Throughput Upper Limit for IEEE 802.11 Networks with Block Acknowledge and Frame Aggregation

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Abstract. The paper presents new transmission procedures present in IEEE 802.11 standard and compares them to the "traditional" frame exchange method. On the basis of their operating rules, analytical equations are derived that allow calculate network efficiency or effective throughput. The throughput upper limit is also calculated and compared for all considered frame exchange procedures.

Keywords: IEEE 802.11 standard, block acknowledge, frame aggregation, throughput upper limit.

1 Introduction

IEEE 802.11 standard [1] is currently the leading solution in the range of wireless local area networks. Peripherials compatible with this standard are available for numerous types of devices, not necessarily being computers. For example, they can be embedded into laptops, palmtops, but also high-class digital photo cameras (like Canon EOS 1D), DVD players, digital satellite receivers etc. In addition, 802.11 has now several modifications necessary for QoS (802.11e) and high throughput (802.11n) support.

The standard architecture, in a brief, consists of data link and physical layers specification. While data link layer is uniform, there are several physical layer definitions, applying various modulation and encoding methods that allow achieve multiple data rates. However, in conformance with ISO/OSI network model, physical layer details must be transparent to higher layers. Thus, necessary mechanisms must be included in physical layer signaling rules that are not visible to data link; unfortunately, such approach introduces additional protocol overhead that does not remain without influence on overall network performance.

Several paper exist that analyse the efficiency of 802.11 protocol, e.g., [2,3]. In [3] a good explanation of transmission procedures and their influence on effective throughput is given using analytical methods. Using similar approach, it has been proved [2], that "traditional" frame exchange rule has a throughput upper limit (TUL) of about 75 Mbps even when transmission rate is infinite. However, new transmission methods have been introduced in 802.11 standard since then. In

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this paper, using methods similar to those shown in [2,3], these transmission procedures are analyzed and compared to the "traditional" one. Thus, the paper extends some results presented in [2].

2 Data Transmission in IEEE 802.11 Standard

In IEEE 802.11 standard, data transmission may proceed according to few frame exchange procedures. For many years, only a single procedure, has been defined. Further in this paper it is referred to as basic frame exchange. Later, together with QoS enhancements, block acknowledge has been proposed in IEEE 802.11e in order to reduce protocol overhead by reducing number of acknowledge frames. Finally, 802.11n [4] introduces frame aggregation which allows even further overhead reduction by merging frames into long frame sequences.

2.1 Basic Frame Exchange

In basic frame exchange using DCF (*Distributed Coordination Function*) protocol, Data and Ack frames alternate. Each frame must be preceded by PLCP (*Physical Layer Convergence Protocol*) preamble and header. Thus, frame exchange process runs as presented on Fig. 1.

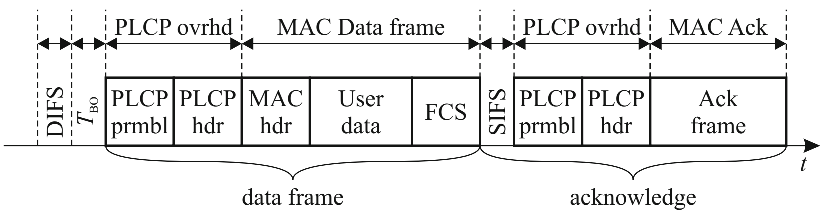

Fig. 1. Basic frame transmission exchange

Bearing in mind frame exchange elements shown on the diagram, transmission cycle duration might be expressed as:

$$T_{\mathrm{p}} = T_{\mathrm{DIFS}} + T_{\mathrm{BO}} + T_{\mathrm{SIFS}} + 2T_{\mathrm{PLCP}} + T_{\mathrm{Data}} + T_{\mathrm{Ack}} \ , \tag{1}$$

where: T_{DIFS} and T_{SIFS} are DIFS (*Distributed Inter-Frame Space*) and SIFS (*Short Inter-Frame Space*) duration, respectively, while T_{PLCP} – duration of PLCP preamble (T_{prmbl}) and header (T_{hdr}). These values are defined in specifications of individual physical layers and collected in table 1. In turn, T_{BO} represents backoff period duration, which, under perfect conditions and according to explanations given in [3], may be simplified to

$$T_{\mathrm{BO}} = \frac{CW_{\min}}{2} T_{\mathrm{slot}} \ . \tag{2}$$

T_{slot} is a slot time [s] (Table 1), while $CW_{\min}$ (*Contention Window*) – minimum number of contention slots for a given physical layer. In turn, bearing in mind MAC frames formats,

$$T_{\mathrm{Data}} = \frac{8(28+L)}{R_{\mathrm{wl}}} \qquad \text{and} \qquad T_{\mathrm{Ack}} = \frac{8 \cdot 14}{R'_{\mathrm{wl}}} \ , \tag{3}$$

where: L – data field capacity (often referred to as payload) in bytes, R_{wl} – Data frame transmission rate [bps], and R'_{wl} – Ack frame transmission rate [bps]. Within a single transmission cycle, exactly L bytes are transmitted. During calculation of frame transmission times, we must take into account any additional overhead resulting from modulations used in a given physical layer, e.g., 32/33 encoding in FHSS (*Frequency Hopping Spread Spectrum*) as well as tail and pad bits in OFDM (*Orthogonal Frequency Division Multiplexing*) and ERP (*Enhanced Rate Physical*).

Table 1. PLCP-dependent parameters of IEEE 802.11 standard

PLCP	$CW_{\min}$	$CW_{\max}$	T_{SIFS}	T_{slot}	T_{prmbl}	T_{hdr}	Additional overhead
DSSS	31	1023	10	20	144	48	—
FHSS	15	1023	28	50	96	32	32/33 encoding
Ir (1 Mbps)	63	1023	10	8	16	41	—
Ir (2 Mbps)	63	1023	10	8	20	25	—
HR-DSSS (sp)	31	1023	10	20	72	24	—
OFDM	15	1023	16	9	20	4	≥ 22 bits
ERP-DSSS (lp)	15 or 31	1023	10	9 or 20	144	48	18 μs
ERP-DSSS (sp)	15 or 31	1023	10	9 or 20	72	24	18 μs
HT	15	1023	16	9	16	4	—
HT-mixed	15	1023	16	9	16	16 to 40	—
HT-GF	15	1023	16	9	16	12 to 36	—

All times given in [μs]; sp – short preamble, lp – long preamble

2.2 Block Acknowledge

Block acknowledge mechanism allows for transmission of series of multiple data frames which are then commonly acknowledged. The acknowledge itself may be immediate or delayed; the first one is assumed to support higher transmission efficiency [1]. Block Acknowledge procedure must be set up prior to transmission and torn down after the transfer is finished. Assuming that the information to be transmitted is sufficiently long, these initial and final frame exchanges do not play an important role from the point of view of protocol efficiency and thus they will not be further considered.

When using Block acknowledge, transmission cycle consists of multiple (but no more than 64) Data frames. The latest of them is followed by the BlockAckReq frame, after which BlockAck frame appears. All frames are separated by SIFS period and preceded by PLCP preamble and header. On the data link layer level, BlockAckReq frame is 24 bytes long. BlockAck is even longer by 128 bytes as it carries fragmentation-specific information for every acknowledged frame. Information exchange process with Block acknowledge is explained on Fig. 2.

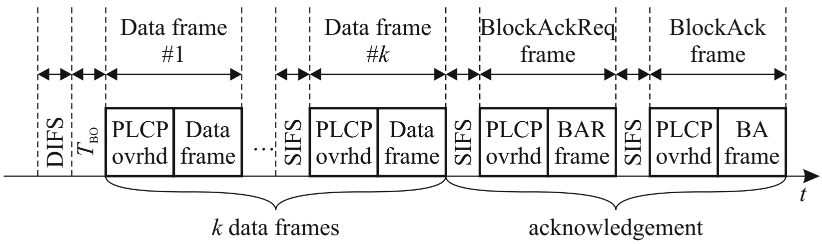

Fig. 2. Frame transmission in Block Acknowledge procedure

Bearing in mind transmission course described above, transmission cycle length may be expressed as:

$$T_{\mathrm{p}} = T_{\mathrm{DIFS}} + T_{\mathrm{BO}} + (k+1)T_{\mathrm{SIFS}} + (k+2)T_{\mathrm{PLCP}} + kT_{\mathrm{Data}} + T_{\mathrm{BAR}} + T_{\mathrm{BA}} \ , \quad (4)$$

where T_{BAR} – transmission time of a BlockAckReq frame, equal to

$$T_{\mathrm{BAR}} = \frac{8 \cdot 24}{R'_{\mathrm{wl}}} \quad (5)$$

and T_{BA} – transmission time of a BlockAck frame, equal to

$$T_{\mathrm{BA}} = \frac{8 \cdot (24+128)}{R'_{\mathrm{wl}}} \ . \quad (6)$$

Assuming constant Data frame length, $L_{\mathrm{D}} = k\mathrm{L}$ data bytes are sent within a single transmission cycle.

2.3 Frame Aggregation

Frame aggregation is introduced to reduce the PLCP overhead. As the PLCP frame format is set, the only way to reduce the overhead is using a single preamble and header for multiple Data frames. It is especially important for high transmission rates, because PLCP overhead is always transmitted at the lowest rate defined for a given physical layer. Thus, we can say that preamble and header transmission time is constant, while that of PSDU (*Physical layer Service Data Unit*) decreases with increasing transmission rate. Therefore, protocol overhead increases, while its efficiency – decreases. In order to avoid it, in IEEE 802.11n standard two aggregation methods are proposed: A-MSDU (*MAC Service Data Unit*) and A-MPDU (*MAC Protocol Data Unit*).

A-MSDU Aggregation. A-MSDU aggregation, similarly to Block acknowledge, allows for transmission of a series of Data frames, which are then commonly acknowledged. However, while Block acknowledge requires that each frame was an individual unit containing PLCP preamble and header, frame aggregation allows precede the entire series with a single preamble and header, which are common for all the Data frames. MAC header is also common for all these frames. Each of them is completed by a short, individual header.

When using A-MSDU aggregation, transmission cycle consists of a series of subframes containing individual headers. They are preceded by PLCP preamble and header and typical MAC header. All this information is protected by a common FCS (*Frame Check Sequence*) and acknowledged with a single Ack frame. Information exchange process with A-MSDU aggregation is explained on Fig. 3.

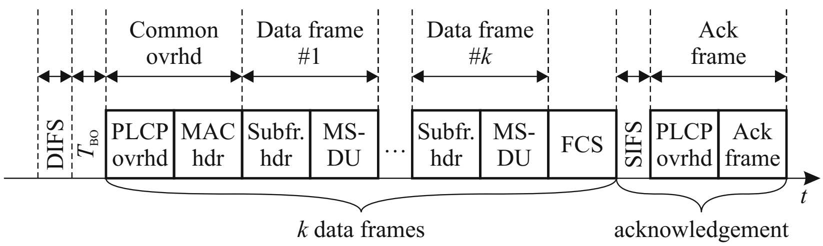

Fig. 3. Frame transmission with A-MSDU frame aggregation

Bearing in mind transmission course described above, transmission cycle length may be expressed as:

$$T_{\mathrm{p}} = T_{\mathrm{DIFS}} + T_{\mathrm{BO}} + T_{\mathrm{SIFS}} + 2T_{\mathrm{PLCP}} + T_{\mathrm{MAC}} + kT_{\mathrm{SubFr}} + T_{\mathrm{Ack}} \ , \qquad (7)$$

where k – data block size, while T_{MAC} and T_{SubFr} – transmission times of MAC header and a subframe with its header, respectively. Bearing in mind their formats,

$$T_{\mathrm{MAC}} = \frac{8 \cdot 28}{R_{\mathrm{wl}}} \qquad (8)$$

and

$$T_{\mathrm{SubFr}} = \frac{8 \cdot 4 \left\lceil \frac{14+L}{4} \right\rceil}{R_{\mathrm{wl}}} \ . \qquad (9)$$

The length of an aggregated frame is limited to 3839 or 7935 bytes, depending on capabilities of communicating stations. This limit may alter the number and length of subframes in two ways.

In the first method, the sender collects MSDU units of a constant size until the remaining buffer space is not sufficient to place a new unit. In this case, the number of aggregated frames equals to

$$k = \left\lfloor \frac{L_{\max}}{4 \left\lceil \frac{14+L}{4} \right\rceil} \right\rfloor \ , \qquad (10)$$

thus, the number of data bytes transmitted within a transmission cycle equals to

$$L_{\mathrm{D}} = kL = L \left\lfloor \frac{L_{\max}}{4 \left\lceil \frac{14+L}{4} \right\rceil} \right\rfloor \quad . \tag{11}$$

In the second method, the sender collects MSDU units, and when the remaining buffer space is not sufficient to place a new unit, a shorter unit is added. Its length is selected so that the limit of an aggregated frame is utilised entirely. This variant is less real because of possible difficulties in its implementation. However, as it allows utilise frame length limit more efficiently, it should support higher efficiency. The number of aggregated MSDU units equals to

$$k = \left\lceil \frac{L_{\max}}{4 \left\lceil \frac{14+L}{4} \right\rceil} \right\rceil \quad , \tag{12}$$

while the number of data bytes transmitted within a transmission cycle equals to $L_{\max}$ decreased by organisation information (subframe headers and stuff bytes). As a result,

$$L_{\mathrm{D}} = L_{\max} - \left\lfloor \frac{L_{\max}}{4 \left\lceil \frac{14+L}{4} \right\rceil} \right\rfloor \left(4 \left\lceil \frac{14+L}{4} \right\rceil - L \right) - 14 \quad . \tag{13}$$

Regardless of A-MSDU data field capacity, the total length of the aggregated frame equals always to $L_{\max}$.

A-MPDU Aggregation. When using A-MPDU Aggregation, transmission cycle consists of a series of Data frames, preceded with only a single PCLP preamble and header. The Data frames are transmitted immediately one after another, without even a SIFS gap. The cycle ends with a slightly modified block acknowledge. In A-MPDU aggregation, BlockAckReq frame is not used because aggregation forces the use of block acknowledge. Besides, A-MPDU aggregation does not allow fragmentation, thus, BlockAck frame is substantially shorter than that of Block Acknowledge mechanism. The number of aggregated frames may not exceed 64, and the total length of an aggregated frame may not exceed 65535 bytes. Information exchange process with A-MPDU aggregation is explained on Fig. 4.

Bearing in mind transmission course described above, transmission cycle length may be expressed as:

$$T_{\mathrm{p}} = T_{\mathrm{DIFS}} + T_{\mathrm{BO}} + T_{\mathrm{SIFS}} + 2T_{\mathrm{PLCP}} + kT'_{\mathrm{Data}} + T'_{\mathrm{BA}} \quad , \tag{14}$$

where k – data block size, T'_{Data} represents Data frame transmission time with aggregation overhead:

$$T'_{\mathrm{Data}} = \frac{8\left(4 + 28 + 4\left\lceil \frac{L}{4} \right\rceil\right)}{R'_{\mathrm{wl}}} \tag{15}$$

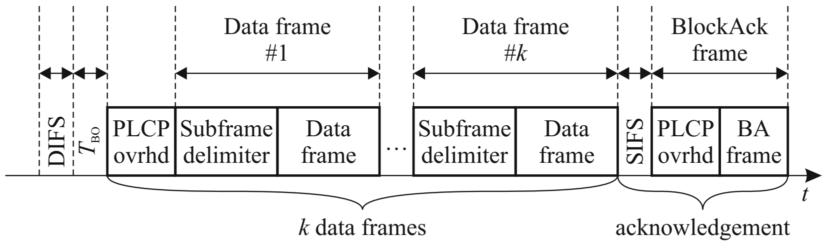

Fig. 4. Frame transmission with A-MPDU frame aggregation

T'_{BA} represents transmission time of a modified BlockAck frame, equal to

$$T'_{\text{BA}} = \frac{8(24+8)}{R'_{\text{wl}}} \ . \tag{16}$$

3 Throughput Upper Limit

It has been proved [2], that throughput upper limit (TUL) exists for 802.11 networks with basic frame exchange. TUL is calculated, assuming perfect operating conditions (no collisions or transmission errors) and infinite transmission rate. In this case, transmission time of all data link layer frames (such as Data, Ack and others) is zero. Thus, during calculation of transmission cycle duration, only PLCP overhead counts, namely, T_{SIFS}, T_{DIFS}, T_{prmbl} and T_{hdr}. Transmission cycle duration does not therefore depend on Data frame length, or – to be more precise – on data field capacity. However, TUL does depend on it, because it influences on number of data bytes transmitted within a cycle.

Calculated TUL values for OFDM physical layer (compatible with IEEE 802.11a and 802.11g standards) are collected in Table 2. Calculations were performed for payload of 2304, 1500, 256 and 48 bytes. The following data exchange methods were considered:

– basic (DCF),
– block acknowledge with block length set to $k = 64$ frames,
– A-MSDU aggregation with aggregated frame length limit set to $L_{\text{max}} =$ 3839 bytes (4k),
– A-MSDU aggregation with aggregated frame length limit set to $L_{\text{max}} =$ 7935 bytes (8k),
– A-MPDU aggregation with aggregated frame length limit set to 65535 bytes and block size limited to $k = 64$ frames.

As shown in Table 2, basic data exchange method in 802.11 standard limits TUL to about 118 Mbps, but only when longest possible frames are used. Decrease of frame length to 1500 bytes causes TUL fall down to about 75 Mbps. It can be easily seen that this method does not ensure effective use of HT (*High Throughput*) physical layer capabilities. Even OFDM physical layer, in some cases, cannot be effectively utilised.

When block acknowledge is used, TUL is almost 4 times as high as for basic method. Using longest frames, we can get TUL of 434 Mbps, while with 1500-bytes frames – about 283 Mpbs. We can therefore assume that block acknowledge allows effectively utilise OFDM layer capabilities, however, for HT layer it is not sufficient.

Table 2. Throughput upper limit for OFDM physical layer [Mbps]

Payload [B]	Basic (DCF)	BlockAck	A-MSDU (4k)	A-MSDU (8k)	A-MPDU
2304	117.78	434.25	111.37	184.12	3119.12
1500	76.68	282.72	145.02	183.35	3093.61
256	13.09	48.25	173.24	174.07	791.98
48	2.45	9.05	136.89	139.26	148.50

Unlike expected, A-MSDU aggregation for the longest frames not only does not bring advantages, but it can even make network achievements worse – when $L_{\max} = 3839$ bytes, TUL is even lower than for basic method. It is caused by larger overhead resulting from aggregation, but, despite aggregation, only a single maximum-size frame (2304 bytes) can be sent. However, for shorter frames, e.g., 1500-bytes long, TUL is twice as high as for besic method. When $L_{\max}$ increases to 7935 bytes, network performance is much better, but still below the capabilities of block acknowledge. Performance does not practically depend on payload size.

A-MSDU aggregation, however, shows high efficiency for shorter frames – TUL is about 135 to 140 Mbps for 48-bytes frames and 173 to 174 Mbps for 256-bytes ones. Similar results for both basic method and block acknowledge are much below these numbers. Thus, we can say that A-MSDU aggregation allows increase network efficiency while transmitting short frames. Nevertheless, it does not ensure effective usage of HT physical layer capabilities, despite they correspond to each other as both are defined in 802.11n standard.

A-MPDU aggregation shows the best performance of all considered transmission methods – TUL for 256-bytes frames exceeds 700 Mbps, while for the longest ones reaches over 3 Gbps. Even for the shortest frames this method is most effective. We can therefore say that A-MPDU aggregation allows effectively utilise transmission rates defined for HT physical layer. It could possibly allow effectively utilise future solutions with even higher transmission rates.

Calculated TUL values for HT physical layer (compatible with IEEE 802.11n standard) are collected in Table 3. The results are slightly worse than those for OFDM, because physical layer preamble and header are longer than in OFDM. It increases protocol overhead and decreases its efficiency.

Table 3. Throughput upper limit for HT physical layer [Mbps]

Payload [B]	Basic (DCF)	BlockAck	A-MSDU (4k)	A-MSDU (8k)	A-MPDU
2304	106.85	363.58	101.55	167.89	2844.16
1500	69.57	236.71	132.23	167.18	2820.89
256	11.87	40.40	157.97	158.72	722.16
48	2.23	7.57	124.83	126.99	135.40

4 Summary and Conclusions

Presented results show that the modifications of data link layer in IEEE 802.11 standard was necessary. In fact, without presented enhancements, the effective throughput would still be limited to relatively low value that would make physical layer utilisation ineffective, and its deployment – useless.

It must be noticed however that the calculations are done for perfect conditions that are far from the real network operating conditions. Nevertheless, such conditions are not impossible, e.g., in a small home network. It would be interesting how the frame exchange procedures that have been analysed in the paper behave in a real network. Such results can be achieved using computer simulations, but still more accurate results could be obtained in an experimental network. However, the results may depend on network hardware and software used for tests. For example, today's access points and network adapter compatible with 802.11n draft standard typically do not allow reach transmission rates higher than 300 Mbps, which is only a half of what is defined in the standard.

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