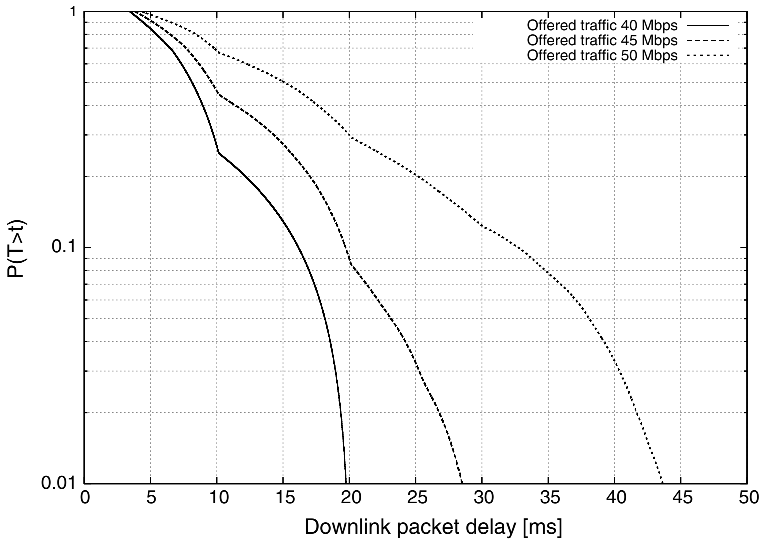

Fig. 16. Downlink packet delay, 64 QAM 3/4.

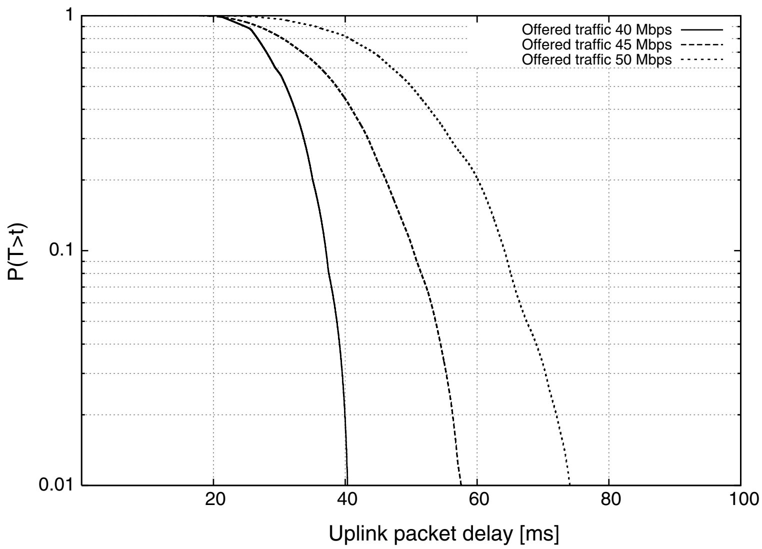

Fig. 17. Uplink packet delay, 64 QAM 3/4.

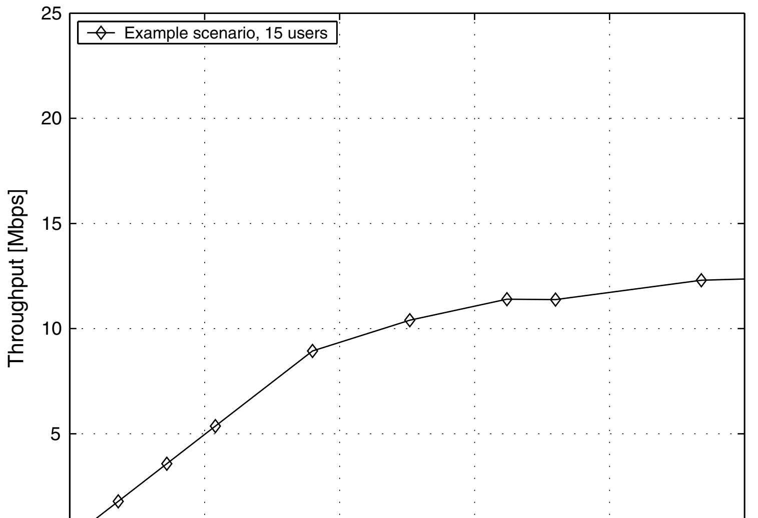

Fig. 18. MAC throughput.

The analysis of the simulation scenario with the mathematical model results in a MAC capacity of 10.67 Mbps. The simulation result does not match the theoretical value exactly because the model of the wireless channel introduces transmission errors. Transmission errors lead to packet losses and that reduces the MAC throughput. The aforementioned effects of contention-based bandwidth-

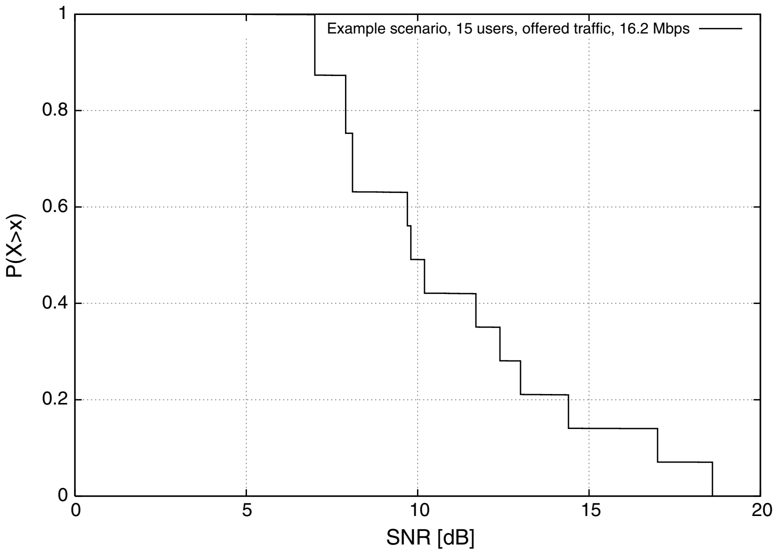

Fig. 19. SNR of received PDUs.

request mechanisms further reduce the MAC throughput.

Fig. 19 shows the CDF of the SNR of received PDUs. In the simulation scenario the SSs are utilizing PHY modes which correspond to their SNR measures. The SNR measures depend on the geographical location of the SSs. The switching point between two adjacent PHY modes (refer to Table 3) are reflected in the CDF of the measured SNRs. In 95% of all transmissions the SNR values are sufficient to allow for error-free packet reception. The remaining 5% perceives a mean packet error ratio around 4%.

7. Summary and conclusions

A detailed introduction to the IEEE 802.16 MAC and PHY layer protocol is presented. The MAC frame structure is illustrated and the basic control elements are described. The basic PHY layer modules of the IEEE 802.16 transmitter-receiver chain are outlined as well.

An analytical system performance evaluation of an example scenario is presented. Basic OFDM parameters as well as capacities of different PHY modes are calculated. Based on the PHY layer capacity the MAC layer capacity is calculated. It is shown that the MAC overhead of the IEEE 802.16 system can be assumed to approximately 10%. Afterwards different features of the protocol are evaluated based on a realistic example scenario. The MAC layer configuration is analyzed in the context of throughput and overhead. Optional fragmentation helps to reduce the overhead and to fill up the MAC frame optimally. Optional features to resist challenging channel conditions are outlined. Their trade off, i.e., a reduced MAC layer capacity, is shown. It is demonstrated that the system can be optimized while maintaining the necessary robustness against environmental challenges.

Furthermore an SDL-based simulator is introduced that implements a prototype IEEE 802.16 protocol including a sophisticated channel model. By means of stochastic event-driven computer simulation the MAC throughput is evaluated. The simulation results show maximum throughput and delay values which can be obtained within the investigated scenario. The simulation results are compared and validated with previous results obtained by theoretical analysis.

It is shown that the achievable IEEE 802.16 capacity is sufficient to provide a powerful wireless last mile technology to potential customers even in a challenging NLOS environment.

Abbreviations and acronyms

ARQ	Automatic repeat request
AWGN	Additive white Gaussian noise
BER	Bit error ratio
BPSK	Binary phase shift keying
BS	Base station
CBR	Constant bit rate
CID	Connection identifier
CP	Cyclic prefix
CRC	Cyclic redundancy check
DL	Downlink
DLFP	Downlink frame prefix
FCH	Frame control header
IE	Information element
LOS	Line of sight
MAC	Medium access control
NLOS	Non line of sight
OFDM	Orthogonal frequency division multiplex
PDU	Protocol data unit
QAM	Quadrature amplitude modulation
QoS	Quality of service
QPSK	Quadrature phase shift keying
RTG	Receive/transmit transition gap
SDU	Service data unit
SNR	Signal to noise ratio
SS	Subscriber station
TDD	Time division duplex
TTG	Transmit/receive transition gap
UL	Uplink
WiMAX	Worldwide interoperability for microwave access

Acknowledgements

I would like to thank Prof. B. Walke of ComNets for his support and all partners involved in the IST-STRIKE project.

References

[1] IEEE, IEEE Std 802.16-2001, IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems, April 2002.

[2] IEEE, IEEE Std 802.16a-2003, IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems—Amendment 2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2–11 GHz, January 2003.

[3] IEEE, IEEE Std 802.16-2004, IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems, October 2004.

[4] ETSI, ETSI Broadband Radio Access Networks (BRAN); HIPERMAN; Data Link Control (DLC) Layer. Standard TS 102 178, 2003.

[5] ETSI, ETSI Broadband Radio Access Networks (BRAN); HIPERMAN; Physical (PHY) Layer. Standard TS 102 177, 2003.

[6] I. Koffman, V. Roman, Broadband Wireless Access Solutions Based on OFDM Access in IEEE 802.16 IEEE Communications Magazine, April 2002.

[7] WiMAX Forum. Available from: <www.wimaxforum.org>.

[8] S.M. Cherry, The wireless last mile, IEEE Spectrum, September 2003.

[9] C. Hoymann, I. Forkel, MAC Layer concepts to support space division multiple access in IEEE 802.16a, in: Seventh International Symposium on Wireless Personal Multimedia Communications (WPMC), Italy, 2004.

[10] CEPT/ERC/REC 13-04, Preferred frequency bands for fixed wireless access in the frequency range between 3 and 29.5 GHz, Technical report, European Radiocommunications Committee, 1998.

[11] ETSI, Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference Document for HIPERMAN in the band 5.725 GHz to 5.875 GHz, Technical Report TR 102 079, 2002.

[12] R. van Nee, R. Prasad, OFDM for Wireless Multimedia Communications, Artech House, 2000.

[13] J.F. Kepler, T.P. Krauss, S. Mukthavaram, Delay spread measurements on a wideband MIMO channel at 3.7 GHz, in: Vehicular Technology Conference (VTC2002 Fall), 2002.

[14] H.D. Lüke, Signalübertragung: Grundlagen der Digitalen and Analogen Nachrichtenübertragungssysteme, Springer, 1995.

[15] I. Forkel, M. Salzmann, Radio propagation modelling and its application for 3G mobile network simulation, in: Proceedings of the 10th Aachen Symposium on Signal Theory, September 2001, pp. 363–370.

[16] M. Engels, Wireless OFDM Systems: How to Make Them Work? Kluwer Academic Publishers, 2002.

[17] A. Hutter, C. Hoymann, B. Wächter, E. Cianca, N. Cassiau, Advanced link level techniques for broadband MIMO metropolitan area networks, in: Seventh International Symposium on Wireless Personal Multimedia Communications (WPMC), Italy, 2004.

[18] IST-STRIKE. Available from: <www.ist-strike.org>.

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He has published several papers, tutorials, and he was actively involved in the standardization of SDMA technologies for IEEE 802.16.