IEEE P802.11
Wireless LANs

Theoretical Throughput Limits

TGT Draft Appendix A

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Abstract

Appendix A provides a methodology for calculating Theoretical Throughput Limits (TTL) for IEEE 802.11a/b/g networks. A Four-Step Methodology is based on sequential steps to calculate TxTime, Frame Start-to-Frame Start interval, Frame Rate and Theoretical Throughput Limit measured in megabits per second. Equations and timing parameters are provided for all IEEE 802.11 modulation types.

The TTL calculation methodology is useful in predicting throughput performance of IEEE 802.11 networks

This contribution is intended to be inserted as Annex A into IEEE P802.11.2, TGT Draft 0.90, Recommended Practice for the Evaluation of 802.11 Wireless Performance.

Equations and timing parameters throughout this document are considered to be accurate, but may vary from one implementation to another. Actual test results may also be influenced by proprietary implementations of the IEEE 802.11 Standard.

1.0 Introduction

Annex A provides a methodology for calculating Theoretical Throughput Limits (TTL) for IEEE 802.11a/b/g networks. The IEEE 802.11 standard defines data rates in terms of signaling rate at the Physical Layer Convergence Procedure (PLCP) Layer, in the form of PLCP Protocol Data Units (PPDUs). The PPDU data is modulated and transmitted over the RF link at this rate, generally known as "PHY data rate". In practice, MSDU data throughput will be significantly lower than the PHY data rate.

The basic Theoretical Throughput Limit (TTL) calculation takes into account the overhead associated with frame preambles, PLCP header, RF modulation type, interframe spacing, packet acknowledgement delay, and number of backoff slots, resulting in a theoretical limit on MSDU throughput. IFS and related frame timing is defined by DCF mechanisms.
This upper boundary is useful in predicting performance of 802.11a/b/g networks.

For simplification, basic TTL is calculated over a single unidirectional data path by assuming constant-size data frames transmitted with minimum frame spacing, without collisions, without retries, without RTS/CTS controls, without fragmentation, without EDCA services, and without management frame overhead. These forms of overhead may be factored into the basic TTL calculation as needed. Upper layer protocol processing and application overhead is not considered in TTL calculations. Note that TTL calculations may be influenced by special algorithms used in proprietary 802.11a/b/g devices.

Clause references are made to IEEE P802.11-REVma/D7.0, dated June, 2006.

2.0 TTL Calculation Methodology

2.1 Four-Step Methodology

The TTL calculation methodology is based on four sequential steps:

1) Calculate **TxTime,** the time in microseconds to transmit one data frame, including frame preamble, frame header, and RF modulation parameter fields.

2) Calculate **Frame Start-to-Frame Start Interval,** the time in microseconds to transmit one data frame, with acknowledgement, including SIF, DIF and backoff time. For backoff time, the average backoff in the best case is used where the medium is available at first attempt and the number of backoff slots is selected from [1 to CWmin].

3) Calculate **Frame Rate,** the number of frames per second that can be transmitted across the air interface.

4) Derive **Theoretical Throughput Limit** in megabits per second. This value represents an upper boundary on 802.11 network performance at the MSDU level.

An example of the Four-Step Methodology calculation is provided for 802.11a OFDM in Section 4.4, deriving the Theoretical Throughput Limit in megabits per second.

2.2 PHY Modes and Modulation Types

TTL calculations are derived from equations and parameters based on 802.11 modulation types, protocol timing and frame preambles, organized by clauses in the 802.11 Standard:

Clause 14 FHSS
Clause 15 DSSS
Clause 16 IR
Clause 17 OFDM, including an example of TTL calculation for 802.11a
Clause 18 HR/DSSS
Clause 19.1 ERP-OFDM
Clause 19.5 ERP-OFDM
Clause 19.6 ERP-PBCC
Clause 19.7 DSSS-OFDM

3.0 Terminology for TTL Calculations

Ceiling…….round up to nearest multiple of significance
CkSwTime...Clock Switch Time for PBCC
CWmin……best-case (theoretical) Contention Window time measured in Slots
DIFS………Distributed Inter-frame Space
Floor………round down to nearest multiple of significance
FS…………Frame Start
Length…….number of octets in data payload
Ndbps……..number of data bits per symbol (function of PHY rate)
PLCPtime…time to transmit PLCP header
PHYrate…...data transfer rate in bits per second at PLCP Layer
Slot time…..backoff timing interval
SIFS……....Short Inter-Frame Space
SigEx……...Signal Extension
Tack……....time to transmit Acknowledgement (ACK) Frame of 14-bytes
Tpream……time to transmit preamble
TxTime…....time to transmit one data frame
Tsignal…....time to transmit Signal Field
Tsym……....time to transmit Service Field (defines symbol clock and code)

4.0 TTL Equations and Timing Parameters

4.1 FHSS Clause 14
Step 1) TxTime Calculation (usec)
TxTime = Tpream + PLCPtime + Ceiling ((Length * 8) / PHYrate)
Tpream = 96 usec PLCPtime = 32 usec
Backoff Slot = 50 usec CWmin = 15
SIFS = 28 usec PHYrate = 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5
Tack @ 1 Mbps = 208 usec

Step 2) Frame Start-to-Frame Start Interval (usec)
FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff
DIFS = SIFS + 2 Slots = 28 + (2 * 28) = 84 usec
Best-case Backoff = CWmin / 2 = 15 / 2 = 7.5

Step 3) Frame Rate Calculation (frames per second)
FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)
TTL = Frame Rate * Length * 8 / 1000000

4.2 DSSS Clause 15
Step 1) TxTime Calculation (usec)
TxTime = Tpream + PLCPtime + Ceiling ((Length * 8) / PHYrate)
Tpream = 144 usec PLCPtime = 48 usec
Backoff Slot = 20 usec CWmin = 31
SIFS = 10 usec PHYrate = 1, 2 Mbps
Tack @ 2 Mbps = 152 usec

Step 2) Frame Start-to-Frame Start Interval (usec)
FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff
DIFS = SIFS + 2 Slots = 10 + (2 * 20) = 50 usec
Best-case Backoff = CWmin / 2 = 31 / 2 = 15.5

Step 3) Frame Rate Calculation (frames per second)
FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)
TTL = Frame Rate * Length * 8 / 1000000

4.3 IR Clause 16

Step 1) TxTime Calculation (usec)

1 Mbps TxTime = Tpream + PLCPtime + Ceiling ((4 + (Length * 8) / PHYrate)

2 Mbps TxTime = Tpream + PLCPtime + Ceiling ((2 + (Length * 8) / PHYrate)

For 1 Mbps: Tpream = 16 usec PLCPtime = 41 usec Tack = 208 usec

For 2 Mbps: Tpream = 20 usec PLCPtime = 25 usec Tack = 152 usec

CWmin = 63 SIFS = 10 usec PHYrate = 1, 2 Mbps

Backoff Slot = 8 usec

Step 2) Frame Start-to-Frame Start Interval (usec)

FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff

DIFS = SIFS + 2 Slots = 10 + (2 * 8) = 26 usec

Best-case Backoff = CWmin / 2 = 63 / 2 = 31.5

Step 3) Frame Rate Calculation (usec)

FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)

TTL = Frame Rate * Length * 8 / 1000000

4.4 OFDM 802.11a Clause 17

Step 1) TxTime Calculation (usec)

TxTime = Tpream + Tsignal + Tsym * Ceiling ((Pad + (Length * 8) + Tail) / Ndbps)

Tpream = 16 usec Tsig = 4 usec Tsym = 4 usec

SIFS = 16 usec Backoff Slot = 9 usec CWmin = 15

Tack @ 24 Mbps = 28 usec Pad = 16 Tail = 6

PHY Rate (Mbps) =	6	9	12	18	24	36	48	54
Ndbps =	24	36	48	72	96	144	192	216

Step 2) Frame Start-to-Frame Start Interval Calculation (usec)

FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff

DIFS = SIFS + 2 Slots = 16 + (2 * 9) = 34

Best-case Backoff = CWmin / 2 = 15 /2 = 7.5

Step 3) Frame Rate Calculation (frames per second)
FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)
TTL = Frame Rate * Length * 8 / 1000000

With default parameters of the BSS basic rate set, the duration and PHY rate at which ACKs are transmitted is listed in Table 1.

Table 1 ACK PHY Rate and Duration

MPDU PHY Rate	ACK PHY Rate	ACK Duration
54	24	28
48	24	28
36	24	28
24	24	28
18	12	32
12	12	32
9	6	44
6	6	44

Example TTL Calculation for Clause 17, 802.11a OFDM

PHYrate = 54 Mbps
Length = 1024 bytes (This is an arbitrary value chosen for this example and may range from 0 to 2304 octets without encryption.)

Step 1) TxTime as a function of PHY Rate and Length
TxTime = 16 + 4 + 4 * Ceiling ((16 + (8 * 1024 + 6) / 216) = 176 usec

Step 2) Frame Start to Frame Start Interval
FS-to-FS Interval = 176 + 16 + 28 + 34 + (7 * 9) = 321.5 usec

Step 3) Frame Rate
FR = Floor (1000000 / 321.5 = 3110.4 frames per second

Step 4) Theoretical Throughput Limit
TTL = 3110.4 * (1024 * 8) / 1000000 = 25.48 Mbps

4.5 HR/DSSS Clause 18

Step 1) TxTime Calculation (usec)
TxTime = Tpream + PLCPtime + Ceiling(((Length + PBCC) * 8) / PHYrate)
PBCC Indicator = 1 for PBCC, 0 for CCK
PBCC Mode @ 33 Mbps, add 1 usec for Clock Switch Time

Long Preamble = 144 usec	Long PLCP Header = 48 usec
Short Preamble = 72 usec	Short PLCP Header = 24 usec
Backoff Slot = 20 usec	CWmin = 31 SIFS = 10 usec
DSSS PHYrate = 2, 5.5, 11	PBCC PHYrate = 5.5, 11, 22, 33
Tack @ 2 Mbps = 152 usec	

Step 2) Frame Start-to-Frame Start Interval (usec)
FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff
DIFS = SIFS + 2 Slots = 10 + (2 * 20) = 50 usec
Best-case Backoff = CWmin / 2 = 31 / 2 = 15.5

Step 3) Frame Rate Calculation (usec)
FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)
TTL = Frame Rate * Length * 8 / 1000000

4.6 ERP-DSSS/CCK Clause 19.1

Requires Short Preamble and Short PLCP Header

Step 1) TxTime Calculation (usec)

TxTime = Tpream + PLCPtime + Ceiling ((Length * 8) / PHYrate)

Tpream = 72 usec	PLCPtime = 24 usec	Backoff Slot = 20 usec
PHYrate = 2, 5.5, 11 Mbps	Tack @ 5.5 Mbps = 116 usec	CWmin = 31
SIFS = 10 usec		

Step 2) Frame Start-to-Frame Start Interval (usec)

FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff

DIFS = SIFS + 2 Backoff Slots

Best-case Backoff = CWmin / 2 = 31 / 2 = 15.5

Step 3) Frame Rate Calculation (usec)

FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)

TTL = Frame Rate * Length * 8 / 1000000

4.7 ERP-OFDM Clause 19.5

Step 1) TxTime Calculation (usec)

TxTime = Tpream + Tsignal + Tsym * Ceiling ((16 + (8 * Length) + 6) / Ndbps) + SigEx

Tpre = 16 usec	Tsignal = 4 usec	Tsym = 4 usec
SIFS = 10 usec	Backoff Slot = 9 usec	CWmin = 15
Tack @ 24 Mbps = 28 usec	SigEx = 6 usec	

PHY Rate (Mbps) =	6	9	12	18	24	36	48	54
Ndbps =	24	36	48	72	96	144	192	216

Step 2) Frame Start-to-Frame Start Interval (usec)

TxTime + SIFS + Tack + DIFS + Backoff

DIFS = SIFS + 2 Backoff Slots = 10 + (2 * 9) = 28 usec

Backoff = CWmin / 2 = 7.5

Step 3) Frame Rate Calculation (frames per second)
FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)
TTL = Frame Rate * Length * 8 / 1000000

4.8 ERP-PBCC Clause 19.6

Step 1) TxTime Calculation (usec)
For PBCC 5.5 and 11 Mbps:
TxTime = Tpream + PLCPtime + Ceiling(((Length + PBCC) * 8) / PHYrate)

For ERP-PBCC 33 Mbps:
TxTime = Tpream + PLCPtime + Ceiling(((Length + PBCC) * 8) / PHYrate) + CkSwTime

Long Preamble = 144 usec	Long PLCP Header = 48 usec	
Short Preamble = 72 usec	Short PLCP Header = 24 usec	
PBCC: CCK = 0, PBCC =1	CkSwTime = 1 usec	Backoff Slot = 20 usec
SIFS = 10 usec	CWmin = 31	
Tack @ 2 Mbps = 152 usec		

Step 2) Frame Start-to-Frame Start Interval (usec)
FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff
DIFS = SIFS + 2 Backoff Slots
Best-case Backoff = CWmin / 2 = 31 / 2 = 15.5

Step 3) Frame Rate Calculation (usec)
FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)
TTL = Frame Rate * Length * 8 / 1000000

4.9 DSSS-OFDM Clause 19.7

Step 1) TxTime Calculation (usec)

TxTime = TpreamDSSS + PLCPtimeDSSS + TpreamOFDM + Tsignal + 4 * Ceiling ((+ 8 * (Length) + Pad) / Ndbps) + SigEx

Long Preamble = 144 usec	Long PLCP Header = 48 usec
Short Preamble = 72 usec	Short PLCP Header = 24 usec

Tpream = 144 usec	PLCPtime = 48 usec	TpreamOFDM = 8 usec
Tsignal = 4 usec	SIFS = 10 usec	Backoff Slot = 9 usec
Tack @ 24 Mbps = 28 usec	SigEx = 6 usec	CWmin = 31

PHY Rate (Mbps) =	6	9	12	18	24	36	48	54
Ndbps =	24	36	48	72	96	144	192	216

Step 2) Frame Start-to-Frame Start Interval Calculation (usec)

FS-to-FS Interval = TxTime + SIFS + Tack + DIFS + Backoff

DIFS = SIFS + 2 Backoff Slots = 10 + (2 * 9) = 28 usec

Best-case Backoff = CWmin / 2 = 31 / 2 = 15.5

Step 3) Frame Rate Calculation (frames per second)

FR = 1000000 / FS-to-FS Interval

Step 4) Theoretical Throughput Limit Derivation (Mbps)

TTL = Frame Rate * Length * 8 / 1000000

5.0 Frame Sequences

The frame sequences used for data transfer have a large impact on the maximum frame rate. To compute an accurate estimate of the maximum frame rate, identification of the proper frame sequence is required. In general, DCF is the access method most commonly used.

5.1 Distributed Coordination Function (DCF)

In the notation of Clause 9.7, variants of DCF are described as follows:

{{RTS – CTS –} | CTS –} [Frag – ACK –] Last – ACK

A DCF transaction begins with an optional RTS – CTS exchange or a single CTS-to-self, followed by one or more "fragment – ACK" pairs conveying fragments of an MSDU, followed by a final fragment and ACK ("last – ACK"). The em-dash "–" denotes a SIFS between the frames. For the purposes of this section, fragmentation will not be considered, as it does not yield the maximum MSDU rate. Given this, the notation will be changed to refer to an "MSDU" rather than a "last" fragment. This yields the following frame sequence combinations:

MSDU – ACK

CTS – MSDU – ACK

RTS – CTS – MSDU – ACK

Following the completion of each of these frame sequences, there is a DIFS period, followed by a random number of backoff slots, determined by the current contention window. This constitutes a complete DCF transmission.