# IEEE P802.11 Wireless LANs

Theoretical Throughput Limits							
TGT Draft Appendix A							
Date: 2006-07-20							
Author(s):							
Name	Company	Address	Phone	email			
Larry Green	Ixia	402 E. Gutierrez Street Santa Barbara, CA 93101	+1 818 444 2901	lgreen@ixiacom.com			
Ken Balmy	Ixia	402 E. Gutierrez Street Santa Barbara, CA 03101	+1 818 444 2904	kbalmy@ixiacom.com			
Marc Emmelmann	Technical University Berlin	Einsteinufer 25 10587 Berlin, Germany	+49 30 314 24580	emmelmann@ieee.org			

# 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

**Notice:** This document has been prepared to assist IEEE 802.11. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.

**Release:** The contributor grants a free, irrevocable license to the IEEE to incorporate material contained in this contribution, and any modifications thereof, in the creation of an IEEE Standards publication; to copyright in the IEEE's name any IEEE Standards publication even though it may include portions of this contribution; and at the IEEE's sole discretion to permit others to reproduce in whole or in part the resulting IEEE Standards publication. The contributor also acknowledges and accepts that this contribution may be made public by IEEE 802.11.

**Patent Policy and Procedures:** The contributor is familiar with the IEEE 802 Patent Policy and Procedures <<u>http://ieee802.org/guides/bylaws/sb-bylaws.pdf</u>>, including the statement "IEEE standards may include the known use of patent(s), including patent applications, provided the IEEE receives assurance from the patent holder or applicant with respect to patents essential for compliance with both mandatory and optional portions of the standard." Early disclosure to the Working Group of patent information that might be relevant to the standard is essential to reduce the possibility for delays in the development process and increase the likelihood that the draft publication will be approved for publication. Please notify the Chair <<u>stuart.kerry@philips.com</u>> as early as possible, in written or electronic form, if patented technology (or technology under patent application) might be incorporated into a draft standard being developed within the IEEE 802.11

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

CkSwTimeClock Switch Time for PBCC CWminbest-case (theoretical) Contention Window time measured in Slots DIFSDistributed Inter-frame Space Floorround down to nearest multiple of significance FSFrame Start Lengthnumber of octets in data payload Ndbpsnumber of data bits per symbol (function of PHY rate) PLCPtimetime to transmit PLCP header PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble	Ceilinground up to nearest multiple of significance
CWminbest-case (theoretical) Contention Window time measured in Slots DIFSDistributed Inter-frame Space Floorround down to nearest multiple of significance FSFrame Start Lengthnumber of octets in data payload Ndbpsnumber of data bits per symbol (function of PHY rate) PLCPtimetime to transmit PLCP header PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble	CkSwTimeClock Switch Time for PBCC
DIFSDistributed Inter-frame Space Floorround down to nearest multiple of significance FSFrame Start Lengthnumber of octets in data payload Ndbpsnumber of data bits per symbol (function of PHY rate) PLCPtimetime to transmit PLCP header PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTimetime to transmit one data frame	CWminbest-case (theoretical) Contention Window time measured in Slots
Floorround down to nearest multiple of significance FSFrame Start Lengthnumber of octets in data payload Ndbpsnumber of data bits per symbol (function of PHY rate) PLCPtimetime to transmit PLCP header PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble	DIFSDistributed Inter-frame Space
<ul> <li>FSFrame Start</li> <li>Lengthnumber of octets in data payload</li> <li>Ndbpsnumber of data bits per symbol (function of PHY rate)</li> <li>PLCPtimetime to transmit PLCP header</li> <li>PHYratedata transfer rate in bits per second at PLCP Layer</li> <li>Slot timebackoff timing interval</li> <li>SIFSShort Inter-Frame Space</li> <li>SigExSignal Extension</li> <li>Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes</li> <li>Tpreamtime to transmit preamble</li> <li>TxTimetime to transmit one data frame</li> </ul>	Floorround down to nearest multiple of significance
Lengthnumber of octets in data payload Ndbpsnumber of data bits per symbol (function of PHY rate) PLCPtimetime to transmit PLCP header PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble	FSFrame Start
Ndbpsnumber of data bits per symbol (function of PHY rate) PLCPtimetime to transmit PLCP header PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTimetime to transmit one data frame	Lengthnumber of octets in data payload
PLCPtimetime to transmit PLCP header PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTime	Ndbpsnumber of data bits per symbol (function of PHY rate)
PHYratedata transfer rate in bits per second at PLCP Layer Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTime	PLCPtimetime to transmit PLCP header
Slot timebackoff timing interval SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTime time to transmit one data frame	PHYratedata transfer rate in bits per second at PLCP Layer
SIFSShort Inter-Frame Space SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTimetime to transmit one data frame	Slot timebackoff timing interval
SigExSignal Extension Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTimetime to transmit one data frame	SIFSShort Inter-Frame Space
Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes Tpreamtime to transmit preamble TxTimetime to transmit one data frame	SigExSignal Extension
Tpreamtime to transmit preamble	Tacktime to transmit Acknowledgement (ACK) Frame of 14-bytes
Ty Time to transmit one data frame	Tpreamtime to transmit preamble
	TxTimetime to transmit one data frame
Tsignaltime to transmit Signal Field	Tsignaltime to transmit Signal Field
Tsymtime to transmit Service Field (defines symbol clock and code)	Tsymtime 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 usecPLCPtime = 32 usecBackoff Slot = 50 usecCWmin = 15SIFS = 28 usecPHYrate = 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5Tack @ 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)

Tx Time = Tpream + PLCPtime + Ceiling ((Length \* 8) / PHYrate)Tpream = 144 usecPLCPtime = 48 usecBackoff Slot = 20 usecCWmin = 31SIFS = 10 usecPHYrate = 1, 2 MbpsTack @ 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)

## 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 usecPLCPtime = 41 usecTack = 208 usecFor 2 Mbps:Tpream = 20 usecPLCPtime = 25 usecTack = 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 (a) 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) = 34Best-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 I ACK	A I II I Kate and Du	
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

#### Table 1 ACK PHY Rate and Duration

# 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)

Tx Time = 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 DSSS PHYrate = 2, 5.5, 11 Tack @ 2 Mbps = 152 usec	CWmin = 31 SIFS = 10 usec PBCC PHYrate = 5.5, 11, 22, 33

#### 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)

#### 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 usecPLCPtime = 24 usecBackoff Slot = 20 usecPHYrate = 2, 5.5, 11 MbpsTack @ 5.5 Mbps = 116 usecCWmin = 31SIFS = 10 usecSIFS = 10 usecCWmin = 31

#### 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) = 9 12 18 24 36 48 54 6 Ndbps = 2472 36 48 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 usecLong PLCP Header = 48 usecShort Preamble = 72 usecShort PLCP Header = 24 usecPBCC: CCK = 0, PBCC =1CkSwTime = 1 usecBackoff Slot = 20 usecSIFS = 10 usecCWmin = 31Tack @ 2 Mbps = 152 usecCWmin = 31

#### 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)

#### 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 use	Long PLCP Header = 48 usec							
Short Preamble = 72 use	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) = $\underline{6}$	-	<u>9</u>	<u>12</u>	<u>18</u>	24	<u>36</u>	48	<u>54</u>
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)

## **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.