Theoretical Maximum Throughput of IEEE 802.11 and its Applications*

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Abstract

The goal of this paper is to present exact formulae for the throughput of IEEE 802.11 networks in the absence of transmission errors and for various physical layers, data rates and packet sizes. Calculation of the throughput is more than a simple exercise. It is a mandatory part of provisioning any system based on 802.11 technology (whether in ad-hoc or infrastructure mode). We will discuss the practical importance of theoretical maximum throughput and present several applications.

1. Introduction

IEEE 802.11 networks are currently the most popular wireless local area network (WLAN) products on the market. The technology has matured, the prices have come down significantly in the past couple of years and the products fulfill clear needs of many classes of consumers.

End consumers use IEEE 802.11 products for mobile networking both in the residential and business markets, enjoying untethered Internet access. Internet Service Providers, realizing the significant cost savings that wireless links offer when compared to classical access techniques (cable and xDSL), embraced the technology as an alternative for providing last mile broadband Internet access. Various companies are using IEEE 802.11 off-the-shelf products to provide wireless data access to devices without a need for special cabling, e.g. remote surveillance cameras, cordless speakers, etc. WLANs make it possible to network historical buildings where it is impossible or impractical to use cables. Researchers in ad-hoc networking are finally offered a high data rate, reliable, low cost implementation radio interface for their testbeds.

One of the most common misconceptions about 802.11b is that the throughput is 11 Mbps. However, the 11 Mbps so hugely advertised on all IEEE 802.11b products only refers to the radio data rate (of only a part) of the packets. The throughput offered to a user of IEEE 802.11 technology is significantly different. For example with no transmission errors and 1460 byte sized packets, the throughput of an "1 Mbps" system is just 6.1 Mbps. The efficiency is significantly lower for smaller packet sizes. The efficiency of IEEE 802.11 is in sharp contrast to wired technologies where, for example, a 10 Mbps Ethernet (802.3) link offers the users almost 10 Mbps.

The main contribution of this paper is the exact calculation of the theoretical maximum throughput for 802.11 networks, for a variety of technologies (802.11, 802.11b, 802.11a) and data rates. All of the information for the calculation of these data rates is available in the IEEE standards [1–3]. However, actually doing it is a laborious procedure requiring data gathering from various standards and a thorough understanding of the mechanisms presented in the standard. By publishing the calculations in this paper, we hope to spare other research teams and system designers the tedium of wading through the standards to determine the theoretical maximum throughput. Referenced publications [4–8], concentrate on the analysis of contention window sizes and qualitative performance of the IEEE 802.11 standard.

To emphasize the importance of the theoretical maximum throughput, we will present several applications which require knowledge of the maximum throughput if they are to be designed correctly. The most common use of 802.11 technology is for LAN data access, and correctly provisioning such a network implies more than just providing adequate coverage. The theoretical maximum throughput can be used to facilitate optimal network provisioning, both for data as well as multimedia applications. In the case of ad-hoc networks, it turns out to be a primary factor influencing topological distribution of nodes.

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2 Assumptions

We define the upper limit of the throughput that can be achieved in an IEEE 802.11 network as its theoretical maximum throughput (TMT). Since the 802.11 standard covers the medium access control (MAC) and physical layer in terms of the OSI reference model [9], we are interested in the actual throughput provided by the MAC layer. Therefore, the TMT of 802.11 can also be defined as the maximum amount of MAC layer service data units (SDUs) that can be transmitted in a time unit. A typical encapsulation between application layer and 802.11 is transmission control protocol (TCP) or user datagram protocol (UDP) over the Internet protocol (IP), over logical link control (LLC). The higher the layer, the lower the maximum throughput of that layer, as overhead accumulates at each layer. Also, the maximum throughput at the application layer can be limited by TCP dynamics as well as overhead due to protocol headers. The effect of TCP dynamics on the maximum throughput is out of the range of this paper. Maximum throughput observed by an application is described by the following equation when no fragmentation is involved in the lower layers:

$$TMT_{APP} = \frac{\beta}{\alpha + \beta} \times TMT_{802.11} \ \ (bps) \qquad (1)$$

where,
TMT_{APP} is the TMT of the application layer,
α is the total overhead above MAC layer,
β is the application datagram size and
$TMT_{802.11}$ is the TMT of 802.11 MAC layer.
In the rest of this paper the term TMT refers to the TMT of the 802.11 MAC layer ($TMT_{802.11}$), unless explicitly mentioned to the contrary.

TMT is defined under the following assumptions:

- Bit error rate (BER) is zero.
- There are no losses due to collisions.
- Point coordination function (PCF) mode is not used.
- No packet loss occurs due to buffer overflow at the receiving node.
- Sending node always has sufficient packets to send.
- The MAC layer does not use fragmentation.
- Management frames such as beacon and association frames are not considered.

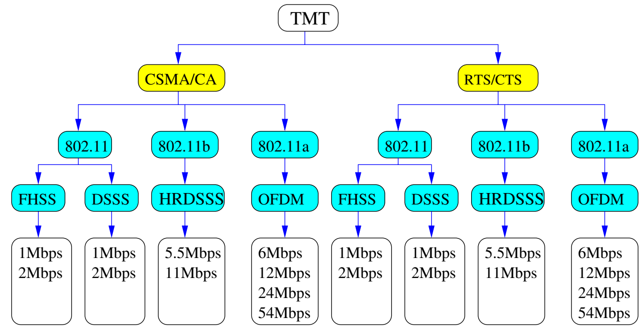

Figure 1. TMT classification based on different MAC and PHY schemes and basic data rates

3 Classification

TMT calculation is classified based on different MAC schemes, spread spectrum technologies and basic data rates. This classification is required because the standard specifies different values for inter-frame spacing (IFS), minimum contention window size (CW_{min}), etc. These parameters substantially affect the calculation of TMT. Although 802.11 provides a standard for infrared (IR) medium, we consider only the radio frequency (RF) medium because IR implementations are so unpopular.

With respect to the MAC schemes, two different sets of TMTs are calculated - one for CSMA/CA and the other for RTS/CTS. Within those two sets, calculations are grouped based on different spread spectrum technologies - frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS), high-rate DSSS (HR-DSSS) and orthogonal frequency division multiplexing(OFDM). Finally, the TMT of 802.11 and 802.11b is calculated for different basic data rates - 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps. For 802.11a, mandatory data rates of 6 Mbps, 12 Mbps, 24 Mbps and the highest data rate of 54 Mbps are used. All of the overheads associated at each sublayer (MAC sublayer, physical layer convergence protocol (PLCP) sublayer and physical medium dependent (PMD) sublayer) are considered. Fig. 1 illustrates the classification of the presented TMT calculations.

In terms of the OSI reference model [9], IEEE 802.11 covers the MAC and PHY layers. The PHY layer is again divided into a PLCP sublayer and a PMD sublayer. A protocol data unit (PDU) at each layer is defined as the length of the transmission unit at that layer including the overhead. A service data unit (SDU) is defined as the length of the payload that a particular layer provides to the layer above. Therefore, when a higher layer pushes a user packet down to the MAC layer as a MAC SDU (MSDU), overheads occur at each intermediate layer. Fig. 2 shows the type of

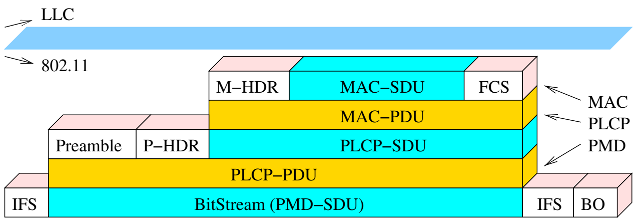

Figure 2. Overhead at different sublayers of IEEE 802.11

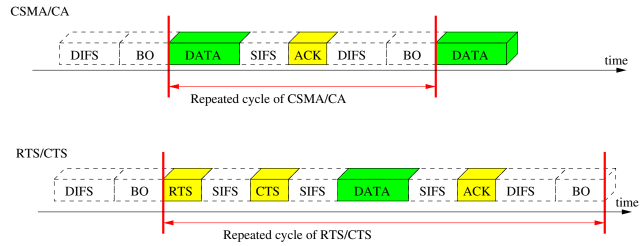

Figure 3. Timing diagram for CSMA/CA and RTS/CTS

overheads added at different sublayers when an MSDU is transmitted through an 802.11 interface. At the MAC layer, the MAC layer header and trailer (FCS) are added before and after the MSDU, respectively, and form a MAC PDU (MPDU). Similarly, the PLCP preamble and PLCP header are attached to the MPDU at the PLCP sublayer. Different IFSs are added depending on the type of MPDU. The time consumed by 802.11's backoff scheme cannot be neglected. We will consider the IFS and the backoff duration as overhead at the PMD layer.

4 Calculation of the TMT

In order to calculate the TMT, we first convert all of the overheads at each sublayer into a common unit - time. To obtain the maximum throughput, we will divide the MAC SDU by the time it takes to transmit it:

$$TMT = \frac{MSDU\ size}{Delay\ per\ MSDU} \tag{2}$$

The data rate is not always the same even within the same PLCP PDU. The data rate of a MAC PDU is determined by its type. Control frames such as RTS, CTS, and ACK are always transmitted at 1 Mbps for backward compatibility. When FHSS is used, the number of PLCP frame bits may increase because of DC-bias suppression scheme. Fig. 3 illustrates how data packets are transmitted. The same pattern will be repeated with a specific cycle when back-to-back traffic is offered at the transmitting node. The timing diagram is different for CSMA/CA and RTS/CTS. The exact duration of each block varies for different spread spectrum technologies and basic data rates.

The duration of each delay component was determined from the standards [1–3]. All delay components vary with the spread spectrum technology but not with the data rate. The transmission time of an MPDU depends on its size and data rate. The contention window size (CW) does not increase exponentially since there are no collisions. Thus, CW is always equal to the minimum contention window size (CW_{min}), which varies with different spread spectrum technologies. The backoff time is selected randomly following a uniform distribution from $(0,\ CW_{min})$ giving the expected value of $CW_{min}/2$. Table 1 lists the constant and varying delay components.

The total delay per MSDU is calculated as a summation of all the delay components in Table 1 as follows:

$$\begin{aligned} Delay\ \ per\ MSDU &= (T_{DIFS} + T_{SIFS} + T_{BO} + T_{RTS} \\ &+\ \ T_{CTS} + T_{ACK} + T_{DATA}) \times 10^{-6}s. \end{aligned} \tag{3}$$

The total delay per MSDU is simplified to a function of the MSDU size in bytes, x as:

$$Delay\ per\ MSDU(x) = (ax + b) \times 10^{-6}s. \tag{4}$$

We can get the TMT simply by dividing the number of bits in MSDU ($8x$) by the total delay (4). Table 2 shows parameters a and b for the TMT formula:

$$TMT(x) = \frac{8x}{ax+b} \times 10^6\ \ bps. \tag{5}$$

When the MSDU size tends to infinity, the TMT is bounded by:

$$\lim_{x\to\infty} TMT(x) = \frac{8}{a} \times 10^6\ \ bps. \tag{6}$$

Also, as the data rate tends to infinity, parameter a in (4) tends to zero:

$$\lim_{a\to 0, b\to b'} TMT(x) = \frac{8x}{b'} \times 10^6\ \ bps, \tag{7}$$

where b' is the sum of all the delay components that are not affected by the data rate. Existence of such a limit is shown by Xiao et al. [4].

The use of the parameters a and b in the calculation of the TMT for OFDM technology is based on the assumption that the total delay per MSDU is continuous. In fact, the delay is not continuous due to the ceiling operation in the formulae. However, the approximation error due to this operation is relatively small - less than 2% in the worst case.

Table 1. Delay components for different MAC schemes and spread spectrum technologies

Scheme	*Constant and varying delay components* ($10^{-6}s$)						
	T_{DIFS}	T_{SIFS}	T_{BO}	T_{RTS}	T_{CTS}	T_{ACK}	T_{DATA} $(MSDU\ in\ bytes)$
CSMA/CA							
FHSS-1	128	28	375	N/A	N/A	240	$128 + 33/32 \times 8 \times (34 + MSDU)/1$
FHSS-2	128	28	375	N/A	N/A	240	$128 + 33/32 \times 8 \times (34 + MSDU)/2$
DSSS-1	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/1$
DSSS-2	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/2$
HR-5.5	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/5.5$
HR-11	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/11$
OFDM-6	34	9	67.5	N/A	N/A	44[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/24\rceil$
OFDM-12	34	9	67.5	N/A	N/A	32[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/38\rceil$
OFDM-24	34	9	67.5	N/A	N/A	28[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/96\rceil$
OFDM-54	34	9	67.5	N/A	N/A	24[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/216\rceil$
RTS/CTS							
FHSS-1	128	28×3	375	288	240	240	$128 + 33/32 \times 8 \times (34 + MSDU)/1$
FHSS-2	128	28×3	375	288	240	240	$128 + 33/32 \times 8 \times (34 + MSDU)/2$
DSSS-1	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/1$
DSSS-2	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/2$
HR-5.5	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/5.5$
HR-11	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/11$
OFDM-6	34	9×3	67.5	52[1]	44[2]	44[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/24\rceil$
OFDM-12	34	9×3	67.5	36[1]	32[2]	32[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/38\rceil$
OFDM-24	34	9×3	67.5	28[1]	28[2]	28[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/96\rceil$
OFDM-54	34	9×3	67.5	24[1]	24[2]	24[2]	$20 + 4 \times \lceil(16 + 6 + 8 \times (34 + MSDU))/216\rceil$

5 Analysis

In this section we will analyze the behavior of the TMT and spectral efficiency both for single and multiple transmitter systems.

5.1. Analysis of TMT

Using (5), we plotted TMT curves for different MAC schemes. Fig. 4 and Fig. 5 depict the variation of TMT as a function of MSDU for the CSMA/CA and RTS/CTS, respectively. In each figure a comparison of different data rate and spread spectrum technologies is presented. Since the TMT difference between FHSS and DSSS is negligible, both 1 Mbps and 2 Mbps curves are marked by only one label regardless of the spread spectrum technology. The figures show the curve for an MSDU size up to 4095 bytes because the 802.11, 802.11b and 802.11a standards specify that maximum MSDU size is 4095 bytes for FHSS and HR-DSSS, and 8191 bytes for DSSS.

[1] $T_{RTS} = 20+4\times\lceil \frac{16+6+8\times20}{N_{DBPS}}\rceil$ = 52, 36, 28 & 24 for each N_{DBPS}

[2] $T_{CTS} = 20+4\times\lceil \frac{16+6+8\times14}{N_{DBPS}}\rceil$ = 44, 32, 28 & 24 for each N_{DBPS}

where N_{DBPS} is 24, 48, 96 and 216 for OFDM-6, OFDM-12, OFDM-24 and OFDM-54, respectively. Also note that $T_{CTS} = T_{ACK}$.

Fig. 4 and Fig. 5 show that TMT is quite low compared to the basic data rate. When basic data rate is 11 Mbps, MSDU is 1500 bytes and RTS/CTS scheme is used, TMT is 4.52 Mbps. TMT is higher for CSMA/CA due to fewer control frames, and still only 6.06 Mbps (for 1500 byte MSDUs). Therefore, it is almost impossible to see throughputs of over 6.1 Mbps in real deployments where IP packets carrying TCP segments over 1500 bytes are not common. Furthermore, the slope of the curves shows that the higher the basic data rate is, the more sensitive TMT is to MSDU size. In other words, performance will be substantially degraded when small-sized data packets are transmitted especially for high data rates. Fig. 4 and Fig. 5 show that the TMT of higher data rates saturates much later than the TMT of lower data rates.

The TMT comparison of 802.11a OFDM and 802.11b HR-DSSS is presented in Fig. 6 and Fig. 7 for CSMA/CA and RTS/CTS, respectively. In order to get a clear comparison, the curves are plotted for only the mandatory data rates and the maximum data rate of 802.11a along with the curve for 11 Mbps of 802.11b. TMT close to 6 Mbps can be achieved in 802.11a when the data rate is 6 Mbps. 802.11a saturates earlier than 802.11b because of smaller inter frame spacing and time slot duration.

Table 2. TMT parameters for different MAC schemes and spread spectrum technologies

Scheme	*Data Rate*	***a***	***b***
CSMA/CA			
FHSS	1 Mbps	8.25	1179.5
	2 Mbps	4.125	1039.25
DSSS	1 Mbps	8	1138
	2 Mbps	4	1002
HR-DSSS	5.5 Mbps	1.45455	915.45
	11 Mbps	0.72727	890.73
OFDM	6 Mbps	1.33333	223.5
	12 Mbps	0.66667	187
	24 Mbps	0.33333	170.75
	54 Mbps	0.14815	159.94
RTS/CTS			
FHSS	1 Mbps	8.25	1763.5
	2 Mbps	4.125	1623.25
DSSS	1 Mbps	8	1814
	2 Mbps	4	1678
HR-DSSS	5.5 Mbps	1.45455	1591.45
	11 Mbps	0.72727	1566.73
OFDM	6 Mbps	1.33333	337.5
	12 Mbps	0.66667	273
	24 Mbps	0.33333	244.75
	54 Mbps	0.14815	225.94

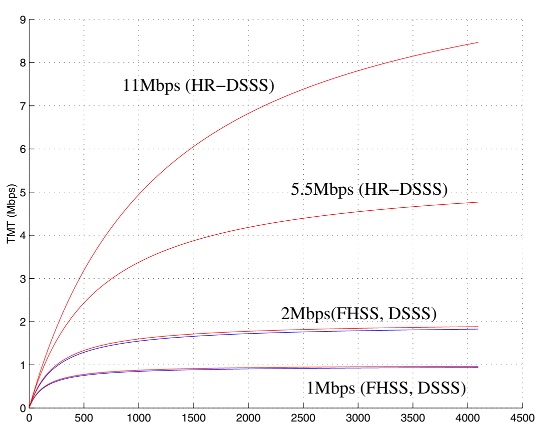

Figure 4. TMT curve for CSMA/CA - FHSS, DSSS, HR-DSSS

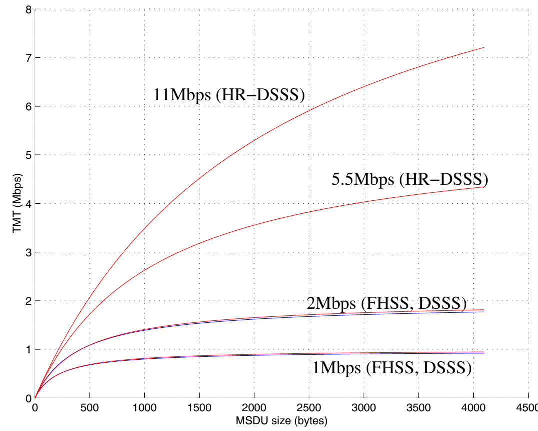

Figure 5. TMT curve for RTS/CTS - FHSS, DSSS, HR-DSSS

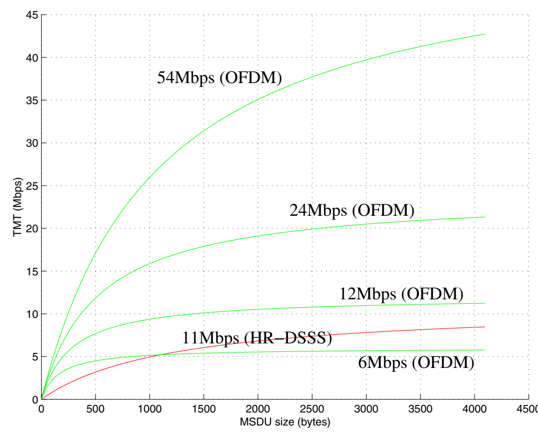

Figure 6. TMT curve for CSMA/CA - 11 Mbps HR-DSSS, OFDM

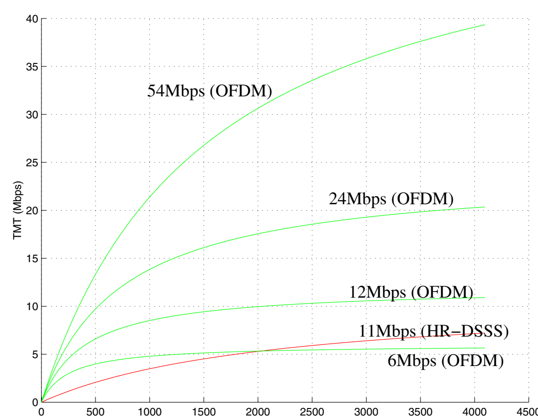

Figure 7. TMT curve for RTS/CTS - 11 Mbps HR-DSSS, OFDM

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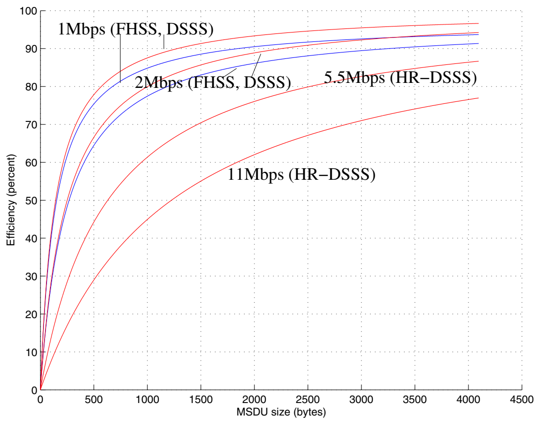

Figure 8. Bandwidth efficiency curve for CSMA/CA - FHSS, DSSS, HR-DSSS

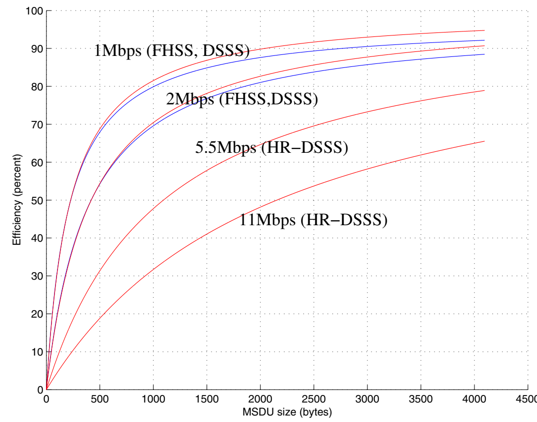

Figure 9. Bandwidth efficiency curve for RTS/CTS - FHSS, DSSS, HR-DSSS

5.2. Analysis of bandwidth efficiency

As a measure of spectral utilization, we define bandwidth efficiency ε:

$$\varepsilon = \frac{TMT}{R}, \tag{8}$$

where R is the basic data rate.

Fig. 8 and Fig. 9 show the bandwidth efficiency for CSMA/CA and RTS/CTS, respectively. From the formula, bandwidth efficiency is inversely proportional to basic data rate. Bandwidth efficiency is only 41% when the data rate is 11 Mbps and RTS/CTS is used, and it is 55% when CSMA/CA is used. In the bandwidth curves, we can observe the saturation tendency more clear than in the TMT curve. It is also evident that bandwidth efficiency increases as MSDU size is increased.

The bandwidth efficiency comparison of 802.11a OFDM and 802.11b HR-DSSS is presented in Fig. 10 and Fig. 11 for CSMA/CA and RTS/CTS, respectively. The higher data rates are compared in a separate figure and low data rates such as 1 Mbps and 2 Mbps with FHSS and DSSS are not included. CSMA/CA performs better than RTS/CTS because of less control frames. For the same MAC scheme, 802.11a outperforms 802.11b in terms of bandwidth efficiency.

6 Applications

In this section we discuss the practical utility of the TMT calculations and present an application that uses these values to measure the bandwidth utilization at any given point (on a particular channel) in an 802.11 network.

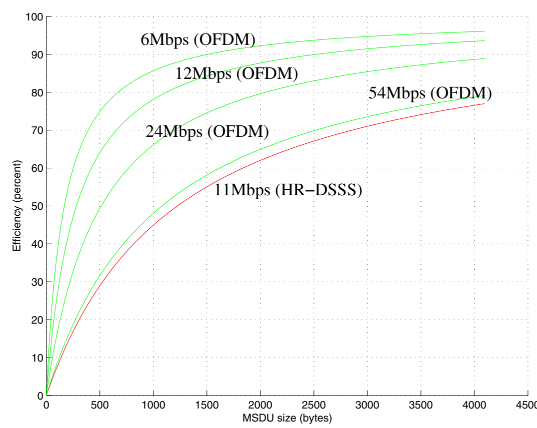

Figure 10. Bandwidth efficiency curve for CSMA/CA - 11 Mbps HR-DSSS, OFDM

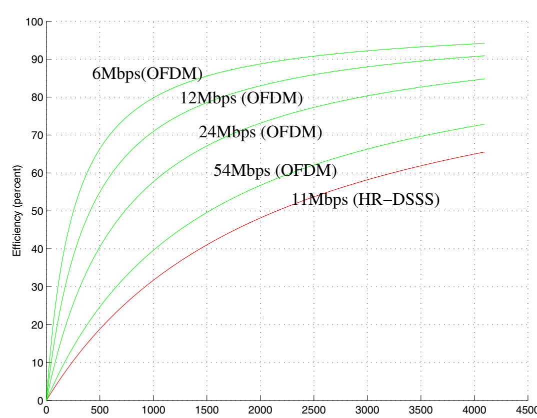

Figure 11. Bandwidth efficiency curve for RTS/CTS - 11 Mbps HR-DSSS, OFDM

6.1. Importance of TMT

TMT is important to researchers as well as system designers. It is a strict barrier that cannot be overcome by any means while remaining standard-compliant. It is a numerical upper bound on the throughput given the MAC scheme, spread spectrum technology, basic data rate and packet size. It can be used to derive any one of the parameters that describe the performance of a network (maximum allowable MSDU size, delay, throughput or number of users) given the others.

TMT can be used in call admission and control procedures for QoS schemes to determine accurate upper bounds on available bandwidth. For instance, consider ARME [10] and DIME [11] - protocols that aim to provide throughput guarantees in a wireless LAN based on the Differentiated Services architecture. A node running these protocols would require the knowledge of current link utilization and the maximum throughput that can be achieved at any given point in order to perform accurate statistical bandwidth allocation.

The knowledge of the bandwidth efficiency curves (Figs. 8-10) enables an application protocol designer to observe the effects of a trade off between the size of the data unit passed to the MAC layer and the delay in generating the data unit on the bandwidth efficiency. This is especially useful to minimize jitter in multimedia applications.

As demonstrated in [12], TMT is vital in the estimation of the maximum number of voice channels that can be accommodated in a wireless LAN. Voice and video applications can use TMT to calculate the optimum MSDU size to maximize throughput and, hence, determine the amount of buffering required for a communication link. TMT formulae can be used to validate and check the sanity of network simulators that model 802.11 protocols.

One of the most important aspects of designing the layout of a wireless LAN is provisioning. Extensive traffic modeling and workload analysis have to be carried out to correctly estimate the infrastructure needs of any given location. Over-provisioning in a wireless LAN is just as damaging as under-provisioning as noted in the comprehensive study done on a campus-wide wireless network at Dartmouth [13] and also in [14]. They observed that unnecessary handoffs between access points that are placed too close to each other result in considerably lower throughput. Also, it is straightforward to see that when we consider a network where each node is within the transmission range of every other node, the sum of the throughputs achieved by all the nodes in the network cannot exceed the TMT of the network. Thus, the ability to accurately measure the link utilization at various locations in order to perform provisioning is extremely useful. We have implemented an application called WeNoM (Wireless Network Monitor) that does exactly that.

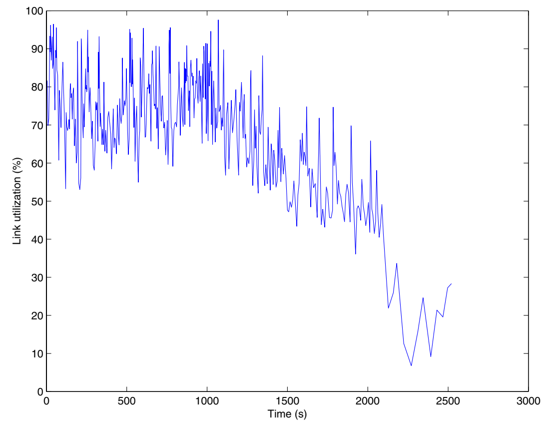

Figure 12. Bandwidth utilization at MobiCom 2002

6.2. Wireless Network Monitor - WeNoM

WeNoM was implemented on a Redhat Linux system using the libpcap library from the tcpdump project [15]. It was later ported to an Intel StrongArm based HP iPAQ running Familiar Linux so that it could be used as a handy mobile network monitor. The source code and documentation for the application is available [16].

The principle behind the application is to use the values presented in Table 2 to calculate the actual transmission time of an 802.11 frame given the length of the frame and the rate at which it was transmitted. WeNoM passively listens to the traffic in the network on a single channel and gathers from each frame the transmission rate, length of the MSDU and the time at which it was received. Using this data and the appropriate constants from Table 2 in (4) (Section 4) for the transmission time, an accurate estimate for the time taken to transmit each frame is obtained. The ratio of the transmission time to the inter-arrival time between frames gives the instantaneous link utilization at the place of measurement. The sensitivity of the measurements can be controlled by using either a weighted average of the cumulative and instantaneous utilization values, or a running average of the utilization for a certain number of consecutive frames.

We used WeNoM to measure the WLAN traffic at the MobiCom 2002 conference at Atlanta for a period of about 40 minutes. Given that there were 2 access points and over 200 users, one would expect the network to be fairly saturated. The plot in Fig. 12, depicts the bandwidth utilization toward the end of the day. One can observe the link utilization decrease as the participants leave the conference.

7 Conclusion

In this paper we presented the calculation of the theoretical maximum throughput of 802.11 networks. To broaden the applicability of the results, many physical layer and MAC layer variations were considered. To illustrate how to apply the results presented in this paper, we presented an application which monitors the link utilization of an 802.11 network. We hope that the results of this paper will help researchers and system designers to easily and correctly provision systems based on IEEE 802.11 technology.

References

[1] Wireless LAN medium access control (MAC) and physical layer (PHY) specification, IEEE Standard 802.11, June 1999.

[2] Wireless LAN medium access control (MAC) and physical layer (PHY) specification: High-speed physical layer extension in the 2.4 GHz band, IEEE Standard 802.11, Sept. 1999.

[3] Wireless LAN medium access control (MAC) and physical layer (PHY) specification: High-speed physical layer in the 5 GHz band, IEEE Standard 802.11, Sept. 1999.

[4] Y. Xiao and J. Rosdahl, Throughput and delay limits of IEEE 802.11, *IEEE Communications Letters*, vol. 6, no. 8, pp. 355–357, Aug. 2002.

[5] B. Bing, Measured performance of the IEEE 802.11 wireless LAN, in *Local Computer Networks - LCN '99*, 1999, pp. 34–42.

[6] F. Cali, M. Conti, and E. Gregori, IEEE 802.11 wireless LAN: capacity analysis and protocol enhancement, in *Proc. of INFOCOM '98, Seventeenth Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 1, 1998, pp. 142–149.

[7] Y. Tay and K. C. Chua, A capacity analysis for IEEE 802.11 MAC protocol, *Wireless Networks*, vol. 7, pp. 159–171, 2001.

[8] J. C. Chen and J. M. Gilbert, Measured performance of 5-GHz 802.11a wireless LAN systems, http://www.airvia.com/AtherosRangeCapacityPaper.pdf.

[9] A. S. Tanenbaum, *Computer Networks*, 4th ed. Prentice-Hall, 2002.

[10] A. Banchs and X. Perez, Providing throughput guarantees in IEEE 802.11 wireless LAN, in *Proc. of IEEE Wireless Communications and Networking Conference - WCNC2002*, vol. 1, 2002, pp. 130–138.

[11] A. Banchs, M. Radimirsch, and X. Perez, Assured and expedited forwarding extensions for IEEE 802.11 wireless LAN, in *Proc. of the Tenth IEEE International Workshop on Quality of Service*, 2002, pp. 237–246.

[12] M. Veeraraghavan, N. Cocker, and T. Moors, Support of voice services in IEEE 802.11 wireless LANs, in *Proc. of INFOCOM '01, Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 1, 2001, pp. 488–497.

[13] D. Kotz and K. Essien, Analysis of a campus-wide wireless network, in *Proc. of Mobicom*, Sept. 2002.

[14] A. Balachandran, G. M. Voelker, P. Bahl, and P. V. Rangan, Characterizing user behavior and network performance in a public wireless LAN, in *Proc of. ACM SIGMETRICS*, vol. 30, no. 1, June 2002.

[15] Tcpdump public repository, 2002, http://www.tcpdump.org.

[16] Wireless network monitor, http://www4.ncsu.edu/∼mlsichit/Software/Wenom/wenom−release−1.0.tar.gz, 2002.