THROUGHPUT AND LATENCY PERFORMANCE OF IEEE 802.11E WITH 802.11A, 802.11B, AND 802.11G PHYSICAL LAYERS

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ABSTRACT

IEEE 802.11e is an amendment of the medium-access control (MAC) layer of the standard for wireless local area networking IEEE 802.11. The goal of 802.11e is to provide 802.11 networks with Quality of Service (QoS). 802.11 has three physical layers (PHY) of practical importance: 802.11b, 802.11a, and 802.11g. 802.11a and 802.11g provide data rates between 6 and 54 Mbps, and 802.11b provides data rates of 5.5 Mbps and 11 Mbps. However these data rates are not the actual throughput. The actual throughput that a user will experience will be lower. The throughput depends on both the PHY and MAC layers. It is important to estimate what exactly is the throughput when the physical layer is 802.11a, 802.11b, or 802.11g, and the MAC layer is 802.11e. In other words, how does providing QoS change the throughput for each of the three physical layers? In this paper we provide answers to this problem. Analytic formulae are derived. The maximum achievable throughput and minimum delay involved in data transfers are determined. The obtained results have further significance for the design of high-throughput wireless protocols.

KEYWORDS

IEEE 802.11e EDCF, MAC layer, PHY layer, Throughput performance

INTRODUCTION

Wireless communications is a very active research area and there is a significant industry interest in it. 802.11, developed by the IEEE, is the most successful standard for wireless networking. IEEE 802.11 consists of two layers: medium-access control (MAC) layer and a physical (PHY) layer (Ref. [2]). Six different physical layers have been standardized: three within the original 802.11, and three additional: 802.11a, 802.11b, and 802.11g. The three original physical layers provide data rates of 1 and 2 Mbps. 802.11a and 802.11g provide data rates between 6 and 54 Mbps, 802.11b provides data rates of 5.5 Mbps and 11 Mbps. However these data rates are not the actual throughput. The throughput is, of course lower. It is recognized that the actual throughput depends not only on the physical layer. It depends on both the MAC layer and on the PHY layer. Therefore it is important to estimate what exactly is the throughput that the MAC and PHY combination will produce. This was investigated recently in the paper.

Recently, 802.11 has been increasingly used not only for the transport of computer data, but also for the transport of voice, audio, and video data (Ref [1]). To meet the Quality of Service requirements, IEEE 802.11 task group E has been working on an enhanced 802.11 MAC protocol to support applications with QoS requirements. The result of this work is the amendment IEEE 802.11e.

Throughput and latency are the most important QoS parameters. The problem, what is the exact throughput when the MAC protocol is 802.11e, and the PHY is 802.11a, 802.11b, or 802.11g, has not been answered. This is the problem that is answered in this paper. In section 2 and 3, the working mechanisms of the legacy 802.11 and 802.11e MAC protocols are discussed. In Section 4, the new analytic formulae for the throughput of 802.11e are derived. In Section 5, the equation has been derived for the maximum achievable throughput when the data rate goes to infinite. Section 6 deals with the minimum delay in the data transfer due to the overhead time delays involved. Simulation plots and Numerical results are presented in Appendix B. The paper concludes with summary in section 7.

2. IEEE 802.11E

In this section we analyze the effect on throughput of the QoS mechanism provided by the enhanced distributed channel access (EDCA) defined in 802.11e.

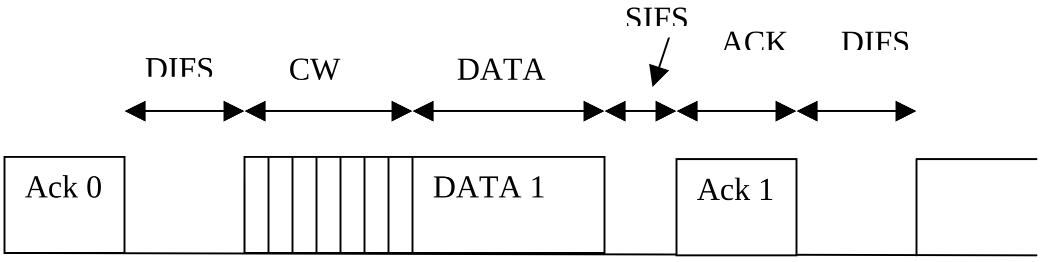

Figure 1. Legacy DCF timing diagram

Figure 1 represents the timing diagram of the legacy 802.11 Distributed Coordination Function (DCF). It is well known that the medium-access protocol of 802.11 is carrier-sense multiple accesses with collision avoidance (CSMA/CA) [3]. Stations can transmit frames after they detect that the medium is available for a period equal to DIFS+backoff interval. The backoff interval is a random number with a uniform distribution between 0 and CW-1, where CW is the contention window. After any unsuccessful transmission, the CW is doubled, up to a certain limit.

802.11e introduced traffic prioritization. IEEE 802.11e is using a standard called IEEE Std 802.1D-1998, Annex H.2, which adds three bits to the packet header and gives the LAN the capability to recognize eight levels of priority. Priority 7 is the highest priority and priority 1 is the lowest priority, with priority 0, which is used for best effort traffic, ordered between priority 3 and priority 2. The resulting default ordering is {7, 6, 5, 4, 3, 0, 2, 1}, as shown in Table 1.

Table 1. Priority to Access Category Mapping and CW values

Priority (Traffic category)	Traffic type (Access category)	AIFSN	$CW_{\min}$	$CW_{\max}$
Lowest 1 2	Background (BK) – aperiodic data -	7 6	$CW_{\min}$	$CW_{\max}$
0 3	Best effort (BE) – aperiodic data Excellent effort (EE) – isochronous data	3 2	$CW_{\min}$	$CW_{\max}$
4 5	Controlled load Video (VI) – periodic	3 2	$\frac{CW_{\min}+1}{2}-1$	$CW_{\min}$
6 7 Highest	Voice (VO) – periodic Network control (NC)	2 1	$\frac{CW_{\min}+1}{4}-1$	$\frac{CW_{\min}+1}{2}-1$

The EDCA is also a contention-based channel access mechanism that uses Arbitration Interframe Space (AIFS) instead of DIFS. Prior to each transmission a station will defer until the medium is determined to be idle without interruption for a period of time equal to the arbitration IFS for that queue (AIFS[*i*]). Note that AIFS [*i*] is variable, assigned either by a management entity, or by the AP and measured in time is equal to the integer AIFSN [*i*] multiplied by the slot time plus SIFS:

$$\text{AIFS[AC]} = \text{AIFSN[AC]} \times \text{slot time} + \text{SIFS}\,. \quad (1)$$

The integer AIFSN must be greater than 2 for stations, and greater than 1 for the AP. In this way the AP has a higher priority for this channel access mechanism. The values of AIFSN for the different access categories is advertised in the beacons and probe response frames transmitted by the AP. An example is given in Table 1. Furthermore the contention window values are different for each priority level. According to the EDCA, service differentiation is achieved through varying the length of the contention window, and/or varying the duration a station may transmit after it acquires channel access. Note that the slot time and the contention window values depend on the physical layer that is used. (Therefore the MAC layer is not entirely independent of the physical layer.)

Table 2 Timing parameters for 802.11b, 802.11a and 802.11g

Parameter	802.11b	802.11a	802.11g
SIFS duration, μs	10	16	10 (with virtual extension of $6\mu s$)
Slot time, μs	20	9	20 or 9
$CW_{\min}$, time slots	31	15	15

Another change brought by 802.11e is the introduction of negotiable acknowledgements. The IEEE 802.11 standard prior to 802.11e required an acknowledgement for every frame. IEEE 802.11e makes acknowledgments negotiable. Such negotiable acknowledgments lead to a more efficient utilization for the available channel and enable such applications a reliable multicast. According to 802.11e there are four acknowledgment types: normal (as in the legacy 802.11), no acknowledgment, no explicit acknowledgment, and block acknowledgment. Clearly, no acknowledgment is used whenever acknowledgment is not required. This could be appropriate for delay-sensitive traffic. The option of no explicit acknowledgment allows acknowledgments to be piggybacked onto different frames. The block acknowledgement mechanism allows a block of QoS frames to be transmitted, each separated by a SIFS period. This improves latency and jitter. There are two types of block acknowledgements: immediate and delayed. Immediate block acknowledgment is suitable for highbandwidth, low latency traffic while the delayed block acknowledgment is suitable for applications that tolerate moderate latency.

4. THROUGHPUT PERFORMANCE OF EDCA

In this section, the throughput equation for the EDCA as defined in the 802.11e is derived. Matlab simulations have been carried out using different physical layer parameters of IEEE 802.11a, 802.11b and 802.11g standards.

The backoff period can be calculated by multiplying the slot time, T_{SLOT}, with the size of contention Window. Since the backoff time has uniform distribution, the expected value will be $CW/2$. The transmission time of the data can be given as T_{D_DATA}. The transmission time of the acknowledgement frame can be given by T_{D_ACK}. An acknowledgement is transmitted T_{SIFS} after the data is received. In addition, there is the propagation delay. Therefore we have, as shown in Figure 1,

$$T = T_{AIFS} + \frac{CW_{\min}}{2} T_{SLOT} + T_{D\_DATA} + \tau + T_{SIFS} + T_{D\_ACK} + \tau \ , \quad (2)$$

if an acknowledgment is required. According to 802.11e there may be no acknowledgement. In this case

$$T = T_{AIFS} + \frac{CW_{\min}}{2} T_{SLOT} + T_{D\_DATA} + \tau \, . \qquad (3)$$

The minimum value of the contention window is used, because it is assumed that transmissions do not result in errors. If there are errors, at the next transmission attempt the contention window doubles, T increases and the throughput decreases. Clearly, only T_{D_DATA} is useful time, the other time periods represent protocol overhead. Therefore the throughput, measured in bits per second, is given by

$$Throughput = \frac{Payload\ Size}{T} \, . \quad (4)$$

Therefore the throughput as a function of the traffic category is

$$Throughput(TC) = \frac{8L_{DATA}}{T} \ , \quad (5)$$

where L_{DATA} is the payload in bytes, and T is either as in (2) or (3) depending on whether an acknowledgment is required or not.

It must be noted that this is the throughput only as a result of the channel access procedure. While the throughput for all physical layers is given by these equations, for each physical layer T_{D_DATA} and T_{D_ACK} will be different. The physical layers will introduce additional overhead (their own preambles and headers), which will reduce the throughput. This is examined in the following sections.

5. THROUGHPUT OF IEEE 802.11e + 802.11a

The 802.11a physical layer adds a preamble and a header to the packet. The total preamble is $T_{\text{Pr}eamble}$=16 μs long. A header follows the preamble. This header comprises one OFDM symbol, and therefore takes T_{H_PHY}=4 μs. After the header, the packet is transmitted using a variable number of OFDM symbols. However, there is additional physical layer protocol overhead, consisting of 16 bits for the service field, 6 tail bits, and a certain number of pad bits, to make the total number of OFDM symbols integer. The number 16+6+8*28+$8*L_{DATA}$+pad bits divided by the number of data bits per symbol N_{DBPS} must be an integer. The number N_{DBPS} is 24, 36, 48, 72, 96, 144, 192, and 216 bits, correspondingly for the data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mb/s. Therefore the time to transmit a 802.11a packet is

$$T_{D\_DATA} = T_{\text{Pr}eamble} + T_{H\_PHY} + T_{SYM} * Ceiling\left(\frac{16+6+8*28+8L_{DATA}}{N_{DBPS}}\right). \quad (6)$$

Formula (6) takes into account the MAC overhead of 28 bytes, which includes the MAC header and the FCS. $T_{SYM} = 4\mu s$ is the time to transmit one OFDM symbol. If a normal acknowledgement is required, then this acknowledgment will be transmitted SIFS after the end of the data transmission. The normal acknowledgement takes 14 bytes. The time to transmit the acknowledgment is

$$T_{D\_ACK} = T_{\text{Pr}eamble} + T_{H\_PHY} + T_{SYM} * Ceiling\left(\frac{16+6+8*14}{N_{DBPS\_ACK}}\right). \quad (7)$$

Note that the acknowledgment is transmitted at the control rate, which may be different than the data rate of the packet. The control rate always must be smaller than or equal to the data rate. The control rate in 802.11a is 6, 12, and 24 Mb/s. Therefore N_{DBPS_ACK} in (7) can be 24, 48, or 96, and can be different from N_{DBPS} in (6). Therefore the 134 bits in the acknowledgment in 802.11a require 6, 3, or 2

OFDM symbols, if it is transmitted at 6, 12, or 24 Mb/s, correspondingly. As a result T_{D_ACK} takes 44 μs, 32 μs, or 28 μs, correspondingly.

In our simulations we assume that the channel is perfect, i.e. there are no transmission errors. We also assume that stations have always data to transmit. If these assumptions are not true, the throughput will decrease. Furthermore it is assumed that the priority level is constant, i.e. there is no dynamic change of priority. Using these assumptions the throughput simulations have been carried out for all 8 different traffic categories. Figures from 2 to 9 and Tables from 6 to 13 in Appendix B, show the Simulation Plots and the throughput results for the respective plot for all TCs.

Throughput IEEE 802.11b EDCF

802.11b is a single-carrier physical layer, achieving data rates of 5.5 and 11 Mb/s, in addition to the data rates of 1 and 2 Mb/s of the original 802.11. There are two preambles: long, which is mandatory and short, which is optional. The long preamble length in bits is 144 bits, and in time is 144 μs, since it is sent at 1Mb/s. If the long preamble is used, then the header is also according to the original 802.11. The short preamble is provided in the standard precisely to increase the throughput. Therefore it is important to analyze the throughput when the short preamble is used. The short preamble is 72 bits at 1 Mb/s, or 72 μs. If the short preamble is used, the header is transmitted at 2 Mb/s, or in time 24 μs. Therefore for 802.11b there are two sets of physical layer parameters: $T_{\mathrm{Pr}eamble}$=144 μs , T_{H_PHY}= 48 μs, and $T_{\mathrm{Pr}eamble}$= 72 μs , T_{H_PHY}= 24 μs. The MAC data that follows the header is transmitted at 2, 5.5, or 11 Mb/s. The actual data rate used is denoted in the header. Therefore the transmission time for 802.11b is

$$T_{D\_DATA} = T_{\mathrm{Pr}eamble} + T_{H\_PHY} + \left(\frac{8*28+8*L_{DATA}}{1000000*R_{DATA}} \right) \quad (8),$$

and the time to transmit an acknowledgment, if required, is

$$T_{D\_ACK} = T_{\mathrm{Pr}eamble} + T_{H\_PHY} + \left(\frac{8*14}{1000000*R_{ACK}} \right) \quad (9).$$

Note that again the acknowledgment is transmitted at the control rate, which is smaller than or equal to the data rate of the packet. The 14 bytes of the acknowledgment can be transmitted at a data rate of either 1 or 2 Mb/s. Using the values given in the table above, the throughput performance for all 8 priority levels can be determined. Simulations have been carried out for one Traffic Category from each Access Category (AC) unlike as has been done for IEEE 802.11a in last section for all TCs. The reason is that as we can notice from the simulation results from IEEE 802.11a EDCF in the previous section, there is very small difference in throughput results of the TCs of the same Access Category. The throughput simulation plots and their respective throughput results for the given data rates are given in Figures 10 to 13 and tables 14 to 17 in Appendix B.

Throughput of IEEE 802.11g EDCF

Almost as soon as 802.11b and 802.11a were approved, work began on another physical layer for operation in the 2.4 GHz band. The requirement was at least to double the data rate of 802.11b, while achieving backwards compatibility with 802.11b. Another motivation was the change in FCC regulations. While previous regulations required spread-spectrum technology in the 2.4 GHz band, the new regulations allow any digital modulation to be used. In this section we evaluate the throughput only assuming the mandatory physical layer of 802.11g. (The two optional physical layers of 802.11g are not analysed in this paper.) The mandatory physical layer is in principal identical to 802.11a, but works in the 2.4 GHz band. 802.11g is the first standard for wireless data communications in the 2.4 GHz band which is not using spread-spectrum technology. Since 802.11a was standardized before 802.11g, and it was widely understood technology, the investment in 802.11a could be leveraged by using the same physical layer, and only changing the frequency band of operation. One small difference between 802.11a and 802.11g is that the SIFS for 802.11a is $16\mu s$ and the SIFS for 802.11g is $10\mu s$. 802.11a uses $16\mu s$ to allow enough time for the time-consuming convolutional decoding. To give 802.11g equipment the same time to perform convolutional decoding, an 802.11g packet is followed by $6\mu s$ of silence. The duration field of every packet includes this $6\mu s$ signal extension. This is called a virtual extension of SIFS. Therefore in the throughput evaluation formula SIFS is considered to be $16\mu s$. IEEE 802.11g specifies two slot times – 20 μs and optionally 9 μs. Again, the purpose of providing the short slot time is to increase the throughput. Therefore it is important to analyze what this increase is for 802.11e. With these assumptions, the simulations have been done for one Traffic category from different Access Categories (ACs). Figures 14 through 16 in Appendix B represent the throughput simulations for 802.11g throughputs.

5. THROUGHPUT UPPER LIMIT FOR IEEE 802.11e EDCF

One question worth asking is what will happen if the data rate that the physical layer provides is increased to infinity. Then the transmission of the actual data will take negligible amount of time. In the paper the throughput upper limit is derived for the original 802.11 MAC and the 802.11a and 802.11b physical layers. However, in deriving the throughput upper limit the authors assume that there still will be a preamble and a header, transmitted according to 802.11a and 802.11b, i.e. transmitted at 6 Mb/s in the case of 802.11a and 1 or 2 Mb/s in the case of 802.11b. This assumption is justified if backward compatibility at the physical layer is required. Therefore

$$T_{D\_DATA} = T_{D\_ACK} = T_{\mathrm{Pr}eamble} + T_{H\_PHY} \quad (11)\,.$$

Now assuming that the MAC protocol is 802.11e the throughput upper limit can be calculated. If backward compatibility at the physical layer and acknowledgment are required, the throughput upper limit as a function of the priority level is

$$TUL_1(TC) = \frac{8L_{DATA}}{\frac{CW_{\min}(TC)T_{slot}}{2} + T_{AIFS}(TC) + T_{SIFS} + 2\tau + 2T_{PREAMBLE} + 2T_{H-PHY}} \quad (12)$$

However, according to 802.11e an acknowledgment may not be required. One can readily notice that not requiring an acknowledgment can have a substantial effect on throughput, because according to () as the data rate goes to infinity, the time to transmit the actual data is equal to the time to transmit the acknowledgment. If an acknowledgment is not required then the throughput upper limit is

$$TUL_2(TC) = \frac{8L_{DATA}}{\frac{CW_{\min}(TC)T_{slot}}{2} + T_{AIFS}(TC) + \tau + T_{PREAMBLE} + T_{H-PHY}} \quad (13)\,.$$

Backwards compatibility is desirable so that legacy equipment can work with new equipment in a network. Legacy devices will decode the preamble and header and will not initiate transmissions as a result of the virtual carrier sense mechanism. The throughput achievable by new devices is lower. Therefore as the data rate goes to infinity it is not very efficient to have backwards compatibility at the physical layer. Vendors are aware of this tradeoff. It is also desirable to “turn-off” backwards compatibility to achieve higher throughput, for example when there are only new devices. Backwards compatibility can also be provided at a higher layer, e.g. the MAC layer. If backwards compatibility at the physical layer is “turned-off” then it can be assumed that the preamble and the header will also be transmitted at a data approaching infinity. Then, if an acknowledgment is still required the throughput upper limit is

$$TUL_3(TC)=\frac{8L_{DATA}}{\frac{CW_{\min}(TC)T_{slot}}{2}+T_{AIFS}(TC)+T_{SIFS}+2\tau} \quad (14),$$

and if an acknowledgment is not required the limit is

$$TUL_4(TC)=\frac{8L_{DATA}}{\frac{CW_{\min}(TC)T_{slot}}{2}+T_{AIFS}(TC)+\tau} \quad (15).$$

These are more useful estimates of the throughput limit, compared with the paper [], considering that in the next several years 802.11 will standardize new physical layers providing data rates in the order of 1 Gb/s. These physical layers will operate under the 802.11e protocol, which is exactly the case analyzed here.

The throughput limit is a function of the packet size and the traffic category. While the throughput limit does not depend on the data rate, it depends on certain physical layer parameters such as SIFS and slot time values. Tables 21, 22, and 23 shows the throughput upper limits for each traffic category, assuming the physical layer is 802.11a, 802.11b, and 802.11g.

6. MINIMUM DELAY AND DELAY LOWER LIMIT

It is also of interest to analyze the minimum delay that 802.11e provides. It is independent of the data rate, and moreover it is also independent of the payload size. The minimum delay as a function of the traffic category is

$$MD(TC)=\frac{CW_{\min}T_{SLOT}}{2}+T_{AIFS}(TC)+T_{D\_DATA}+\tau \quad (16).$$

The delay lower limit can be calculated in a manner similar to the calculation of the throughput upper limit. As the data rate approaches infinity T_{D_DATA} will consist of only preamble and header time periods in the backwards-compatible case. Therefore the delay lower limit is

$$DLL_1(TC)=\frac{CW_{\min}T_{SLOT}}{2}+T_{AIFS}(TC)+T_{PREAMBLE}+T_{H-PHY}+\tau \quad (17).$$

In the high-throughput case the preamble and the header are also transmitted at a data rate that approaches infinity. Then the delay lower limit is

$$DLL_2(TC) = \frac{CW_{\min} T_{SLOT}}{2} + T_{AIFS}(TC) + \tau \text{ .}$$

Tables () contain the minimum delay and the delay lower limit for the three different physical layers considered here.

7. CONCLUSION

In this paper, we have proved that the IEEE 802.11e EDCF mechanism provides Quality of Service (QoS) by using prioritized data transfers. From the simulation plots and tables, it is clear that the throughput rate is higher for the higher priory data, e.g. voice and video. Higher throughput rate helps providing QoS for the real time applications. We have also proved that by simply increasing the data rate without reducing overhead, the maximum achievable throughput is bounded even when the data rate goes to infinite high. To achieve higher throughput, overhead needs to be reduced.

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APPENDIX A - NOTATIONS

AC	Access Category
ACK	Acknowledgement
AIFS	Arbitration Inter Frame Space
AP	Access Point
CA	Collision Avoidance
CDF	Complementary Cumulative Distribution Function
CFP	Contention Free Period
CF-Poll	Contention Free-Poll
CF-End	Contention Free-End
CP	Contention Period
CSMA	Carrier Sense Multiple Access
CW	Contention Window
CW_{max}	Contention Window Maximum
CW_{min}	Contention Window Minimum
DCF	Distributed Coordination Function
EDCF	Enhanced Distributed Coordination Function
HC	Hybrid Coordinator
HCF	Hybrid Coordination Function
ISM	Industrial, Science, Medical
MAC	Medium Access Control
MDSU	MAC Service Data Unit
NAV	Network Allocation Vector
PC	Point Coordinator
PCF	Point Coordination Function
PF	Persistence Factor
PIFS	PCF Inter Frame Space
QoS	Quality of Service
SIFS	Short Inter Frame Space
TC	Traffic Category
TXOP	Transmission Opportunity
WLAN	Wireless Local Area Network

APPENDIX B - SIMULATION PLOTS AND TABLES

IEEE 802.11a EDCA

Traffic Category 1

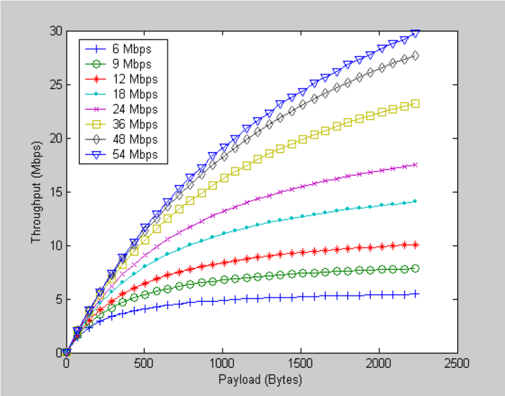


Fig 2. Throughput for 802.11a TC1

For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.43
9	7.83
12	10.05
18	14.04
24	17.50
36	23.24
48	27.72
54	29.75

Table 3. Throughput results for 802.11a TC1

Traffic category 2

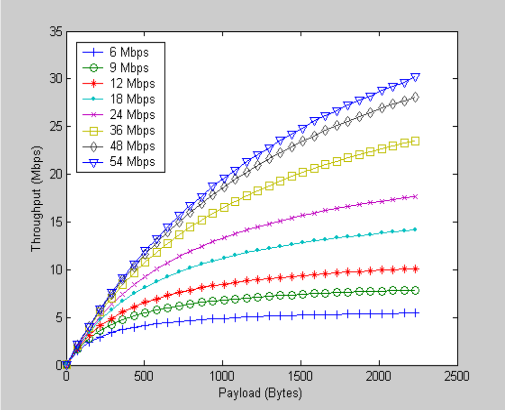
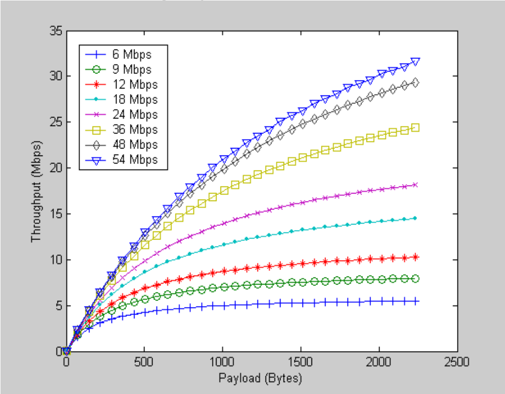


Fig 3. Throughput for 802.11TC2

For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.45
9	7.86
12	10.11
18	14.14
24	17.66
36	23.52
48	28.11
54	30.20

Table 4. Throughput results for 802.11a TC2

Traffic Category 0

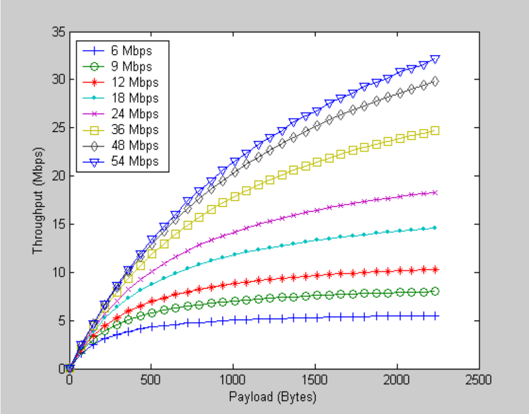


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.50
9	7.96
12	10.26
18	14.45
24	18.15
36	24.39
48	29.36
54	31.65

Fig 4. Throughput for 802.11a TC0

Table 5. Throughput results for 802.11a TC0

Traffic Category 3

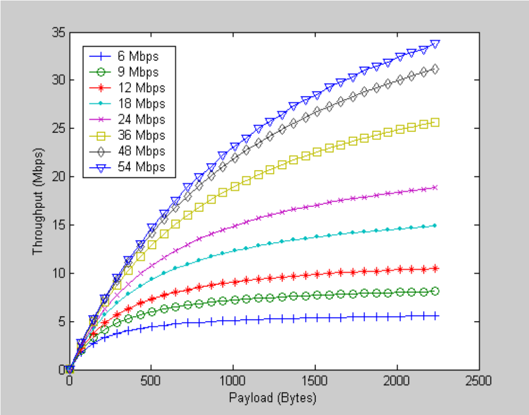


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.51
9	7.99
12	10.32
18	14.55
24	18.31
36	24.69
48	29.80
54	32.16

Fig 5. Throughput for 802.11a TC3

Table 6. Throughput results for 802.11a TC3

Traffic Category 4

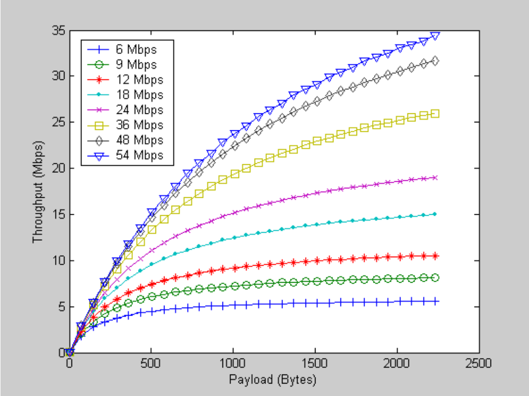


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.56
9	8.09
12	10.48
18	14.88
24	18.83
36	25.65
48	31.20
54	33.80

Fig 6. Throughput for 802.11a TC4

Table 7. Throughput results for 802.11a TC4

Traffic Category 5

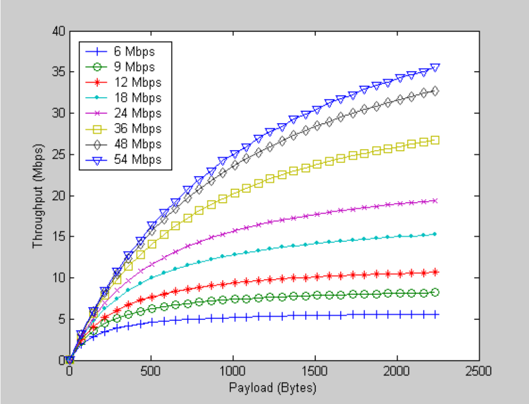


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.58
9	8.12
12	10.54
18	14.99
24	19.01
36	25.98
48	31.70
54	34.39

Fig 7. Throughput for 802.11a TC5

Table 8. Throughput results for 802.11a TC5

Traffic Category 6

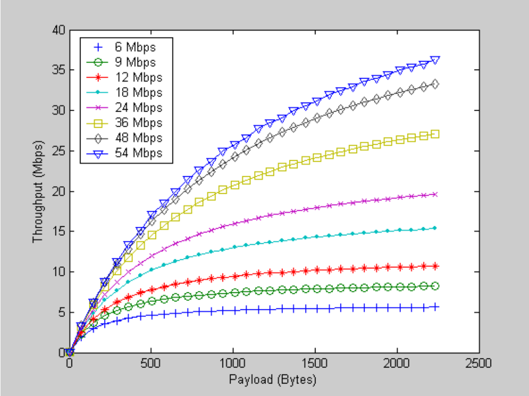


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.61
9	8.19
12	10.65
18	15.22
24	19.39
36	26.68
48	32.75
54	35.62

Fig 8. Throughput for 802.11a TC 6

Table 9. Throughput results for 802.11a TC6

Traffic Category 7



For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.62
9	8.22
12	10.70
18	15.34
24	19.58
36	27.05
48	33.20
54	36.27

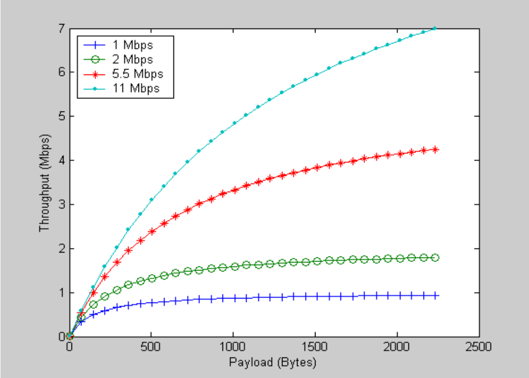
Fig 9. Throughput for 802.11a TC 7

Table 10. Throughput results for 802.11a TC 7

IEEE 802.11b EDCA

LONG PREAMBLE ($T_{Preamble}$= 144 microsec, T_{H_PHY}=48 microsec)

Traffic Category 1

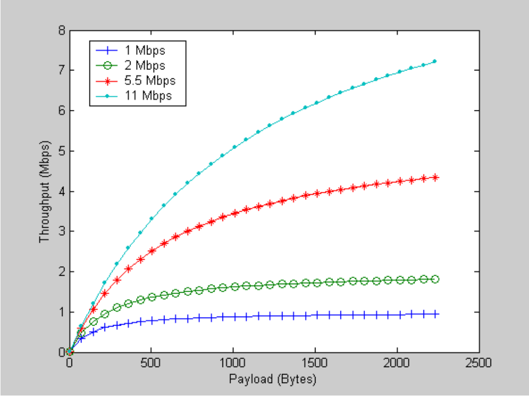


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.94
2	1.79
5.5	4.25
11	6.99

Fig 10. Throughput for 802.11b TC 1

Table 11. Throughput results for 802.11b TC 1

Traffic Category 0

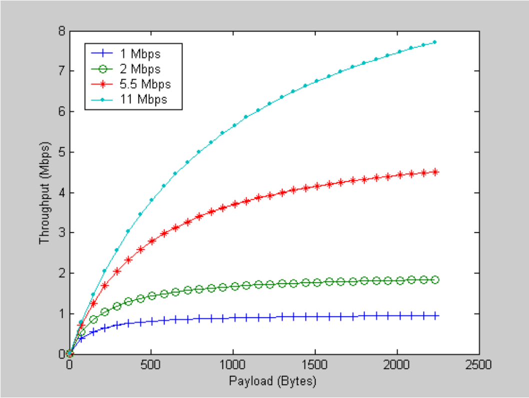


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.94
2	1.81
5.5	4.33
11	7.21

Fig 11. Throughput for 802.11b TC 0

Table 12. Throughput results for 802.11b TC 0

Traffic Category 4

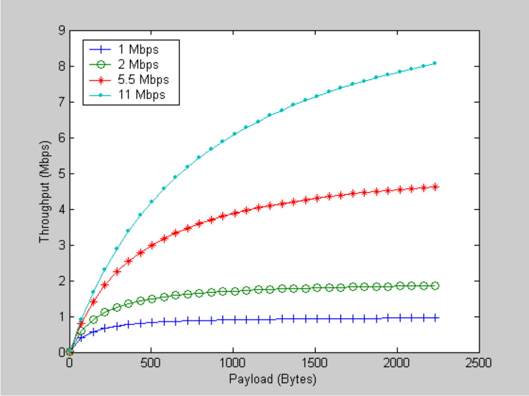


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.95
2	1.84
5.5	4.51
11	7.71

Fig 12. Throughput for 802.11b TC 4

Table 13. Throughput results for 802.11b TC 4

Traffic Category 6



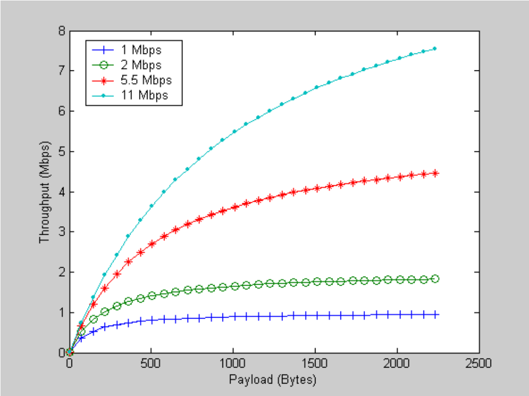
For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.95
2	1.86
5.5	4.63
11	8.06

Fig 13. Throughput for 802.11b TC 6

Table 14. Throughput results for 802.11b TC 6

SHORT PREAMBLE ($T_{Preamble}$= 72 microsec, T_{H_PHY}=24 microsec)

Traffic Category 1

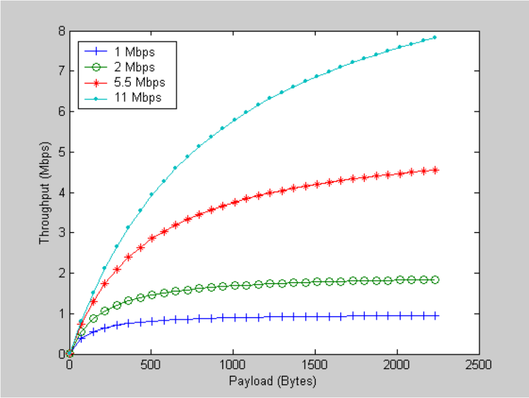


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.95
2	1.83
5.5	4.46
11	7.55

Fig 14. Throughput for 802.11b TC 1

Table 15. Throughput results for 802.11b TC 1

Traffic Category 0

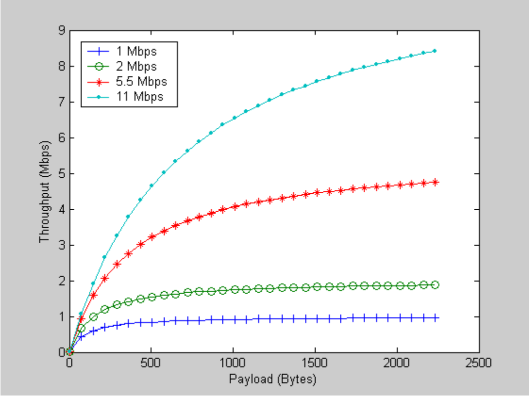


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.95
2	1.84
5.5	4.55
11	7.82

Fig 15. Throughput for 802.11b TC 0

Table 16. Throughput results for 802.11b TC 0

Traffic Category 4

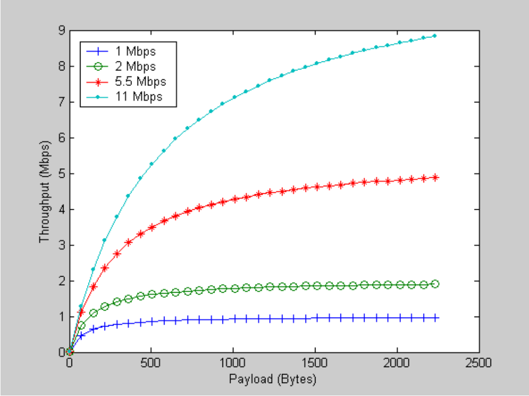


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.96
2	1.88
5.5	4.74
11	8.41

Fig 16. Throughput for 802.11b TC 4

Table 17. Throughput results for 802.11b TC 4

Traffic Category 6



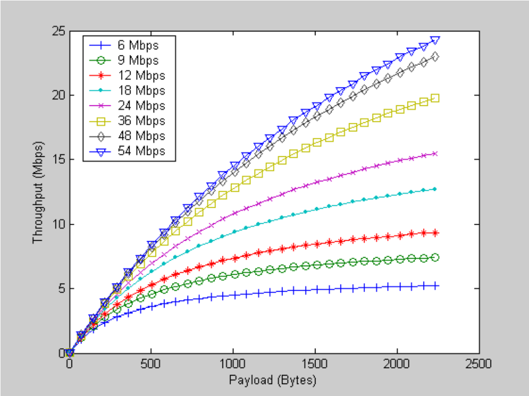
For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
1	0.96
2	1.90
5.5	4.87
11	8.82

Fig 17. Throughput for 802.11b TC 6

Table 18. Throughput results for 802.11b TC 6

IEEE 802.11g EDCA
WITH T_{SLOT} = 20 microsec

Traffic Category 2

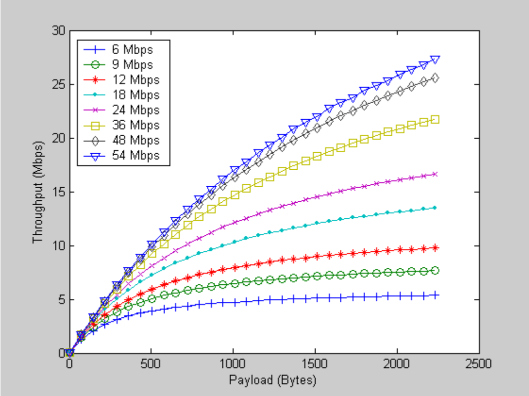


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.23
9	7.40
12	9.35
18	12.71
24	15.48
36	19.81
48	22.96
54	24.34

Fig 18. Throughput for 802.11g TC 2

Table 19. Throughput results for 802.11g TC 2

Traffic Category 3



For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.35
9	7.65
12	9.76
18	13.47
24	16.63
36	21.73
48	25.60
54	27.32

Fig 19. Throughput for 802.11g TC 3

Table 20. Throughput results for 802.11g TC 3

Traffic Category 5

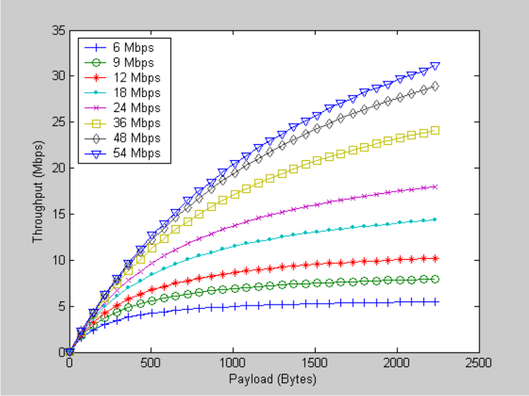


Fig 20. Throughput for 802.11g TC 5

For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.48
9	7.93
12	10.21
18	14.34
24	17.97
36	24.08
48	28.91
54	31.12

Table 21. Throughput results for 802.11g TC 5

Traffic Category 7

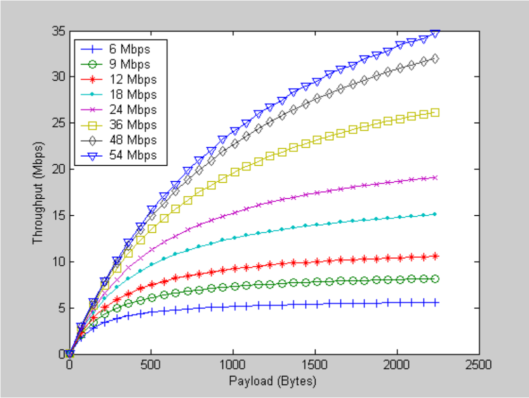


Fig 21. Throughput for 802.11g TC 7

For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.59
9	8.14
12	10.57
18	15.06
24	19.13
36	26.19
48	32.01
54	34.75

Table 22. Throughput results for 802.11g TC 7

IEEE 802.11g EDCA
WITH T_{SLOT} = 9 microsecond

Traffic Category 2

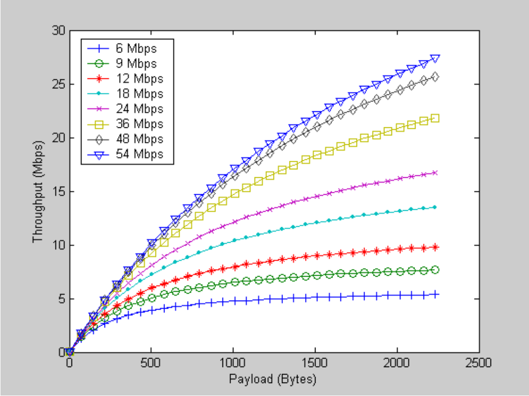
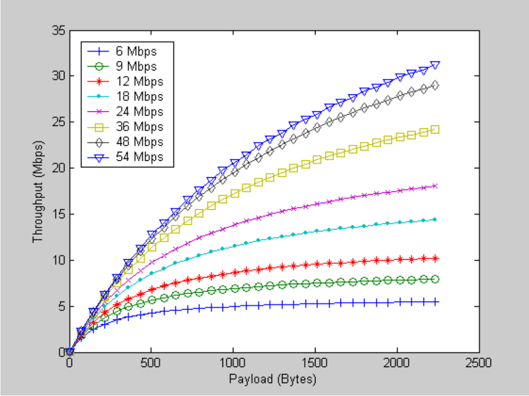


Fig 22. Throughput for 802.11g TC 2

For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.36
9	7.66
12	9.77
18	13.50
24	16.67
36	21.80
48	25.69
54	27.42

Table 23. Throughput results for 802.11g TC 2

Traffic Category 3

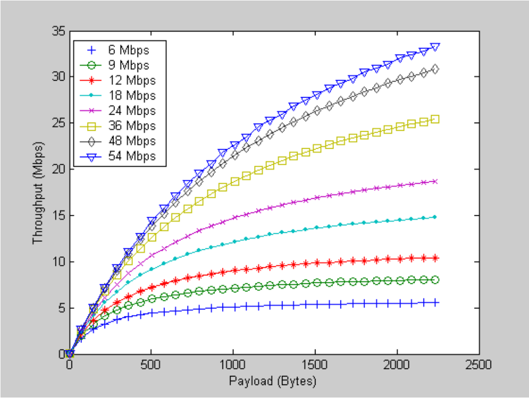


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.49
9	7.93
12	10.22
18	14.37
24	18.02
36	24.16
48	29.02
54	31.26

Fig 23. Throughput for 802.11g TC 3

Table 24. Throughput results for 802.11g TC 3

Traffic Category 5

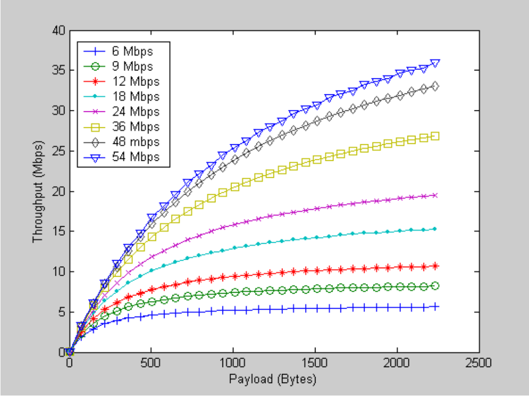


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.55
9	8.06
12	10.44
18	14.79
24	18.70
36	25.39
48	30.83
54	33.36

Fig 24. Throughput for 802.11g TC 5

Table 25. Throughput results for 802.11g TC 5

Traffic Category 7

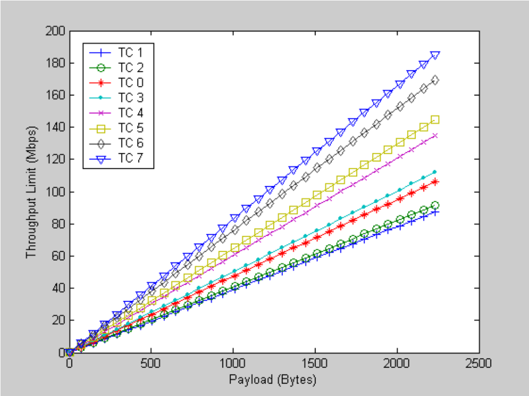


For 2304 bytes payload	
Data Rate (Mbps)	**Throughput (Mbps)**
6	5.62
9	8.20
12	10.68
18	15.28
24	19.47
36	26.84
48	32.99
54	35.91

Fig 25. Throughput for 802.11g TC 7

Table 26. Throughput results for 802.11g TC 7

Throughput Limit
IEEE 802.11a EDCA (CASE 1: WITH ACK)

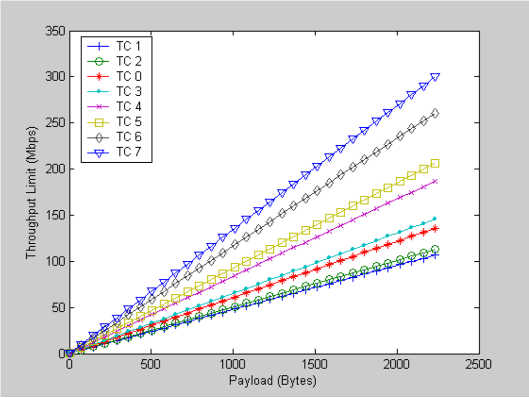


Traffic Category	Throughput Limit (Mbps)
1	87.36
2	91.38
0	106.02
3	112
4	134.82
5	144.65
6	169.33
7	185.12

Fig 26. Throughput limit for 802.11a

Table 27. Throughput limit results for 802.11a

IEEE 802.11a EDCA (CASE 2: WITHOUT ACK)

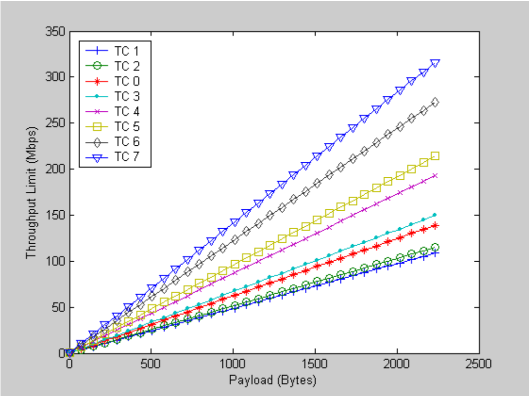


Traffic Category	Throughput Limit (Mbps)
1	106.65
2	112.71
0	135.85
3	145.83
4	187.06
5	206.52
6	260.79
7	300.24

Fig 27. Throughput limit for 802.11a

Table 28. Throughput limit results for 802.11a

IEEE 802.11a EDCA (CASE 3: WITH ACK AND $T_{Preamble}$ & T_{H_PHY} INFINITE)

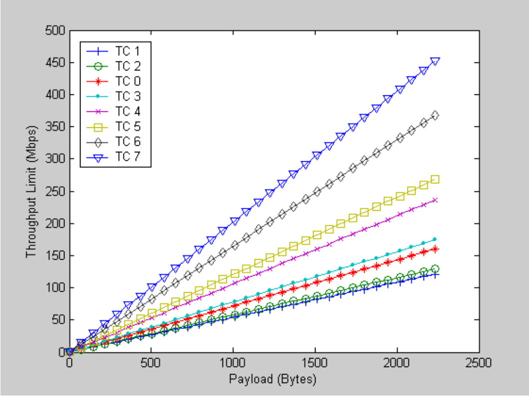


Traffic Category	Throughput Limit (Mbps)
1	108.6
2	114.88
0	139.02
3	149.49
4	193.12
5	213.94
6	272.73
7	316.18

Fig 28. Throughput limit for 802.11a

Table 29. Throughput limit results for 802.11a

IEEE 802.11a EDCA (CASE 4: WITHOUT ACK AND $T_{Preamble}$ & T_{H_PHY} INFINITE)

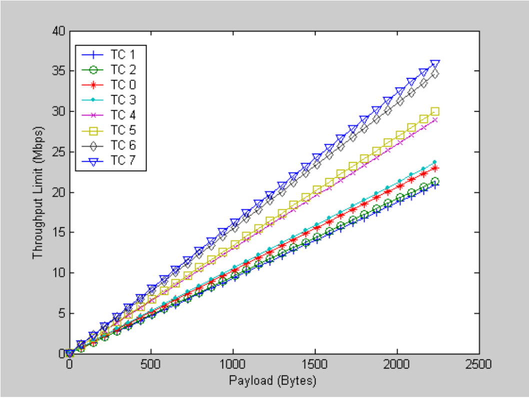


Traffic Category	Throughput Limit (Mbps)
1	121.11
2	128.98
0	160.22
3	174.28
4	236.61
5	268.63
6	368.33
7	452.25

Fig 29. Throughput limit for 802.11a

Table 30. Throughput limit results for 802.11a

IEEE 802.11b EDCA (CASE 1: WITH ACK)

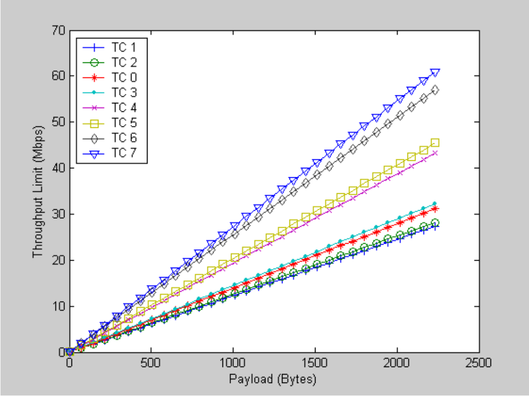


Traffic Category	Throughput limit (Mbps)
1	20.87
2	21.37
0	23.02
3	23.63
4	29
5	29.97
6	34.62
7	36.02

Fig 30. Throughput limit for 802.11b

Table 31. Throughput limit results for 802.11b

IEEE 802.11b EDCA (CASE 2: WITHOUT ACK)

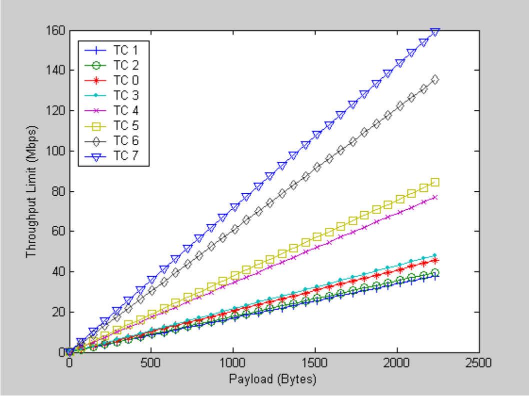


Traffic Category	Throughput limit (Mbps)
1	27.36
2	28.22
0	31.18
3	32.30
4	43.25
5	45.46
6	57.07
7	60.97

Fig 31. Throughput limit for 802.11b

Table 32. Throughput limit results for 802.11b

IEEE 802.11b EDCA (CASE 3: WITH ACK AND $T_{Preambple}$ & T_{H_PHY} INFINITE)

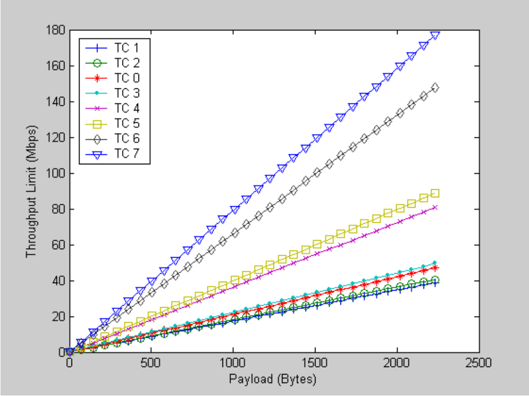


Traffic Category	Throughput limit (Mbps)
1	37.85
2	39.52
0	45.57
3	48.02
4	77.00
5	84.26
6	135.53
7	159.50

Fig 32. Throughput limit for 802.11b

Table 33. Throughput limit results for 802.11b

IEEE 802.11b EDCA (CASE 4: WITHOUT ACK AND $T_{Preambple}$ & T_{H_PHY} INFINITE)

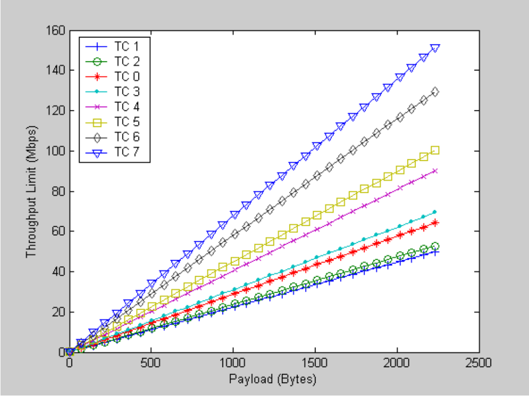


Traffic Category	Throughput limit (Mbps)
1	38.75
2	40.51
0	46.89
3	49.49
4	80.83
5	88.87
6	147.64
7	176.87

Fig 33. Throughput limit for 802.11b

Table 34. Throughput limit results for 802.11b

IEEE 802.11g EDCA (CASE 1: WITH ACK)

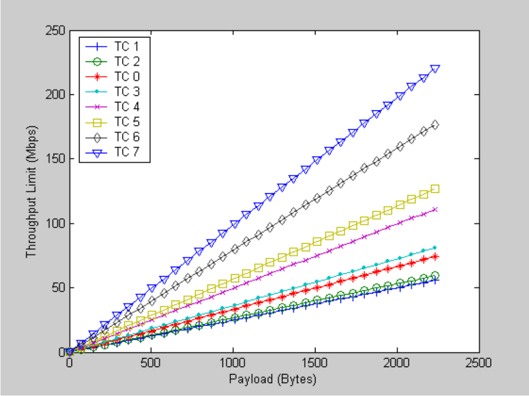


Traffic Category	Throughput limit (Mbps)
1	49.90
2	52.85
0	64.26
3	69.24
4	90.22
5	100.36
6	129.45
7	151.39

Fig 34. Throughput limit for 802.11g

Table 35. Throughput limit results for 802.11g

IEEE 802.11g EDCA (CASE 2: WITHOUT ACK)

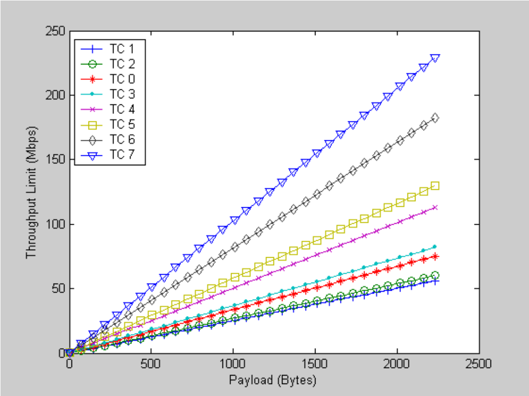


Traffic Category	Throughput limit (Mbps)
1	55.65
2	59.35
0	74.12
3	80.83
4	110.96
5	126.70
6	176.87
7	220.54

Fig 35. Throughput limit for 802.11g

Table 36. Throughput limit results for 802.11g

IEEE 802.11g EDCA (CASE 3: WITH ACK AND $T_{Preamble}$ & T_{H_PHY} INFINITE)

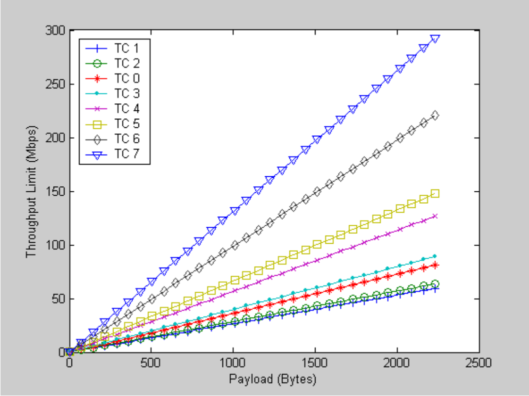


Traffic Category	Throughput limit (Mbps)
1	56.18
2	59.95
0	75.06
3	81.95
4	113.06
5	129.45
6	182.29
7	229.03

Fig 36. Throughput limit for 802.11g

Table 37. Throughput limit results for 802.11g

IEEE 802.11g EDCA (CASE 3: WITH ACK AND $T_{Preamble}$ & T_{H_PHY} INFINITE)



Traffic Category	Throughput limit (Mbps)
1	59.35
2	63.57
0	80.83
3	88.88
4	126.70
5	147.64
6	220.54
7	292.85

Fig 37. Throughput limit for 802.11g

Table 38. Throughput limit results for 802.11g

DELAY LOWER LIMIT

IEEE 802.11a EDCA

(CASE 1: Preamble & Header not infinite)

TC	Minimum Delay (milisec)
0	0.168
1	0.159
2	0.132
3	0.123
4	0.096
5	0.087
6	0.069
7	0.060

Table 39. Delay Lower Limit case 1 802.11a

(CASE 2: Preamble & Header infinite)

TC	Minimum Delay (milisec)
0	0.148
1	0.139
2	0.112
3	0.103
4	0.076
5	0.067
6	0.049
7	0.040

Table 40 Delay Lower Limit case 2 for 802.11a

IEEE 802.11b EDCA

(CASE 1: Preamble & Header not infinite)

TC	Minimum Delay (milisec)
0	0.653
1	0.633
2	0.573
3	0.553
4	0.413
5	0.393
6	0.313
7	0.293

Table 41 Delay Lower Limit case 1 for 802.11b

(CASE 2: Preamble & Header infinite)

TC	Minimum Delay (milisec)
0	0.461
1	0.441
2	0.381
3	0.361
4	0.221
5	0.201
6	0.121
7	0.101

Table 42 Delay Lower Limit case 2 for 802.11b

IEEE 802.11g EDCA

(CASE 1: Preamble & Header not infinite)

TC	Minimum Delay (milisec)
0	0.321
1	0.301
2	0.241
3	0.221
4	0.161
5	0.141
6	0.101
7	0.081

Table 43 Delay Lower Limit case 2 for 802.11g

(CASE 2: Preamble & Header infinite)

TC	Minimum Delay (milisec)
0	0.301
1	0.281
2	0.221
3	0.201
4	0.141
5	0.121
6	0.081
7	0.061

Table 44 Delay Lower Limit case 2 for 802.11g