Initial Performance Evaluation and Analysis of the global OFDM Metropolitan Area Network Standard IEEE 802.16a / ETSI HiperMAN

Christian Hoymann, Markus Püttner, Ingo Forkel

RWTH Aachen University,
Chair of Communication Networks, Aachen, Germany
christian.hoymann@comnets.rwth-aachen.de

***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 European Telecommunications Standards Institute (ETSI) and the Institute of Electrical and Electronics Engineers (IEEE) have lately developed a new standard for fixed broadband wireless access systems in frequency bands below 11 GHz.**

This paper gives a short overview of the IEEE 802.16a/OFDM, respectively ETSI HiperMAN standard. The medium access control (MAC) and the physical layer (PHY) are described. An initial system performance analysis of an example scenario is performed. Further on, the MAC packet data unit (PDU) configuration is analyzed. The two optional features packing and fragmentation are evaluated. An optimal MAC PDU length is calculated in the presence of rest bit errors. Especially the interaction of fragmenting MAC PDUs and the padding of orthogonal frequency division multiplex (OFDM) symbols is evaluated in detail. It is shown that the options packing and fragmentation are powerful to optimize the system throughput.

A prototypical IEEE 802.16a protocol stack has been implemented into a simulator by utilizing the specification and description language. Based on the event-driven simulator, downlink and uplink delay as well as throughput evaluation is performed. Thus, performance results based on meaningful MAC configuration examples are provided. These results are compared with previously obtained analytical results.

1. Introduction

The two global fixed broadband wireless access (FBWA) systems, IEEE 802.16a and ETSI High PERformance Metropolitan Area Network (HiperMAN) have been standardized with a close cooperation of both organizations. Hence, the HiperMAN standard [5, 4] is very close to the IEEE 802.16a (systems below 11 GHz) [8]. The baseline for these standards is the IEEE 802.16 (systems between 10 and 66 GHz) [7]. Thus, both OFDM-based physical layers shall comply with each other and a global OFDM system should emerge [10].

The main advantage of 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 $450000” [2]. Apart from being wireless the above mentioned FBWA systems IEEE 802.16a and HiperMAN have been designed to fulfill today's most promising challenges: **Non-professional installation of terminals** to significantly cut the deployment cost, is enabled due to non line of sight (NLOS) operation capability. **Rapidly scalable infrastructure deployment** will decrease time to market for new broadband services which will be crucial for the success of new operators. **Efficient spectrum usage** enables operators to offer services requiring high peak bit rates. **Modular cost-effective growth** is possible because the main cost of radio access lies in the equipment itself. Radio offers the possibility of selective access, easier bridging of distances to customers than fiber or copper. **QoS support** for packet-based services is provided by the system.

In the following a system based on the standards IEEE 802.16a respectively ETSI HiperMAN is investigated. From now on it is only referred to as IEEE 802.16a.

In section 2 the IEEE 802.16a standard is described in detail. A performance evaluation of the system is following in section 3. An initial system analysis of an example scenario is performed on the one hand. On the other hand the MAC packet data unit (PDU) configuration is analyzed. An optimal MAC PDU length is calculated in the presence of rest bit errors. Moreover, the interaction of fragmenting MAC PDUs and the padding of OFDM symbols is evaluated. In the last subsection 3.3, a prototypical IEEE 802.16a protocol stack has been implemented. Based on this event-driven simulator, downlink (DL) and uplink (UL) packet delay as well as throughput evaluation is performed. The simulation results are compared with analytical results.

2. IEEE 802.16a Protocol

The scope of the IEEE 802.16a standard [8] comprises the MAC and the PHY layer as illustrated in Fig. 1.

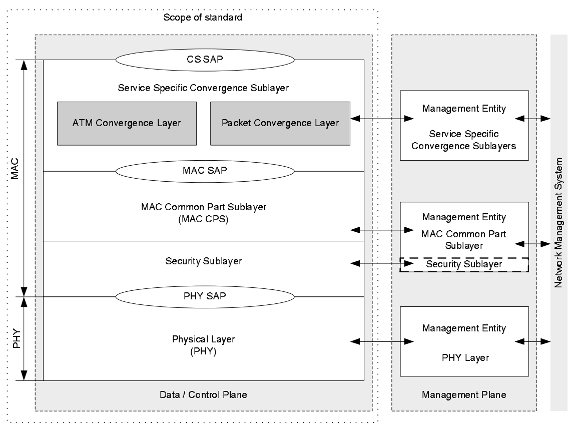

Figure 1: IEEE 802.16a protocol layering

2.1. Medium Access Control

The medium access control (MAC) includes a service specific convergence sublayer that interfaces higher lay-

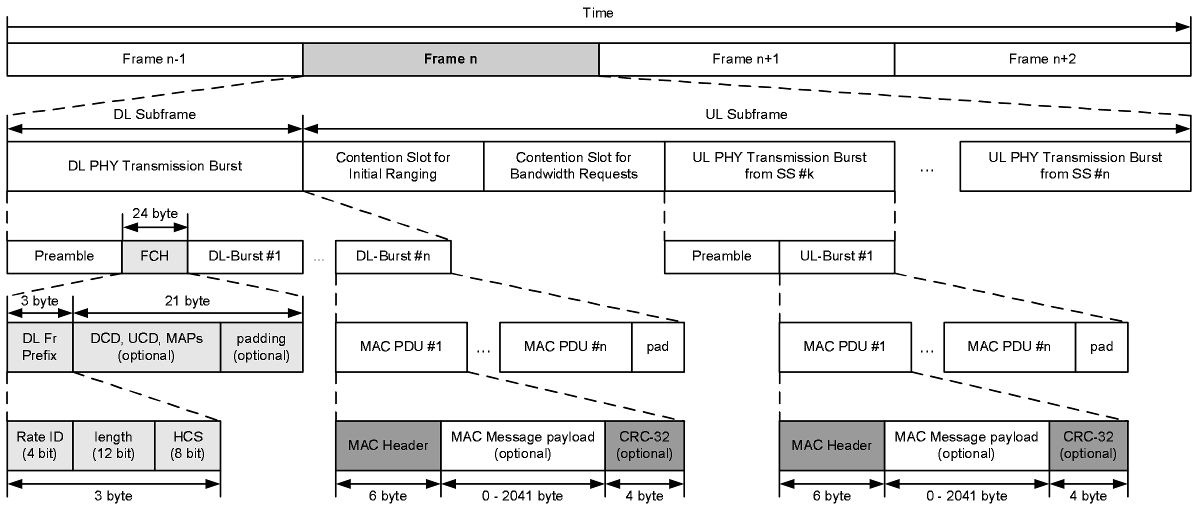

Figure 2: Frame structure TDD

ers. The MAC common part sublayer carries the key functions and below resides the privacy layer. A more detailed description can be found in [6] or the standards themselves [7], [8].

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 to 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 quality of service (QoS).

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 802.16a is optimized for point to multipoint configurations but may allow for flexible mesh deployments. The system supports a frame-based transmission, in which the frame can adopt variable lengths. The frame structure for the OFDM PHY in time division duplex (TDD) mode is illustrated in Fig. 2. Each frame consists of a DL-subframe and an UL-subframe, with the DL-subframe always preceding the UL-subframe. A DL-subframe consists of only one DL PHY transmission burst starting with a preamble used for synchronization. The following frame control header (FCH, mandatory QPSK 1/2) contains the DL frame prefix to specify the modulation/coding (PHY mode) and length of the DL-burst#1. The FCH and/or the DL-burst#1 contains the broadcast MAC control messages, i.e. DL and UL channel descriptor (DCD, UCD) and the UL- and DL-MAP. DCD and UCD define the characteristic of the physical channels. The DL-MAP defines the access to the DL channel, and the UL-MAP allocates access to the UL channel. The PHY modes in UL and DL direction are also specified by the DL- and UL-MAP. The FCH is followed by one or multiple DL-bursts, which are ordered by their PHY mode. While the most robust one is transmitted first, the last burst has the highest PHY mode. Thus, the whole MAC frame is specified by the FCH and/or the DL-burst#1. 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 subscriber station (SS). Each UL PHY transmission burst contains only one UL-burst and starts with a preamble.

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 byte. This allows the MAC to tunnel various higher layer traffic types without knowledge of the formats of those messages.

CS data can be encapsulated to 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 payload of the MAC PDUs as well.

Fragmentation is the process of dividing a MAC SDU onto 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 802.16a automatic repeat request (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.

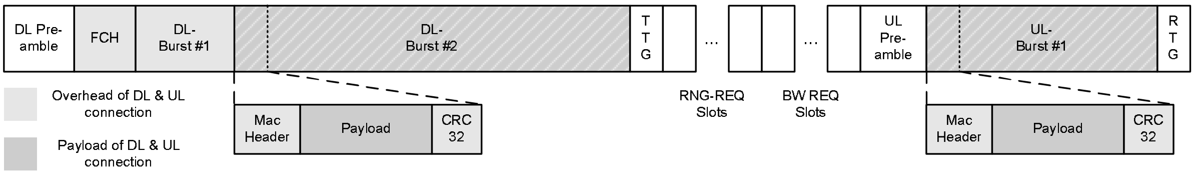

Figure 3: MAC frame of scenario

Security Sublayer

The security sublayer provides subscribers with privacy across the FBWA network by encrypting connections between SS and base station (BS).

2.2. Physical Layer

The investigated IEEE 802.16a PHY uses orthogonal frequency division multiplex (OFDM) with a 256 point transform, designed for NLOS operation in the 2 – 11 GHz frequency bands, both licensed and license-exempt. TDD and FDD variants are defined. Typical channel bandwidths vary from 1.25 to 28 MHz. There are more optional air interface specifications, e.g. based on orthogonal frequency division multiple access (OFDMA) with a 2048-point transform or based on single-carrier modulation.

Since a single harmonized frequency band is not present, [1] 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 favorable propagation properties, as well as the suitable amount of low-cost spectrum (license exempt) and available cheap radio frequency technology, [3] chose the frequency band 5.725 – 5.875 GHz.

Link distances, i.e. cell sizes, will vary strongly based on the environment, propagation conditions and antenna gain. The system will support distances between 2 km and 4 km for NLOS and up to 10 km for LOS condition.

The phenomenon of delay spread is due to multipath scattering. In order to avoid inter-symbol interference (ISI) and inter-carrier interference (ICI), a cyclic prefix (CP) is introduced in front of every data part of an OFDM symbol. 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. Tab. 1 lists common maximum delay spread values in different types of environment. These delay spread values remain unchanged

Type of Environment	Max. Delay Spread
In-Building (house, offi ce)	$< 0.1\,\mu s$
Large building (factory, malls)	$< 0.2\,\mu s$
Open Area	$< 0.2\,\mu s$
Suburban Area LOS	0.2–1.0 μs
Non-LOS	0.4–2.0 μs
Urban Area	1.0–3.0 μs

Table 1: Delay Spread [9, 11]

for any operating frequency above 30 MHz, since the wavelengths become much smaller than human-made architectural structures (recent measurements do confirm the values for frequency bands between 800 MHz and 6 GHz) [9, 11].

IEEE 802.16a's forward error correction (FEC) scheme consists of the concatenation of a Reed-Solomon outer code and a rate-compatible convolutional inner code. The Reed-Solomon outer code may be shortened and punctured. Block turbo coding (BTC) is optional for all modes. The FEC options are paired with the modulation schemes listed in Tab. 3 to form burst profiles of varying robustness and efficiency.

The basic IEEE 802.16a OFDM parameters are outlined in the first two columns of Tab. 2.

OFDM Parameters	Value	Example
Sampling Rate $F_S = 1/T$	$7/6$ resp. $8/7 \cdot BW$	$7/6 \cdot 20$ MHz $= 23.33$ MHz
Useful Time T_B	$256 \cdot T$	10.97 μs
T_G/T_B	$\frac{1}{4}, \frac{1}{8}, \frac{1}{16}, \frac{1}{32}$	
CP Time T_G		$\frac{1}{4} \cdot 10.97\,\mu s = 2.74\,\mu s$
Symbol Time T_{Sym}	$T_G + T_B$	13.7 μs
Carriers N_{FFT}	256	
Data-Carriers	192	

Table 2: Basic OFDM parameters

3. Performance Evaluation

In the first subsection of this chapter an analysis is presented in which the system throughput of an example IEEE 802.16a scenario is calculated. In the second subsection the optimal MAC PDU configuration is investigated. Optimal payload lengths in the attendance of rest bit errors and the optional packing/fragmentation mode is discussed. In the third subsection the IEEE 802.16a simulator is introduced. By means of this simulator performance results based on throughput and delay values are obtained.

3.1. System Performance of an Example Scenario

An exemplary system with 20 MHz bandwidth operating in TDD mode in licensed spectrum bands is evaluated. The frame length is set to 10 ms and a cyclic prefix of 1/4 of the useful time (T_B) is chosen to deal with delay spread values for NLOS operation in suburban areas (refer to Tab. 1). Fig. 3 illustrates the MAC frame which is analyzed. The scenario deals with one DL and one UL connection between one BS and one selected SS, which are located 4 km apart. The MAC frame consists of the DL preamble, the FCH, DL-burst#1 and #2, the TTG (5.14 μs), four RNG-REQ slots, with the

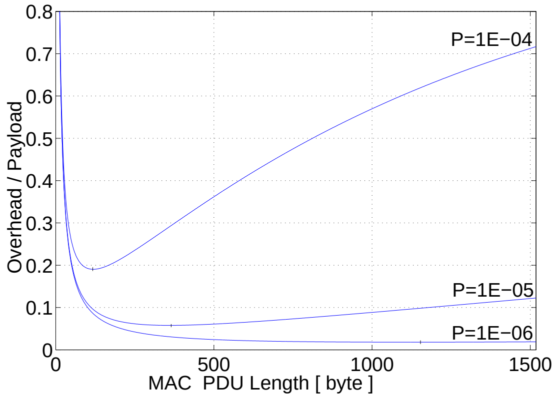

Figure 4: Optimum MAC PDU length with rest bit errors

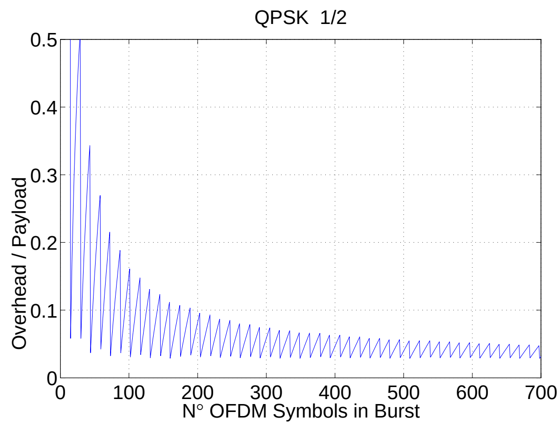

Figure 5: No fragmentation

respective round trip delay (RTD, 26.74 μs) considered for each slot, 10 BW-REQ slots, one UL-preamble, UL-burst #1 and the RTG (5.14 μs). The payload was assumed to be Ethernet traffic with a fixed packet size of 1518 byte. These packets are encapsulated into MAC PDUs without being packed or fragmented. For the theoretical analysis, the last PDU of a burst is fragmented so that it perfectly fits. Thus, padding of bursts can be avoided. ARQ is also disabled. Resulting values for the basic OFDM parameters can be observed in Tab. 2.

Based on these values gross bit rates on PHY level (bit_{sym}/T_{sym}) between 14 and 63 Mbps can be realized depending on the chosen PHY mode (see Tab. 3).

Modulation/ Coding	Example PHY Gross Bit Rate	Example MAC Net Bit Rate
QPSK 1/2	14.0 Mbps	12.7 Mbps
QPSK 3/4	21.0 Mbps	18.9 Mbps
16 AM 1/2	28.0 Mbps	25.2 Mbps
16 QAM 3/4	42.0 Mbps	38.0 Mbps
64 QAM 2/3	56.0 Mbps	50.5 Mbps
64 QAM 3/4	63.0 Mbps	56.9 Mbps

Table 3: PHY modes and dependent bit rates

To get the resulting static system throughput, the overhead must be subtracted. Thus, all frame elements which do not contain payload have been taken off (white and light grey parts of Fig. 3). Remaining is the payload of the MAC PDUs. Now the net bit rate on MAC level can be calculated to values ranging from 12.7 to 56.9 Mbps (see Tab. 3). Approximately 90% of the gross bit rates on PHY level is available to higher layers, or in other words the PHY and the MAC protocol reduces the bit rate by 10% due to overhead.

3.2. Optimal MAC PDU Configuration

Two optional features of the IEEE 802.16a standard have not been considered in the evaluation of the static system performance above, which are ARQ and packing/fragmentation. Both features have to be considered while efficiently filling the MAC frame with data.

The packet length of incoming traffic may vary significantly between 53 byte for ATM cells, up to 1518 byte for Ethernet traffic and up to 65535 byte for IP packets. These packets may be fragmented and/or packed into the MAC PDU payload. Encapsulating the data in MAC PDUs means adding additional overhead, i.e. headers and CRC. As the payload increases, the ratio overhead to payload decreases for the error free transmission.

The assumption of rest bit errors leads to an optimum size which is different to the result of the error free case. Rest 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.

These two competing effects can now be expressed in the following formulas. The calculation denotes the MAC overhead (OH_{mac}) and the retransmission overhead (OH_{ret}). The variable p signifies the rest bit error ratio and N_{mac} the total length of the MAC PDU in bit.

$$OH_{mac} = \frac{header + CRC}{N_{mac} - (header + CRC)} \quad (1)$$

$$OH_{ret} = \frac{(1-(1-p)^{N_{mac}})}{(1-p)^{N_{mac}}} \cdot \frac{N_{mac}}{payload} \quad (2)$$

The addition of equation 1 and equation 2 leads to the overhead in the case of rest bit errors in Fig. 4. The rest bit error ratios of 10^{-4}, 10^{-5}, and 10^{-6} lead to optimal MAC PDU sizes of 107, 349 and 1113 byte, respectively.

Having found an optimal MAC PDU length for every rest bit error ratio another effect appears. Several MAC PDUs are concatenated and transmitted in a single burst. A burst always contains an integer number of OFDM symbols, i.e. it is filled up with padding bit. Padding overhead becomes more significant in the case of longer MAC PDUs since small ones better fill up the burst. But padding overhead can be avoided by fragmenting the last MAC PDU of each burst to the precise length to fill up the burst. For the exemplary scenario the number of OFDM symbols per MAC frame (10 ms) is 730. Normally there are several bursts within one MAC frame so the size of a single burst will be much smaller than 700 OFDM symbols. Fragmentation is enabled and all incoming data packets are fragmented to the optimal size of 349 byte for a rest bit error ratio of 10^{-5}. Thus, the MAC PDU length is fixed. Overhead due to retransmissions is neglected in the following.

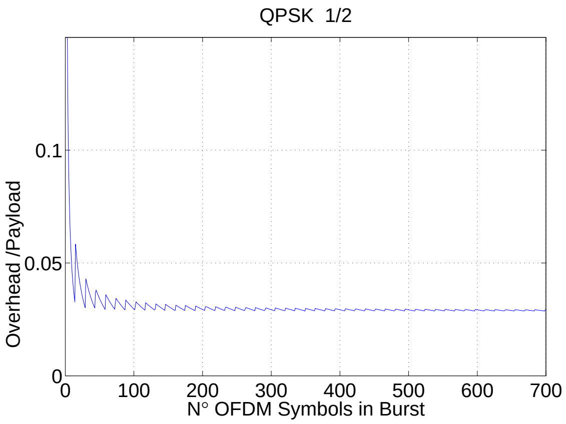

Figure 6: Enabled fragmentation

Fig. 5 illustrates the ratio overhead to payload over the burst length without fragmenting the last MAC PDU. The graph shows a sawtooth-like shape. The size of the teeth increases with decreasing length of the overall burst, i.e.# the less OFDM symbols within a burst, the more significant the padding overhead. Overhead ratios of more than 30% can be observed for a small burst length.

Fig. 6 shows the same scenario but now the last MAC PDU of each burst is fragmented that it fits perfectly into the burst. Thus, the overhead due to padding is avoided. Only the additional fragmentation overhead is still there. Especially for burst lengths below 100 OFDM symbols, it is advisable to fragment the last PDU to fill the burst.

The graphs are examples for PHY mode QPSK 1/2. Although the significance of fragmentation to avoid padding decreases with higher PHY modes, fragmentation in general is still recommended to minimize the MAC overhead due to MAC header / CRC fields and retransmissions. Especially when having small bursts, the adaptive fragmentation of the last PDU of each burst is suggested to avoid padding.

3.3. Simulation Results

A software-based simulator with a prototypical implementation of the IEEE 802.16a protocol has been developed at the Chair of Communication Networks. 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. 7. The protocol stacks of the subscriber station (SS) and the base station (BS) are implemented. Stochastic traffic models generate a well defined traffic load which is characteristical for several different applications like MPEG, Ethernet or constant bit rate. A physical channel transmits the bursts between the SS and the BS and calculates the propagation delay, interference and noise. Based on the calculated signal to interference plus noise ratio (SINR) look up tables are used to map the SINR to the corresponding bit error ratio. These tables introduce the specific behavior of the IEEE 802.16a modem and the wireless channel. Several control blocks manage the simulation, configure the scenarios and evaluate the transmitted

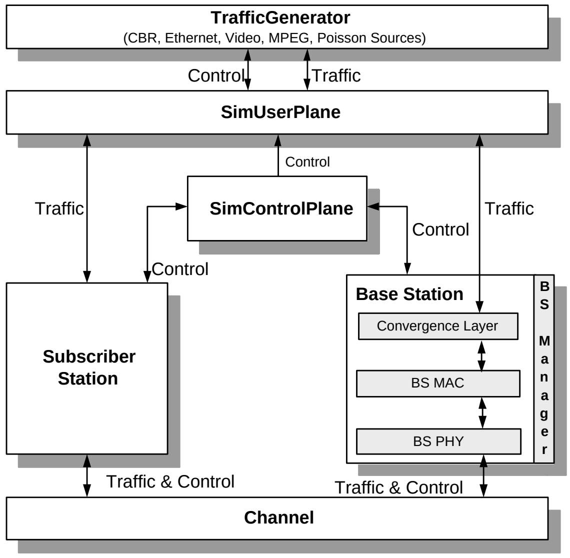

Figure 7: Structure of the SDL Simulator

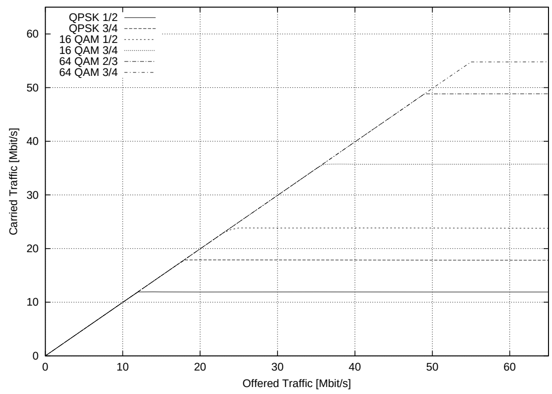

Figure 8: Carried Traffic over Offered Traffic

packets.

The same exemplary IEEE 802.16a system as already described in the preceding subsection is evaluated. The payload was assumed to be Ethernet traffic with a fixed packet size of 1518 byte. These packets are encapsulated into MAC PDUs without being packed or fragmented. Since look up tables for the mapping of bit error ratio to SINR are currently under construction, the following simulation results have been obtained without transmission errors. Thus ARQ is also disabled.

Fig. 8 illustrates the linear relationship between carried and offered traffic. As long as the offered traffic does not exceed the maximum possible value, it is entirely carried. The upmost graph corresponds to the highest modulation and coding scheme (64 QAM 3/4), and the lowest graph to the lowest modulation and coding scheme (QPSK 1/2).

The saturated value of carried traffic for the lowest modulation and coding scheme QPSK 1/2 amounts to 11.9 Mbps, for the highest 64 QAM 3/4 to 54.8 Mbps. The maximum throughput values as they were obtained with the IEEE 802.16a simulator for all modulation and coding schemes are presented in Tab. 4. The upper limits of these throughput values have been predicted through

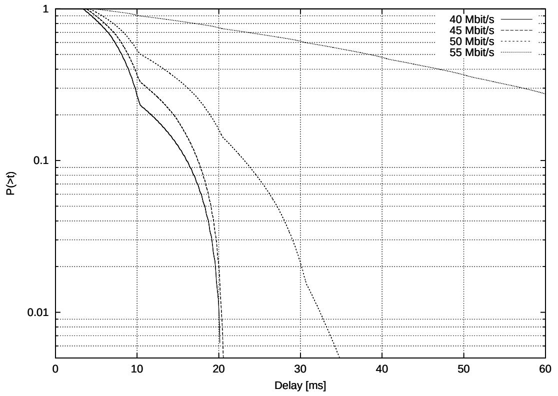

Figure 9: Downlink, CCDF of delay, 64 QAM 3/4

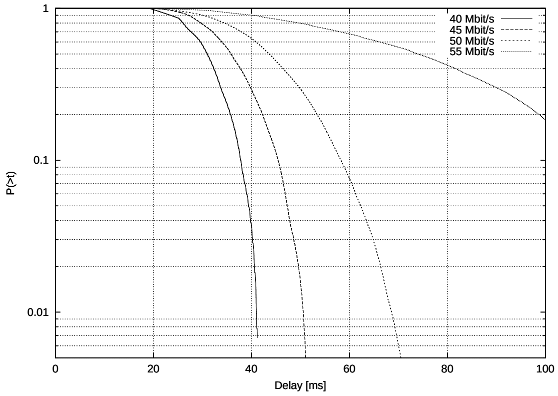

Figure 10: Uplink, CCDF of delay, 64 QAM 3/4

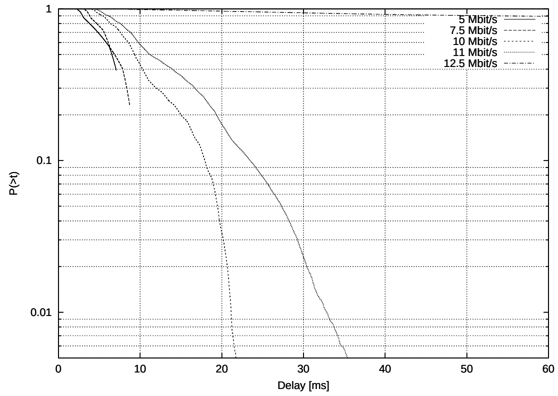

Figure 11: Downlink, CCDF of delay, QPSK 1/2

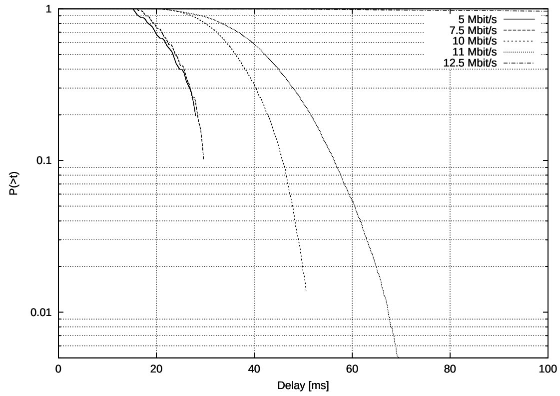

Figure 12: Uplink, CCDF of delay, QPSK 1/2

the theoretical analysis of the previous sections. They could not be reached completely with the IEEE 802.16a simulator since there is no fragmentation algorithm enabled in the simulations, which requests the last packet of a burst to be fragmented in order to avoid padding. The maximum possible overhead due to padding alone may reach 4.3%, assuming a packet length of 1518 byte and the modulation and coding scheme 64 QAM 3/4.

Modulation	Coding	Max. Throughput [Mbps]	
		Simulated	Theoretical
QPSK	1/2	11.9	12.7
	3/4	17.8	18.9
16 QAM	1/2	23.8	25.2
	3/4	35.7	38.0
64 QAM	2/3	48.8	50.5
	3/4	54.8	56.9

Table 4: Maximum throughput per PHY mode

Fig. 9 and Fig. 10 show the complementary cumulative distribution function (CCDF) of DL and UL packet delay values for 64 QAM 3/4. The offered throughput varies between 40 Mbps and 55 Mbps. Since the highest modulation and coding scheme is applied and only one SS is active the results can be seen as an upper bound for an IEEE 802.16a system running with 20 MHz bandwidth. The minimum DL delay for an offered traffic of 40 Mbps (approximately 73% of the maximum, refer to Table 4) is around 3 ms, which signifies that these packets were sent right after the DL preamble, FCH, and DL-burst#1 of the proximate MAC frame. Only 25% of all 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. It is increased to 20 ms. This is due to the bandwidth request mechanism on the SS side. 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 next MAC frame. Other scheduling services like *real-time polling service* (rtPS) and *unsolicited grant service* (UGS) are also foreseen for IEEE 802.16a but have not been considered in this simulation. Another delay can be counted towards the mean duration of the DL subframe, initial ranging and bandwidth request periods. 50% of all arriving UL packets needed more than 30 ms (3 MAC frames) to be transmitted. The delay increases significantly for DL and UL as the offered throughput approaches its maximum at approximately 55 Mbps.

Fig. 11 and Fig. 12 show the CCDF of DL and UL packet delay values for QPSK 1/2. The offered throughput varies between 5 Mbps and 12.5 Mbps. QPSK 1/2 is the most robust burst profile. Thus, the delay results can be seen as the lower bound of the IEEE 802.16a protocol. The minimum DL delay for an offered traffic of 5 Mbps (approximately 40% of the maximum, refer to table 4) is again around 3 ms. The packets were sent directly after the DL preamble, FCH, and DL-burst#1 of the proximate MAC frame. None of the DL packets needed more than one MAC frame (10 ms) to be transmitted. The minimum UL delay for an offered traffic of 5 Mbps is above the minimum DL value. Due to the bandwidth request mechanism for the UL direction and the position of the UL subframe following the DL subframe, the minimum is approximately 17 ms. 70% of all UL packets needed more than 2 MAC frames (20 ms) to be transmitted, but none needed more than 3 frames. As the offered throughput approaches its maximum of approximately 12 Mbps the delay increases significantly for DL and UL

The influence of fragmentation on the system performance has been analytically investigated and presented in section 3.2. This paragraph discusses simulative throughput results obtained with fragmentation. If fragmentation is enabled, arriving IEEE 802.3 Ethernet packets can be fragmented, e.g. into the determined MAC PDU payload length of 339 byte as proposed for a rest bit error ratio of 10^{-5}. The overhead introduced by the shorter PDUs due to fragmentation should be compensated by the reduced overhead due to retransmissions. Since ARQ has been disabled within the simulations no retransmissions occur. The additional overhead per packet amounts to 3.5% of the overall packet length of 339 byte. The overhead is almost 4.5 times higher compared to packets with a length of 1518 byte. The increased overhead is reflected in a smaller possible throughput of user data. The maximum throughput obtained in simulations with enabled fragmentation is 11.6 Mbps for QPSK 1/2 and 52.9 Mbps for 64 QAM 3/4. This indicates a reduction of 2.5% respectively 3.5% compared to the values in table 4. Theoretically, the reduction of throughput due to increased overhead is expected to be around 3% compared to the throughput obtained with packet lengths of 1518 byte. This corresponds with the simulation results.

4. Conclusion

An overview of the IEEE 802.16a / HiperMAN protocol and an initial system performance evaluation of an example scenario by theoretical means is presented in this paper. It is figured out that the overall MAC overhead of the IEEE 802.16a system can be assumed to approximately 10%. The MAC PDU configuration is analyzed in the context of throughput, overhead, packing and fragmentation. It is shown that the optional features packing and fragmentation are powerful to optimize the system throughput while several active connections are sharing the MAC frame in the presence of rest bit errors.

Furthermore an SDL-based simulator is introduced. The simulation results show realistic 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. However, the achievable bit rates and delay values are sufficient to provide a powerful wireless last mile technology to potential customers even in a challenging NLOS scenario.

5. Acknowledgments

The presented work has been done within the STRIKE project and with the financial support by the European Commission under the EU Framework 5 IST programme. We would like to thank Prof. B. Walke of ComNets for his support and all partners involved in IST-STRIKE.

REFERENCES

[1] 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.

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

[3] 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, ETSI, 2002.

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

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

[6] C. Hoymann, M. Püttner, and I. Forkel. The HIPERMAN Standard – a Performance Analysis. In *IST Mobile and Wireless Communications Summit*, pages 827–831, Aveiro, Portugal, June 2003.

[7] IEEE. 802.16: Air Interface for Fixed Broadband Wireless Access Systems. Standard, 2002. IEEE standard for local and metropolitan area networks.

[8] IEEE. 802.16a: Air Interface for Fixed Broadband Wireless Access Systems – Amendment 2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2–11GHz. Standard, IEEE, 2003. IEEE standard for local and metropolitan area networks.

[9] Kepler, Krauss, and Mukthavaram. Delay Spread Measurements on a Wideband MIMO Channel at 3.7 GHz. In *Vehicular Technology Conference (VTC2002 Fall)*, 2002.

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

[11] R. van Nee and R. Prasad. *OFDM for wireless multimedia communications*. Artech, 2000.