Throughput and Delay Performance of IEEE 802.11e Wireless LAN with Block Acknowledgments

Guido R. Hiertz*, Lothar Stibor*, Jörg Habetha†, Erik Weiß*, Stefan Mangold‡
*Chair of Communication Networks, RWTH Aachen University, 52074 Aachen, Germany
hiertz@ieee.org, {lsrlerw}@comnets.rwth-aachen.de
†Philips Research Germany, 52064 Aachen, Germany
joerg.habetha@philips.com
‡ stefan.mangold@ieee.org

***Abstract*— The IEEE 802.11e standard extension for medium access control protocol in wireless local area networks enhances the existing IEEE 802.11 protocol specification towards support for quality of service and improved spectrum management. We look in this paper specifically into an 802.11e concept that is referred to as block acknowledgment. Unlike the original 802.11, where every frame reception must be acknowledged independently, block acknowledgments offer the possibility to acknowledge several consecutive data frames in one response. This obviously may help to decrease the protocol overhead, but is expected to introduce higher end-to end delays for the data frame transmissions. We present a closed-form analytical analysis of the block acknowledgment protocol, and compare our findings to simulation results. Our results show that whereas throughputs improve considerably when block acknowledgments are applied, care has to be taken not to increase the delays above unacceptable durations.**

***Index Terms*— Wireless LAN, IEEE 802.11, IEEE 802.11e, Quality of Service (QoS), Block Acknowledgment (BA), Turbo Mode**

I. Introduction

The *Institute of Electronics and Electrical Engineering (IEEE)* standard 802.11 [1] dominates the market of *Wireless Local Area Networks (WLANs)* systems. High data rates up to 54 Mb/s are introduced by 802.11a [2] and 802.11g [3] at 5 GHz respectively 2.4 GHz. Due to the static overhead included with every frame exchange the efficiency of 802.11 decreases when using small data frames and/or high data rates. Currently *Task Group E (TGe)* of 802.11 establishes an addendum [4] to support *Quality of Service (QoS)*. The addendum includes the *Block Acknowledgment (BA)* mechanism which helps to reduce the protocol overhead. Several vendors are already implementing BA in their products. Especially the market of 802.11g systems is characterized by different “Turbo” mode options. Out of many BA is most promising even without implementing any other feature of 802.11e. Hence the present paper focuses on the enhancements of BA and gives simulative and analytical results.

A. Motivation

Studies [5]–[11] have independently shown that the efficiency of 802.11 depends very much on the *Physical Layer (PHY)* mode. With the usage of 802.11b [12] and especially the introduction of 802.11a [2] or 802.11g

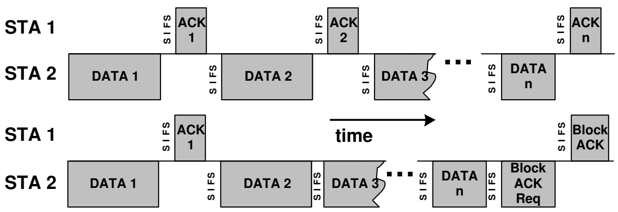


Fig. 1. Compared to a fragmentation burst, BA saves overhead. Depending on the number of MPDUs the BA overhead of BlockACKReq and BlockACK is negligible.

[3] several data rates are available in 802.11. Each of these data rates (e.g. ranging from 6 Mb/s to 54 Mb/s for the 802.11a PHY) uses the same signaling overhead. Hence the efficiency of 802.11 drops at high data rates. Therefore 802.11e introduces a new *Acknowledgment (ACK)* scheme to reduce the overhead.

B. Outline

This paper is outlined as follows. First we explain 802.11e *Block Acknowledgment (BA)* in detail. Following BA is analyzed. Based on simulations we evaluate the BA mechanism and present our results. Our simulations consider the 802.11a *Physical Layer (PHY)*. Finally we conclude and estimate the BA procedure. Throughout this paper all mathematical notations and unit descriptions are given according to [13]. See documents [14] and [15] of the authors for an introduction to 802.11 and its *Quality of Service (QoS)* supporting features of 802.11e.

II. Block Acknowledgment in 802.11e

To increase the efficiency *Block Acknowledgment (BA)* aggregates several *Acknowledgment (ACK)* frames into one frame. Therefore the BlockACK frame replaces several single ACK frames. It consists of a bitmap of 128 B. This BlockACK bitmap indicates the status of reception of up to 64 *MAC Service Data Units (MSDUs)*. Thus 2 B are used to indicate the successful reception of an MSDU or fragments (*MAC Protocol Data Unit (MPDU)*) thereof. To allow a flexible implementation of the BA procedure 802.11e defines immediate or delayed BA. The latter one gives a receiver more time to do computing on the received frames. Hence it allows a software implementation of the 802.11e protocol (e. g. using hardware driver).

Since in [4] the abbreviation "Block Ack" is used to indicate the procedure itself as well as the corresponding frame, confusion may easily occur. In the following text we indicate the BA mechanism by the acronym BA. "BlockACK" indicates the corresponding frame.

To use the BA mechanism the sender must initiate the BA in the receiver by transmitting an "ADDBA" request to the recipient. Afterwards the recipient responds to the request by denying or accepting the usage of BA. It is the receiver which indicates the buffer size that shall be used. The number of buffers and the BA policy may be changed at any time.

Having successfully set up a BA the initiator may use the BA procedure limited by the following constraints only:

- All transmissions are limited by the *Transmission Opportunity (TXOP)* duration. A BA frame exchange burst may not exceed this limit. However, a BlockACK request may be demanded in subsequent TXOPs to the current one.
- The originator may not transmit more frames than the receiver has indicated to be able to buffer.
- To protect the frame burst the *Request To Send/Clear To Send (RTS/CTS)* mechanism shall be used or the first frame in a BA TXOP shall be acknowledged individually to allow a consistent *Network Allocation Vector (NAV)* in all neighboring *Stations (STAs)*.
- A BA may only start using a bitmap indicating an MSDU boundary.

However, according to the intention of 802.11e the originator may split frames using BA across several TXOPs, see Fig. 3. Thus BA can be used as flexible as possible. Fig. 1 presents a comparison of legacy 802.11 frame bursting and BA.

Only when using the delayed BA feature the receiver shall respond of an ordinary ACK frame instead by a BlockACK. This indicates to the originator that the receiver has successfully understood the end of the BA transmission. A soon as the BA frames can be acknowledged the receiving *QoS Station (QSTA)* will transmit the BlockACK as its earliest frame with highest priority. In contrast to the delayed BA the immediate BA procedures avoids the need of a separated TXOP for the BlockACK transmission, see Fig. 2.

After a recipient receives a BlockACKReq it shall indicate to the higher layer all received frames of a sequence number less than the number indicated in the request frame. If the buffer is filled up while new MPDUs are arriving the first successfully received MSDU shall be indicated to the higher layer.

In addition to the immediate and delayed BA procedure the "No ACK" procedure may be used as well. Accordingly 802.11e requires a starting frame exchange to allow NAV setting in all neighboring STAs. Since this scheme cannot guarantee any reliability of transmission it may be suited best for *User Datagram Protocol (UDP)* packets as an example.

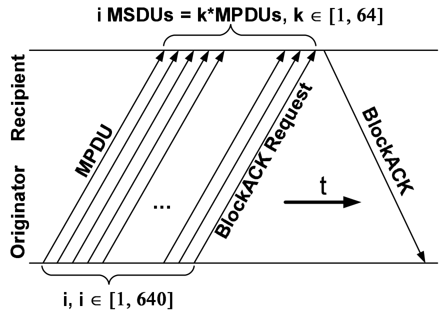


Fig. 2. Message Sequence Chart on the frame exchange procedure using BA. The reception of MSDUs may be interrupted at any time. Thus only after having received a BlockACK Request in the same or in a subsequent TXOP the receiver replies by a BlockACK frame.

Tearing down an established BA session is accomplished by transmitting a "DELBA" frame. The recipient sends a standard ACK frame to acknowledge the session end.

III. Evaluation

A. Theoretical Analysis

A closed form solution for the theoretical limit of the achievable throughput with *Block Acknowledgment (BA)* is given in the following. This limit allows us to verify the simulation results of later sections. For the IEEE 802.11e contention-based protocol, it is in the following assumed that the throughput is maximized if one single *Station (STA)* continuously initiates frame exchanges, and no other STA attempts to initiate frame exchanges in parallel. No collisions would then occur, and frames are never retransmitted, because the channel is further assumed to be error-free. The assumption that such a scenario leads to the maximum throughput is true for typical CWmin values (<100), but not for large CWmin values. With large CWmin values, the throughput actually increases with increasing number of contending STAs up to a certain point, where then collisions become the dominant factor, and the throughput decreases again with the increasing number of STAs. However, in the following we assume reasonably small values for CWmin, hence the throughput is maximal if only one contending STA is active.

1) Maximum achievable throughput without Block Acknowledgment (BA): When using 802.11e *Enhanced Distributed Channel Access (EDCA)* every transmission starts with a backoff. The mean duration for the whole backoff depends on the *Access Category (AC)*. According to the AC the fixed waiting time *Arbitration IFS (AIFS)* is determined. The minimum size of the *Contention Window (CW)* depends on the AC, too. Assuming an error free transmission the CW never enlarges. Thus the number of slots is drawn from the interval $[0, CWmin]$. As the random number of slots is drawn from a uniform distribution its mean value is $^{CWmin}/_{2}$, see (1).

$$Duration(Backoff) = AIFS + \frac{CWmin}{2} * Duration(aSlot) \quad (1)$$

As stated before we consider 802.11a in our simulations. Table I gives an overview of some important

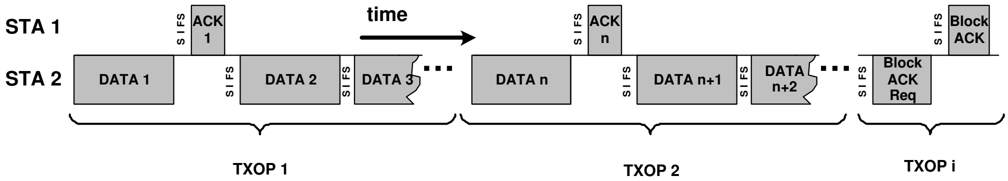


Fig. 3. BA frames may be split across multiple TXOPs.

TABLE I
PARAMETERS FOR THE IEEE 802.11A OFDM PHY

Acronym	Explanation	Value
N_{DPBS}	Data bits per OFDM symbol	depending on PHY mode
MAC-Overhead	Needed for addressing, NAV etc.	34 B
Tail-Bits	Needed for the OFDM convolutional encoder	6 b
Service-Bits	Reserved for future use	2 B
T-SYM	OFDM Symbol interval	4 μs
T-PLCP-Preamble	PLCP preamble duration	Sum of *T-Short* and *T-Long*
T-Short	Short training sequence, 10 symbols	8 μs
T-Long	Long training sequence, 2 symbols	8 μs
T-SIGNAL	Contains information on the transmission rate and the length of the TxVector	4 μs

Physical Layer (PHY) characteristics. The number of Bytes to be transmitted can be calculated according to (2).

$$\begin{aligned} \textit{MAC-PDU} &= \textit{MAC-SDU} + \textit{MAC-Overhead} \\ &= \textit{MAC-SDU} + 34B \\ \textit{PDU-SDU} &= \textit{MAC-PDU} \\ \textit{PHY-PDU} &= \textit{PHY-SDU} + \textit{Service-Bits} + \textit{Tail-Bits} \\ &= \textit{PHY-SDU} + 2B + 6b \end{aligned} \quad (2)$$

The *MAC-Overhead* cannot be easily determined. Depending on the transmission direction (to a *Station (STA)* in the same *Basic Service Set (BSS)* or in the *Extended Service Set (ESS)*, to or from an *Access Point (AP)* et cetera) the number of address fields varies. Additionally legacy *MAC Protocol Data Units (MPDUs)* will have a different length than *Quality of Service (QoS)* 802.11e MPDUs. Therefore the value of 34 B used here is meant as an example only.

Thus the number of *Orthogonal Frequency Division Multiplexing (OFDM)* symbols to be transmitted is given by (3).

$$\textit{N(OFDM)} = \lceil (\textit{PHY-PDU} * \frac{8b}{1B}) / N_{DBPS} \rceil \quad (3)$$

Therefore the transmission duration including the PHY Preamble, *Physical Layer Convergence Protocol (PLCP)* header, Training Sequence et cetera is given by (4).

$$\begin{aligned} \textit{Duration} &= \textit{N(OFDM)} * \textit{T-SYM} + \textit{T-SIGNAL} + \\ &\quad \textit{T-PLCP-Preamble} \\ &= \textit{N(OFDM)} * 4\mu s + 4\mu s + \textit{T-PLCP-Preamble} \\ &= \textit{N(OFDM)} * 4\mu s + 4\mu s + (\textit{T-Short} + \textit{T-Long}) \\ &= \textit{N(OFDM)} * 4\mu s + 20\mu s \end{aligned} \quad (4)$$

Now we can easily calculate the duration of any control, data or management frame. In 802.11e the *Transmission Opportunity (TXOP)* Limit restricts the duration for which a *QoS Station (QSTA)* may use the *Wireless Medium (WM)*. No further restrictions regarding the number of *MAC Service Data Units (MSDUs)* are made. Thus a QSTA may transmit a number of N_{MT} MSDUs per TXOP. Therefore the duration during which the WM is busy is given by (5).

$$\begin{aligned} &\textit{Duration(Transmission)} \\ &= \sum_{i=1}^{N_{MT}} \textit{Duration(N(OFDM(PHY-PDU}_i + \textit{ACK)))} \end{aligned} \quad (5)$$

If *Request To Send/Clear To Send (RTS/CTS)* is used (6) its duration must be added to the WM busy time.

$$\begin{aligned} &\textit{Duration(Protective Frames)} \\ &= \begin{cases} 0 & \text{without RTS/CTS} \\ \textit{Duration(N(OFDM(RTS + CTS)))} & \text{with RTS/CTS} \end{cases} \end{aligned} \quad (6)$$

The duration of all *Interframe Spaces (IFSs)* needed to transmit N_{MT} MSDUs is given in (7). It depends on the usage of RTS/CTS as well.

$$\begin{aligned} &\textit{Duration(IFS)} \\ &= \begin{cases} (2 * N_{MT} - 1) * \textit{SIFS} & \text{without RTS/CTS} \\ (2 * N_{MT} + 1) * \textit{SIFS} & \text{with RTS/CTS} \end{cases} \end{aligned} \quad (7)$$

Hence the total throughput given in Mb/s is calculated by (8).

$$\begin{aligned} &\textit{Throughput} \\ &= \textit{MAC-SDU} * \\ &\quad \textit{Duration(Backoff, Protective Frames,} \\ &\quad \textit{Transmission, IFS)}^{-1} * \frac{8b}{1B} \end{aligned} \quad (8)$$

2) Maximum Block Acknowledgment (BA) throughput: Similar to the (8) the maximum throughput for a given set of backoff values and *Transmission Opportunity (TXOP)*Limit can be calculated when using BA. Assuming that immediate BA is used (5) is altered to (9).

$$\begin{aligned} & \textit{Duration(Transmission)} \\ = \; & \textit{Duration(N(OFDM(BlockACK, BlockACKReq)))} \\ & + \sum_{i=1}^{N_{MT}} \textit{Duration(OFDM(PHY-PDU}_i)) \end{aligned} \tag{9}$$

According to 802.11e a protective mechanism like *Request To Send/Clear To Send (RTS/CTS)* shall be used to avoid collisions during the frame burst. Therefore (6) changes to (10). must be added to (9). If no protective mechanism is used the first *MAC Protocol Data Unit (MPDU)* to be transmitted in each burst shall be acknowledged individually to allow the set up of a *Network Allocation Vector (NAV)* protection for succeeding frames. Hence (6) changes to (10).

$$\begin{aligned} & \textit{Duration(Protective Frames)} \\ = \; & \begin{cases} \textit{Duration(N(OFDM(ACK)))} & \text{without RTS/CTS} \\ \textit{Duration(N(OFDM(RTS,CTS)))} & \text{with RTS/CTS} \end{cases} \end{aligned} \tag{10}$$

With the usage of RTS/CTS the number of *Interframe Spaces (IFSs)* needed for BA increases by one in contrast to the number of IFSs without. Therefore the duration of IFSs needed to transmit N_{MT} *MAC Service Data Units (MSDUs)* is given in (11).

$$\textit{Duration(IFS)} = \begin{cases} (N_{MT} + 2) * \textit{SIFS} & \text{without RTS/CTS} \\ (N_{MT} + 3) * \textit{SIFS} & \text{with RTS/CTS} \end{cases} \tag{11}$$

The total medium busy time is calculated as the sum of (9), (10) and (11). Hence the maximum throughput is calculated by (12).

$$\begin{aligned} & \textit{Throughput} \\ = \; & \textit{MAC-SDU} * \\ & \textit{Duration(Backoff, Protective Frames,} \\ & \textit{Transmission, IFS})^{-1} * \frac{8b}{1B} \end{aligned} \tag{12}$$

B. Analytical Comparison of Block Acknowledgment (BA) and Standard Acknowledgment (ACK) Procedure

Comparing (7) and (11) the advantages of BA are obvious. First of all BA reduces the number of *Short Interframe Spaces (SIFSs)* in a burst of data transmission by approximately 50%. Secondly (9) presents that the number of ACK frames does not depend on the number of transmitted *MAC Protocol Data Units (MPDUs)* any more. Thus the impact of the additional overhead of frames like BlockACK and BlockACKReq is negligible.

C. Simulative Analysis

We use event-driven stochastic simulations to discuss the efficiency of *Block Acknowledgment (BA)* in 802.11e. Simulation campaigns have been performed for the 802.11a *Orthogonal Frequency Division Multiplexing (OFDM) Physical Layer (PHY)*. For delay results, we give empirical *Complementary Cumulative Distribution Function (CDF)* of the resulting stochastic data, using the discrete *Limited Relative Error (LRE)* algorithm that also measures the local correlations of the stochastic data [16]. By measuring local correlations, the accuracy of empirical simulation results can be estimated. All results presented in this paper are within a maximum limited relative error of 5%.

The simulations were performed using the *Wireless Access Radio Protocol 2 (WARP2)* simulation environment developed at the Chair of Communication Networks, RWTH Aachen University [17]. It is programmed in *Specification and Description Language (SDL)* using Telelogics TAU SDL Suite (previously named *SDL Design Tool (SDT)*). The error model used in WARP2 to accurately simulate the *Wireless Medium (WM)* is presented in [18].

D. Results

At the time the simulations were performed draft 5.0 [19] of 802.11e was the latest one. It did not require any protective mechanism for *Block Acknowledgment (BA)*. Thus, our simulations are slightly different from the latest draft [4] which we explain in this paper.

To survey the upper bound of the achievable throughput and a lower bound for the minimal delay when using BA, the simulated scenario consists of a sending and a receiving *Station (STA)* only. They are placed very close to each other.

The *Transmission Opportunity (TXOP)*Limit used in the given scenario is bounded to 64 TXOPslots. Each slot durates $32\mu s$ resulting in an overall TXOPLimit of $2048\mu s$. The simulations are performed using three different *Physical Layer (PHY)* modes (64-QAM¾, 16-QAM½ and BPSK¾), four packet sizes (1500 B, 1024 B, 512 B and 48 B) and three different BA buffer sizes (64, 32 and 8) for the transmit- and reception buffers. For comparison a simulation with standard *Acknowledgment (ACK)* policy is included.

As Fig. 4, 5 and 6 present our simulation results correspond to the analytical model of 802.11e. Especially short frames benefit of the usage of BA at all PHY modes. Large 1500 B frames benefit mainly a high PHY modes since in 802.11 the overhead for large frames is less compared to short frames. Considering the impacts of BA on the delay and implementation issues a buffer size of 32 seems to be an optimum, a buffer size of 64 offers only minor advantages but doubles the mean delay almost.

E. Outlook

Future survey will study the impact of different TXOPLimits on throughput and delay. Also, more complicated scenarios will be studied, that give an understanding of BA when multiple STAs compete on the medium. Furthermore simulations will be performed that combine the advantages of BA and a central coordination instance using the *HCF Controlled Channel Access (HCCA)*. This will allow to survey a scenario competitive to *High Performance Local Area Network 2 (H2)*. At this time *Task Group (TG)* "n" of 802.11 develops a new high speed *Medium Access Control (MAC)*. It shall be able to carry a least 100 Mb/s in a single hop environment. Especially 802.11n will benefit by the usage of BA. Hence future studies on 802.11n will consider BA as well. As it avoids unused idle periods of the *Wireless Medium (WM)* it is a general method to support high throughput services.

IV. Conclusions

Block Acknowledgment (BA) as proposed in [4] is presented in detail. To give a better understanding of the procedure we give simulative and analytical results on the usage of BA. Our results presents upper boundaries to the achievable throughput and lower boundaries to the delay. Therefore, we present best case results, that give an understanding of the impact of BA. The simulation results are very well verified by our analytical methods. The introduction of BA in 802.11e improves the protocol tremendously. Since the overhead is reduced the efficiency increases even when using small buffer sizes. Since its application can be handled very flexible BA is one of the most important features of 802.11e. The ease of use and implementation combined with the introduction of *Transmission Opportunitys (TXOPs)* forms a powerful enhancement to the legacy standard.

Acknowledgment

The authors would like to thank Prof. Dr.-Ing. B. Walke for his support and friendly advice to this work. The contributions of our colleague Sebastian Max are highly appreciated.

References

[1] *IEEE Wireless LAN Edition - A compilation based on IEEE Std 802.11-1999 (R2003) and its amendments*, IEEE Std. 802.11, 2003.

[2] *Suplement to IEEE Standard for Information technology - Telecommunications and Information exchange between systems - Local and metropolitan area networks - Specific Requirements - Part 11 : Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications : High speed Physical Layer in the 5 GHz Band*, IEEE Supplement 802.11a, Jan. 1999.

[3] *802.11g - IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications - Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band*, IEEE Amendment 802.11g, June 2003.

[4] *IEEE Standard for Information Technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications: Amendment: Medium Access Control (MAC) Quality of Service (QoS) Enhancements*, IEEE Draft Amendment IEEE P802.11e/D13.0, Jan. 2005.

[5] J. Jun, P. Peddabchagari, and S. Mihail, "Theoretical Maximum Throughput of IEEE 802.11 and its Applications," in *Second IEEE International Symposium on Network Computing and Applications*. Cambridge, Massachusette, USA: IEEE, Apr. 2003, pp. 249–256.

[6] Y. C. Tay and K. Chua, "A Capacity Analysis for the IEEE 802.11 MAC Protocol," *Wireless Networks - The Journal of Mobile Communication, Computation and Information*, pp. 159–171, 2001.

[7] S. Mangold, "Analysis of IEEE 802.11e and Application of Game Models for Support of Quality-of-Service in Coexisting Wireless Networks," PhD thesis, Communication Networks, Aachen University of Technology, Communication Networks, Aachen University of Technology, June 2003, ISBN 3-86073-985-9.

[8] G. Bianchi, "Throughput Evaluation of the IEEE 802.11 Distributed Coordination Function," in *5th Workshop on Mobile Multimedia Communications*, Berlin, Federal Republic of Germany, 1998, pp. 307–318.

[9] G. Bianchi, "IEEE 802.11 - Saturation Throughput Analysis," *IEEE Communications Letters*, vol. 2, no. 12, pp. 318–320, Dec. 1998.

[10] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE Journal on Selected Areas in Communications*, vol. 18, pp. 535–547, Mar. 2000.

[11] G. Bianchi, L. Fratta, and M. Oliveri, "Performance Evaluation and Enhancement of the CSMA/CA MAC Protocol for 802.11 Wireless LANs," in *Proceedings of PIMRC 1996*, Taipei, Taiwan, Oct. 1996, pp. 392–396.

[12] *Supplement to IEEE Standard for Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band*, IEEE Supplement 802.11b, Sept. 1999.

[13] I. Periodicals Transactions/Journals Department. (2003, Jan.) IEEE Transactions, Journals, and Letters - Information for Authors. auinfo03.pdf. IEEE. 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA. [Online]. Available: http://www.ieee.org/portal/cms_docs/pubs/transactions/auinfo03.pdf

[14] S. Mangold, S. Choi, P. May, and G. R. Hiertz, "IEEE 802.11e - Fair resource sharing between overlapping basic service sets," in *PIMRC 2002 - The 13th IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, Sept. 2002.

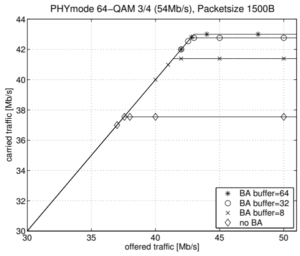
[15] S. Mangold, S. Choi, G. R. Hiertz, O. Klein, and B. Walke, "Analysis of IEEE 802.11 for QoS Support in Wireless LANs," *IEEE Wireless Communications*, vol. 10, no. 6, pp. 2–12, Dec. 2003.

[16] F. Schreiber, "Effective Control of Simulation Runs by a New Evaluation Algorithm for Correlated Random Sequences," *AEÜ International Journal of Electronics and Communications*, vol. 42, no. 6, pp. 347–354, 1988.

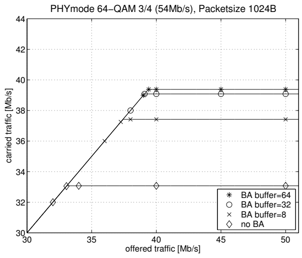
[17] Chair of Communication Networks, RWTH Aachen University, Kopernikusstraße 16, 52074 Aachen, Federal Republic of Germany. [Online]. Available: http://www.comnets.rwth-aachen.de

[18] S. Mangold, S. Choi, and N. Esseling, "An Error Model for Radio Transmissions of Wireless LANs at 5GHz," in *Proc. Aachen Symposium 2001*, Aachen, Sept. 2001.

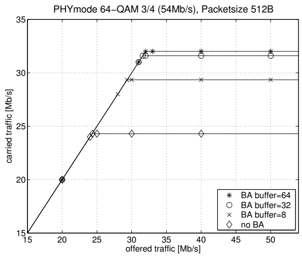
[19] *Draft Supplement to STANDARD FOR Information Technology - Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements - Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications: Medium Access Control (MAC) Quality of Service (QoS)*, IEEE Draft Amendment 802.11e/D5.0, July 2003.



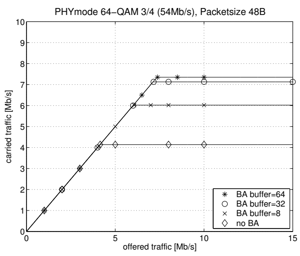
(a) 1500B



(b) 1024B

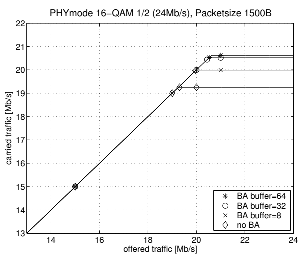


(c) 512B

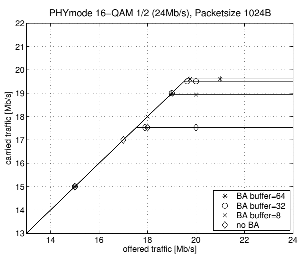


(d) 48B

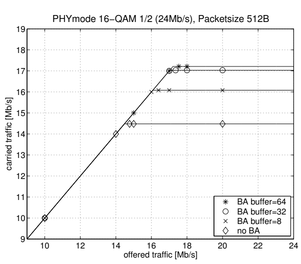
Fig. 4. Maximum throughput using a transmission rate of 54 Mb/s without and with different BA buffer sizes.



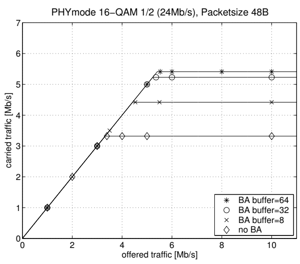
(a) 1500B



(b) 1024B

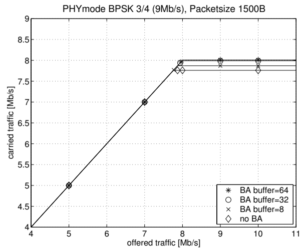


(c) 512B

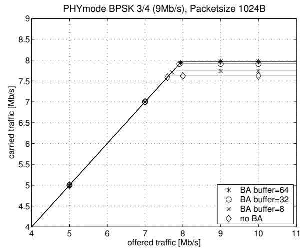


(d) 48B

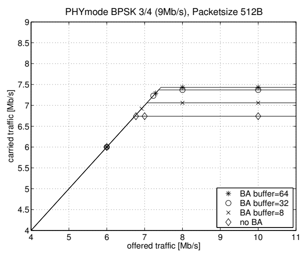
Fig. 5. Maximum throughput using a transmission rate of 24 Mb/s without and with different BA buffer sizes.



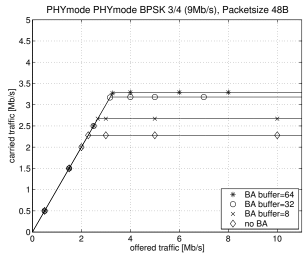
(a) 1500B



(b) 1024B

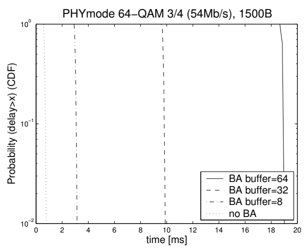


(c) 512B

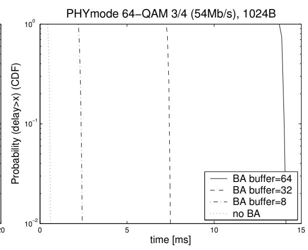


(d) 48B

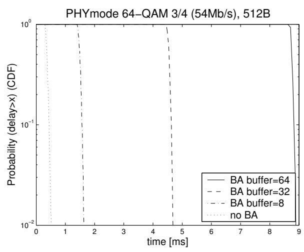
Fig. 6. Maximum throughput using a transmission rate of 9 Mb/s without and with different BA buffer sizes.



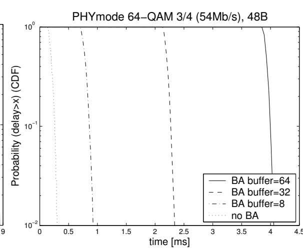
(a) 1500B



(b) 1024B

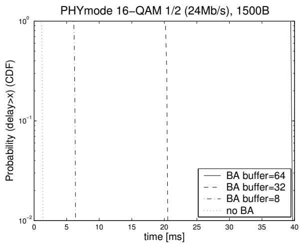


(c) 512B

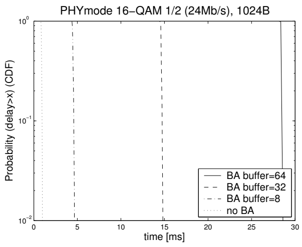


(d) 48B

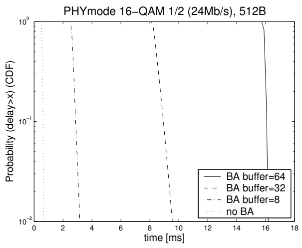
Fig. 7. CDF on the delay when transmitting at a data rate of 54 Mb/s without and with different BA buffer sizes.



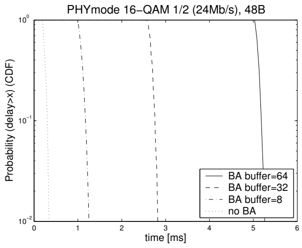
(a) 1500B



(b) 1024B

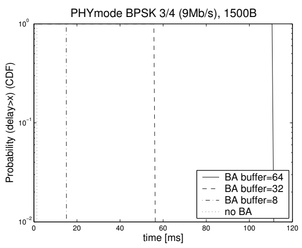


(c) 512B

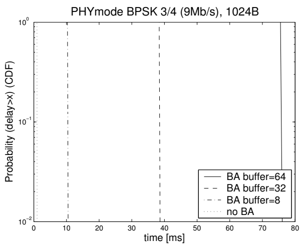


(d) 48B

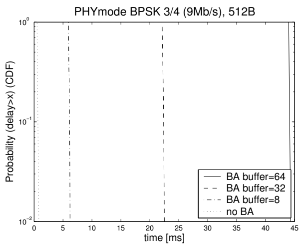
Fig. 8. CDF on the delay when transmitting at a data rate of $24\,\mathrm{Mb/s}$ without and with different BA buffer sizes.



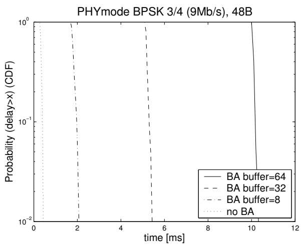
(a) 1500B



(b) 1024B



(c) 512B



(d) 48B

Fig. 9. CDF on the delay when transmitting at a data rate of $9\,\mathrm{Mb/s}$ without and with different BA buffer sizes.