Throughput and Delay Limits of IEEE 802.11

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***Abstract*—The IEEE 802.11 protocol family provides up to 54-Mbps data rate, whereas the industry is seeking higher data rates. This paper shows that a theoretical throughput upper limit and a theoretical delay lower limit exist for the IEEE 802.11 protocols. The existence of such limits indicates that by simply increasing the data rate without reducing overhead, the enhanced performance, in terms of throughput and delay, is bounded even when the data rate goes into infinitely high. Reducing overhead is vital for good performance.**

***Index Terms*—IEEE 802.11 protocol, multiple access control, performance evaluation.**

NOTATIONS

Notations are defined as follows and will be used throughout this paper.

T_{slot}	A slot time.
T_{SIFS}	SIFS time.
T_{DIFS}	DIFS time.
$\mathrm{CW}_{\min}$	Minimum backoff window size.
T_P	Transmission time of the physical preamble.
T_{PHY}	Transmission time of the PHY header.
L_{H_DATA}	MAC overhead in bytes, i.e., 28 bytes.
L_{ACK}	ACK size in bytes, i.e., 14 bytes.
T_{H_DATA}	Transmission time of MAC overhead.
T_{ACK}	ACK transmission time.
L_{DATA}	Payload size in bytes.
T_{DATA}	Transmission time for the payload.
T_{SYM}	Transmission time for a symbol.
τ	Propagation delay.
R_{DATA}	Data rate.
R_{ACK}	Control rate.

I. INTRODUCTION

Wireless LANs have quickly become a significant niche as the cost decreases and the data rate becomes higher. The IEEE 802.11, 802.11b and 802.11a specifications provide up to 2, 11, and 54 Mbps data rates[1]–[3], respectively, whereas the industry is seeking data rates over 100 Mbps [4]–[9]. However, the medium access control (MAC) that they are based upon is the same. The overhead in the MAC magnifies itself when the data rate becomes higher. This paper shows that a throughput upper limit and a delay lower limit exist. Therefore, pursuing only higher data rates without reducing overhead cannot significantly improve performance.

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IEEE 802.11 employs a carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol with binary exponential backoff, called Distributed Coordination Function (DCF) and an optional Point Coordination Function [1]. DCF defines a basic access mechanism and an optional Request-To-Send/Clear-To-Send (RTS/CTS) mechanism. We only consider the basic access mechanism in this paper. Our method can be easily applied to the RTS/CTS mechanism.

A station with a packet to transmit monitors the channel activities until an idle period equal to a distributed inter-frame space (DIFS) is detected. After sensing an idle DIFS, the station waits for a random backoff interval before transmitting. The backoff time counter is decremented in terms of slot time as long as the channel is sensed idle. The counter is stopped when a transmission is detected on the channel and reactivated when the channel is sensed idle again for more than a DIFS. The station transmits its packet when the backoff time reaches zero. At each transmission, the backoff time is uniformly chosen in the range$(0, \mathrm{CW} - 1)$, where CW is the current backoff window size. At the very first transmission attempt, CW equals the minimum backoff window size. After each unsuccessful transmission, CW is doubled until a maximum backoff window size value is reached. After the destination station successfully receives the packet, it transmits an acknowledgment packet (ACK) following a short inter-frame space (SIFS) time. If the transmitting station does not receive the ACK within a specified ACK Timeout, or it detects the transmission of a different packet on the channel, it reschedules the packet transmission according to the previous backoff rules. Readers can refer to the IEEE 802.11 standard [1] for details.

Data frames are transmitted by the data rate and ACK frames are transmitted by the control rate. They may not be the same. A data frame has 28 bytes as overhead including the MAC header and the FCS field and an ACK frame is 14 bytes in length [1]. The physical overhead of IEEE 802.11a is illustrated in Fig. 1 [3]. Data rates of IEEE 802.11a are 6, 9, 12, 18, 24, 35, 48, and 54 Mbps and the corresponding N_{DBPS} (the number of data bits per OFDM symbol) are 24, 36, 48, 72, 96, 144, 192, and 216. Data rates of IEEE 802.11b are 1, 2, 5.5, and 11 Mbps.

II. THROUGHPUT AND DELAY LIMITS

To derive the throughput upper limit (TUL) and the delay lower limit (DLL), we first need to derive two performance metrics: the achievable maximum throughput (MT) and the achievable minimum delay (MD). To derive the MT and the MD, the system must be at the best-case scenario: 1) the channel is an ideal channel without errors and 2) at any transmission cycle, there is one and only one active station which always has a packet to send and other stations can only accept packets and

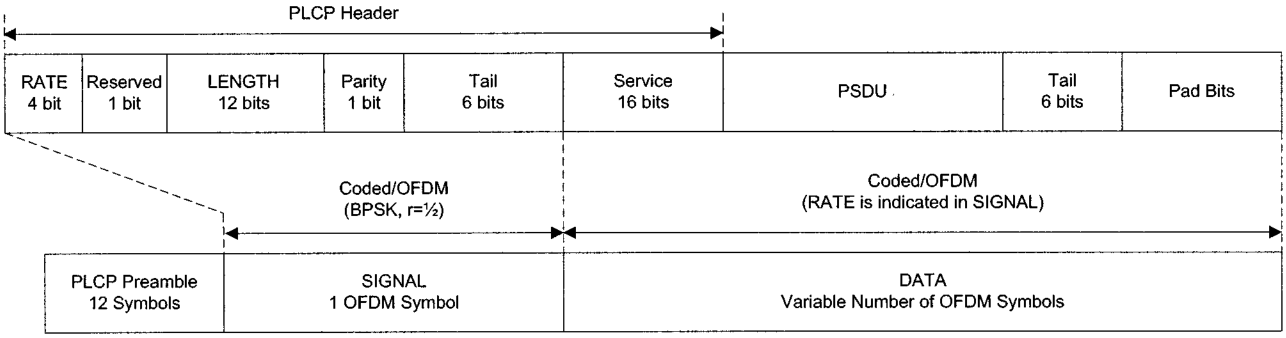

Fig. 1. PPDU frame format of IEEE 802.11a.

provide acknowledgments. Note that in a noisy channel, the throughput is expected to be less than the MT and the delay is expected to be larger than the MD.

A transmission cycle of DCF consists of DIFS deferral, backoff, data transmission, SIFS deferral and ACK transmission. The average backoff time $\overline{\mathrm{CW}}$ is given by

$$\overline{\mathrm{CW}} = \frac{\mathrm{CW}_{\min} T_{\mathrm{slot}}}{2}. \tag{1}$$

The data transmission delay T_{D_DATA}, the ACK transmission delay T_{D_ACK} and the MT are expressed as follows:

$$T_{D\_\mathrm{DATA}} = T_P + T_{\mathrm{PHY}} + T_{H\_\mathrm{DATA}} + T_{\mathrm{DATA}} \tag{2}$$

$$T_{D\_\mathrm{ACK}} = T_P + T_{\mathrm{PHY}} + T_{\mathrm{ACK}} \tag{3}$$

$$\mathrm{MT} = \frac{8L_{\mathrm{DATA}}}{T_{D\_\mathrm{DATA}} + T_{D\_\mathrm{ACK}} + 2\tau + T_{\mathrm{DIFS}} + T_{\mathrm{SIFS}} + \overline{\mathrm{CW}}}. \tag{4}$$

T_{DATA} is the only useful transmission time in the equations above. Packet delay is defined as the time elapsed between the transmission of a packet and its successful reception. The MD is given by:

$$\mathrm{MD} = T_{D\_\mathrm{DATA}} + \tau + T_{\mathrm{DIFS}} + \overline{\mathrm{CW}}. \tag{5}$$

For IEEE 802.11b, the transmission time equals to the ratio of the packet size and the transmission rate:

$$T_{D\_\mathrm{DATA}} = T_P + T_{PHY} + \frac{8L_{H\_\mathrm{DATA}} + 8L_{\mathrm{DATA}}}{100\,000 R_{\mathrm{DATA}}} \tag{6}$$

$$T_{D\_\mathrm{ACK}} = T_P + T_{\mathrm{PHY}} + \frac{8L_{\mathrm{ACK}}}{100\,000 R_{\mathrm{ACK}}}. \tag{7}$$

For IEEE 802.11a, a function Ceiling is used to handle the pad bits illustrated in Fig. 1:

$$T_{D\_\mathrm{DATA}} = T_P + T_{\mathrm{PHY}} + T_{\mathrm{SYM}} {}^{*}\mathrm{Ceiling}\left(\frac{16 + 6 + 8L_{H\_DATA} + 8L_{\mathrm{DATA}}}{N_{\mathrm{DBPS}}}\right) \tag{8}$$

$$T_{D\_ACK} = T_P + T_{PHY} + T_{SYM} {}^{*}\mathrm{Ceiling}\left(\frac{16 + 6 + 8L_{\mathrm{ACK}}}{N_{\mathrm{DBPS}}}\right). \tag{9}$$

It is easy to see that the throughput (delay) is an increasing (decreasing) function of the data rate. From (1) to (9), letting the data rate go into infinite, we have the following Limit Theorem, which holds even when the overhead is reduced.

TABLE I
PARAMETERS OF IEEE 802.11A AND 802.11B

Parameter	802.11a	802.11b	Parameter	802.11a	802.11b
T_{slot}	$9\mu s$	$20\mu s$	T_{SIFS}	$16\mu s$	$10\mu s$
τ	$1\mu s$	$1\mu s$	$CW_{\min}$	15	31
T_P	$16\mu s$	$144\mu s$	T_{PHY}	$4\mu s$	$48\mu s$
T_{DIFS}	$34\mu s$	$50\mu s$	T_{SYM}	$4\mu s$	N/A

Limit Theorem: For the basic access mechanism, the TUL and the DLL exist, independent of the data rate (even when the data rate goes to infinite high), fixed for a given payload size and a given set of overhead parameters and given as follows:

$$\mathrm{TUL} = \frac{8L_{\mathrm{DATA}}}{2T_P + 2T_{\mathrm{PHY}} + 2\tau + T_{\mathrm{DIFS}} + T_{\mathrm{SIFS}} + \frac{\mathrm{CW}_{\min} T_{\mathrm{slot}}}{2}} \tag{10}$$

$$\mathrm{DLL} = T_P + T_{\mathrm{PHY}} + \tau + T_{\mathrm{DIFS}} + \frac{\mathrm{CW}_{\min} T_{\mathrm{slot}}}{2}. \tag{11}$$

Some of the parameters are defined in Table I. In simulation and numerical results, for demonstration purposes, we let all the nodes be homogenous so that they all have the same (data rate, control rate) pairs. For 802.11a, all nodes have one pair among (6,6), (9,6), (12,12), (18,12), (24,24), (36,24), (48,24), and (54,24). For 802.11b, all nodes have one pair among (1,1), (2,2), (5.5,2), and (11,2).

Fig. 2 shows that the TUL upper bounds all the MTs for IEEE 802.11a. When the payload size is 1000 bytes, the MT for 54 Mbps is 24.7 Mbps and the TUL is 50.2 Mbps. The MT for 54 000 Mbps with the same set of overhead parameters almost reaches the TUL. Fig. 3 shows that the DLL lower bounds all the MDs for IEEE 802.11a. The DLL is the same for all payload sizes, i.e., 122.5 μs. When the payload size is 1000 bytes, the MD for 54 Mbps is 278.5 μs. The MD for 54 000 Mbps with the same set of overhead parameters almost reaches the DLL.

Fig. 4 shows that the TUL upper bounds all the MTs for IEEE 802.11b. When the payload size is 1000 bytes, the TUL is 11.49 Mbps. The MT for 11 000 Mbps with the same set of overhead parameters almost reaches the TUL. Fig. 5 shows that the DLL lower bounds all the MDs for IEEE 802.11b. The DLL is the same for all payload sizes, i.e., 523 μs. The MD for 11 000 Mbps with the same set of overhead parameters almost reaches the DLL.

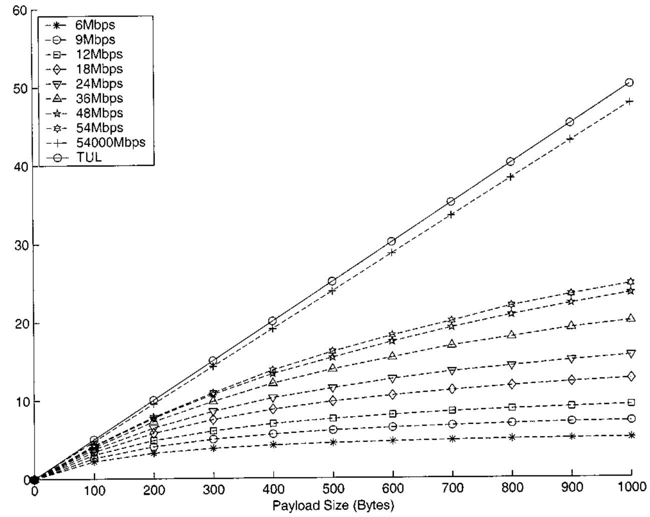

Fig. 2. Maximum throughputs and TUL (Mbps) of 802.11a.

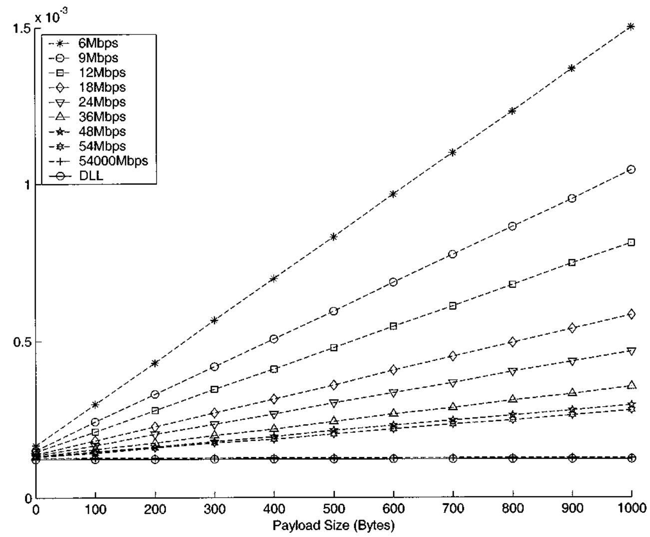

Fig. 3. Minimum delays and DLL (seconds) of 802.11a.

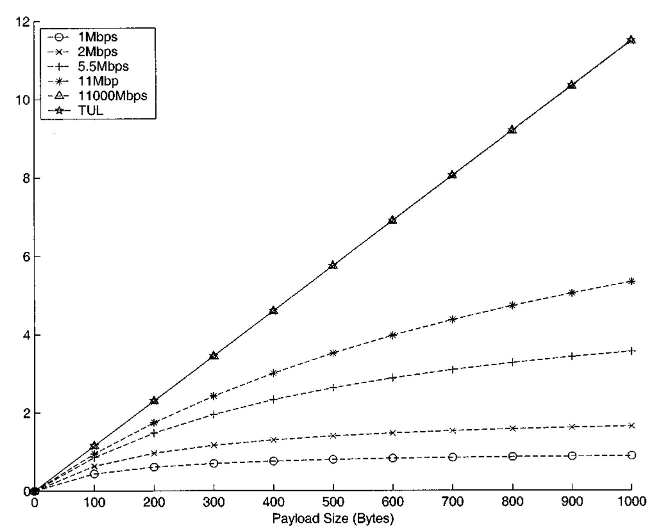

Fig. 4. Maximum throughputs and TUL (Mbps) of 802.11b.

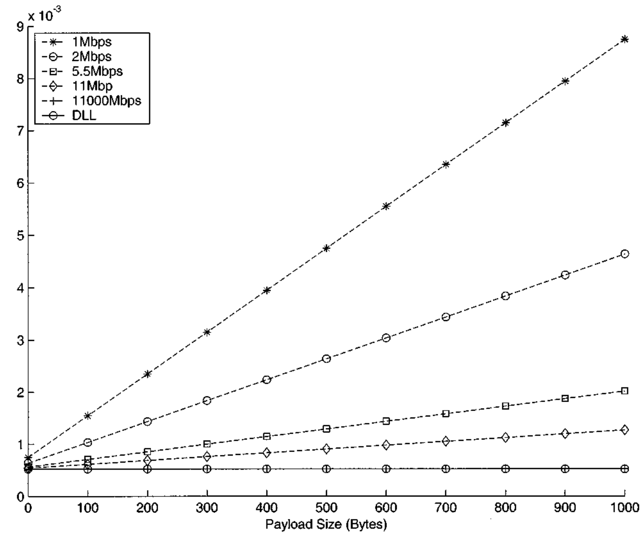

Fig. 5. Minimum delays and DLL (seconds) of 802.11b.

We also conduct simulations for both IEEE 802.11a and 802.11b to validate our model and our studies show that simulation results exactly match numerical results.

III. Conclusions

In this letter, we proved that the TUL and the DLL exist. The existence of the TUL and DLL shows that by simply increasing the data rate without reducing overhead, the enhanced throughput is bounded even when the data rate goes to infinite high. In other words, reducing overhead is necessary for IEEE 802.11 standards to achieve higher throughput.

Acknowledgment

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