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Throughput Analysis of Numerous Wi-Fi Technologies

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ABSTRACT

In just the past few years, wireless LANs have come to occupy a significant niche in the local area network market. Increasingly, organizations are finding that wireless LANs are an indispensable adjunct to traditional wired LANs, to satisfy requirements for mobility, relocation, ad hoc networking, and coverage of locations difficult to wire. One of the key drivers of this new market expansion for WLANs is the IEEE 802.11 (Wi-Fi) standard. The main contribution of this project is the exact calculation of the theoretical maximum throughput for a variety of IEEE 802.11 technologies. This formula 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.

Keywords: CSMA/CA, WLAN, RTS/CTS, Throughput, Inter-frame space, Ad hoc network.

1. Introduction

In 1997 the IEEE adopted the first standard for WLANs, IEEE Std 802.11-1997. This standard was revised in 1999. IEEE Std 802.11-1997 defines a medium access control (MAC) sublayer, MAC management protocols and services, and three physical (PHY) layers [14]. The three PHY layers are an infrared (IR) baseband PHY, a frequency hopping spread spectrum (FHSS) radio in the 2.4 GHz band, and a direct sequence spread spectrum (DSSS) radio in the 2.4 GHz band. All three physical layers describe both 1 and 2 Mbps operation. Later, IEEE 802.11 working group is developed another two PHY layers [23]. The first, IEEE Std 802.11a, is an orthogonal frequency domain multiplexing (OFDM) radio in the UNI bands, delivering up to 54 Mbps data rates. The second, IEEE Std 802.11b, is an extension to the DSSS PHY in the 2.4 GHz band, delivering up to 11 Mbps data rates.

The goals of the IEEE 802.11 standard is to describe a WLAN that delivers services previously found only in wired networks, e.g., high throughput, highly reliable data delivery, and continuous network connections. In addition, IEEE 802.11 describes a WLAN that allows transparent mobility and built-in power saving operations to the network user.

2. Literature Review

The emergence of wireless LANs (WLANs) brings the benefits of user mobility and flexible network deployment in local area computing. With mobility, a network client can migrate between different physical locations within the LAN environment without losing connectivity. A more compelling advantage of wireless LANs is the flexibility to reconfigure or to add more nodes to the network without much planning effort and cost of recabling, thereby making future upgrades inexpensive and easy. The ability to cope with a dynamic LAN population generated by mobile users and portable computing devices is another major consideration for choosing a wireless LAN. Thus, the widespread use of notebook computers and handheld personal digital assistants has led to an increased dependence on wireless LANs in recent years.

2.1. WLAN Configuration

A typical wireless LAN configuration is shown in figure 1 [18]. There is an access point which connects wireless LAN to wired LAN. The access point receives, buffers, and transmits data packets between the WLAN and the wired network infrastructure. A single access point can support a small group of mobile nodes and can function within a range of few hundred meters.

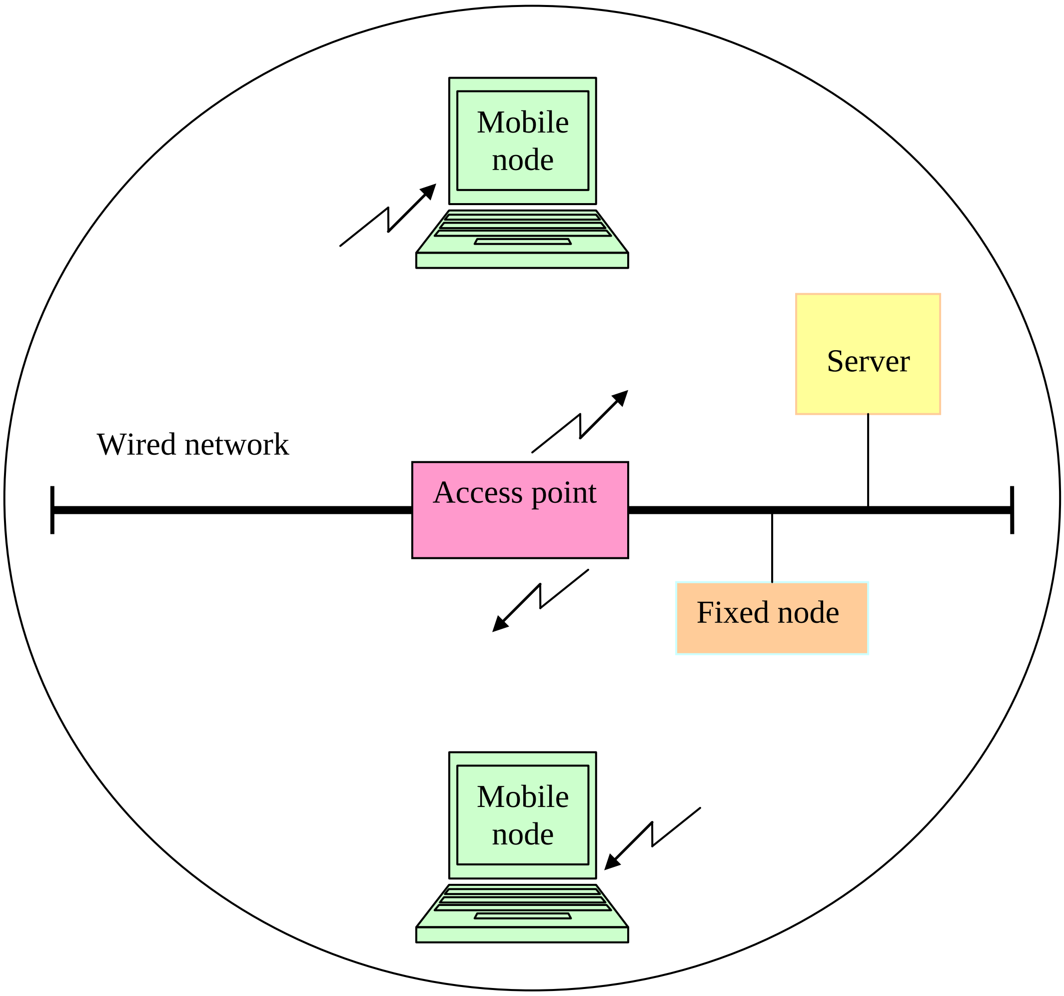

Figure 1: A typical WLAN configuration

The antenna attached to the access point is usually mounted high but may also be placed anywhere that is practical as long as the desired radio coverage is obtained. End-user devices communicate with the access point through wireless LAN adapters which are implemented as PC cards in notebook computers, ISA or PCI cards in desktop computers, or fully integrated devices within handheld computers and printers.

2.2. WLAN Technology

According to transmission technique wireless LAN can be categorized as following technology [8]:

1. **Infrared (IR) LANs**
2. **Spread spectrum LANs**
3. **Narrowband microwave**

Infrared LANs: Infrared light cannot penetrate opaque walls. Therefore, an individual cell of an IR LAN is limited to a single room.

Spread spectrum LANs: This type of LAN makes use of spread spectrum transmission technology. In most cases, these LANs operate in the ISM (Industrial, Scientific, and Medical) bands so that no FCC licensing is required for their use in the United States.

Narrowband microwave: These LANs operate at microwave frequencies but do not use spread spectrum. Some of these products operate at frequencies that require FCC licensing, while others use one of the unlicensed ISM bands.

2.3. IEEE 802.11 Physical Layer

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At the bottom of the OSI stack is the PHY as shown in figure 2. The PHY is the interface between the MAC and wireless media, which transmits and receives data frames over a shared wireless media. The PHY provides three levels of functionality [10]. First, the PHY layer provides a frame exchange between the MAC and PHY under the control of the physical layer convergence protocol (PLCP) sublayer. Secondly, the PHY uses signal carrier and spread spectrum modulation to transmit data frames over the media under the control of the physical medium dependent (PMD) sublayer. Thirdly, the PHY provides a carrier sense indication back to the MAC to verify activity on the media. Each of the PHYs is unique in terms of modulation type and designed to coexist with each other and operate with the MAC.

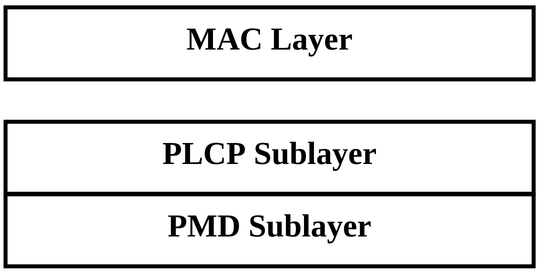

Figure 2: Bottom of the OSI model

The physical layer for IEEE 802.11 has been issued in three stages; the first part was issued in 1997 and the remaining two parts in 1999. The first part, simply called IEEE 802.11, includes the MAC layer and three physical layer specifications, two in the 2.4 GHz band and one in the infrared, all operating at 1 and 2 Mbps. IEEE 802.11a operates in the 5 GHz band at data rates up to 54 Mbps. IEEE 802.11b operates in the 2.4 GHz band at 5.5 and 11 Mbps.

2.3.1. IEEE 802.11a

The IEEE 802.11a PHY is one of the physical layer (PHY) extensions of IEEE 802.11 and is referred to as the orthogonal frequency division multiplexing (OFDM) PHY. The OFDM PHY provides the capability to transmit PSDU frames at multiple data rates up to 54 Mbps for WLAN networks where transmission of multimedia content is a consideration.

The IEEE 802.11a specification makes use of the 5 GHz band. The possible data rates for IEEE 802.11a are 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. The system uses up to 52 subcarriers that are modulated using BPSK, QPSK, 16-QAM, or 64-QAM, depending on the rate required [8], [22].

2.3.2. IEEE 802.11b

The IEEE 802.11b PHY is one of the PHY layer extensions of IEEE 802.11 and is referred to as high-rate direct sequence spread spectrum (HR-DSSS). The HR-DSSS provides two functions. Firstly, the HR-DSSS extends the PSDU data rates to 5.5 Mbps and 11 Mbps using an enhanced modulation technique. Secondly, the HR-DSSS PHY provides a rate shift mechanism, which allows 11 Mbps networks to fall back to 1 and 2 Mbps and interoperate with the legacy IEEE 802.11 2.4 GHz RF PHY layers [14].

Chipping rate of 802.11b is 11 MHz, which is the same as the original DSSS scheme, thus providing the same occupied bandwidth [8]. To achieve a higher data rate in the same bandwidth at the same chipping rate, a modulation scheme known as complementary code keying (CCK) is used.

3. Timing Intervals

The IEEE 802.11 MAC recognizes five timing intervals or interframe spaces (IFSs). These are: slot time, short IFS (SIFS), point coordination function IFS (PIFS), distributed coordination function IFS (DIFS) and extended IFS (EIFS).

Slot time: Slot time corresponds to a time slot used for backoff purposes [2]. Slot time is smaller than any other IFSs other than SIFS. Slot time is the sum of the channel assessment (carrier sensing) time, the transceiver turnaround time, the signal propagation delay, and the MAC processing delay [18].

SIFS: The SIFS is the shortest IFS and is used for all immediate response actions (e.g., transmission of ACK, RTS, CTS packets). SIFS is a function of the receiver delay, delay in decoding the PLCP preamble/ header, the transceiver turnaround time and the MAC processing delay.

PIFS: The PIFS is an intermediate length IFS that is used for polling nodes with time bounded requirements. The PIFS is equal to the SIFS plus one slot time.

DIFS: DIFS is used as a minimum delay between successive data packets. The DIFS is equal to the SIFS plus two slot times.

EIFS: The EIFS is much larger than any other intervals. It is used when a frame that contains errors is received by the MAC, allowing the possibility for the MAC frame exchanges to complete correctly before another transmission is allowed [14].

Figure 3 describes various timing intervals. Through these five timing intervals, both the distributed coordination function (DCF) and point coordination function (PCF) are implemented.

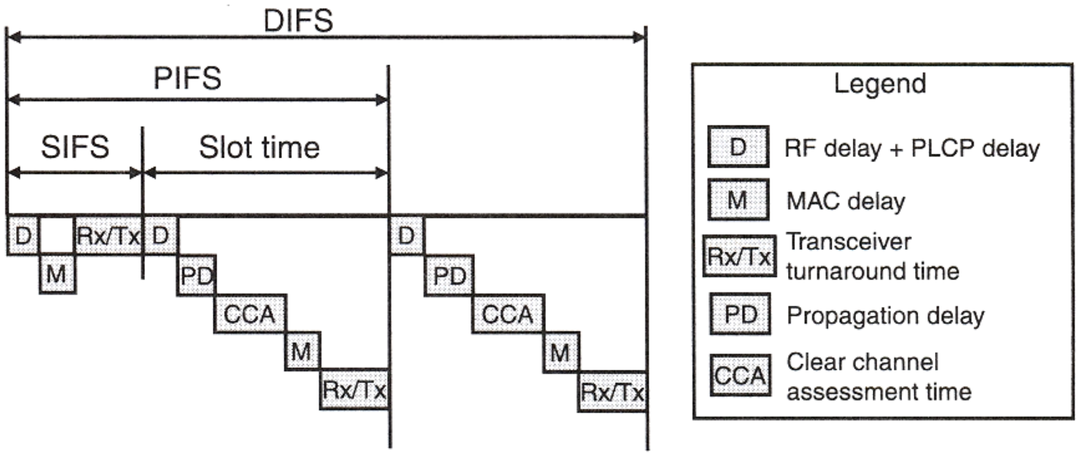

Figure 3: Inter-frame space definitions

4. Maximum Throughput of IEEE 802.11

The main contribution of this section is to present the calculation of the theoretical maximum throughput for IEEE 802.11 networks, for a number of technologies such as 802.11, 802.11b, 802.11a. Here, we determine the theoretical maximum throughput as a function of different parameters and provide an easy way to estimate it numerically. All of the information for the calculation of these data rates is available in the IEEE standards [8], [11], [19]. However, it is a laborious procedure gathering data from various standards and a thorough understanding of the mechanisms presented in the standard.

We define the upper limit of the throughput that can be achieved in an IEEE 802.11 network as its theoretical maximum throughput (TMT). In the subsequent sections we might omit the word 'theoretical', but keep in mind that we are discussing about theoretical maximum throughput. Since the 802.11 standard covers the medium access control (MAC) layer and physical (PHY) layer in terms of the OSI (Open System Interconnection) reference model [13], we are interested in the actual throughput provided by the MAC layer. Therefore, the theoretical maximum throughput of 802.11 can also be defined as the maximum amount of MAC layer service data units that can be transmitted in a time unit.

4.1. Classification for Maximum Throughput

To compute theoretical maximum throughput we need to classify various methods since various standards specifies different values for timing intervals (SIFS, DIFS, PIFS, EIFS), minimum contention window size etc. There are two sets for which we could calculate maximum throughput. Those are:

1. Carrier Sense Multiple Access / Collision avoidance (CSMA/CA)
2. Request to Send / Clear to Send (RTS/CTS)

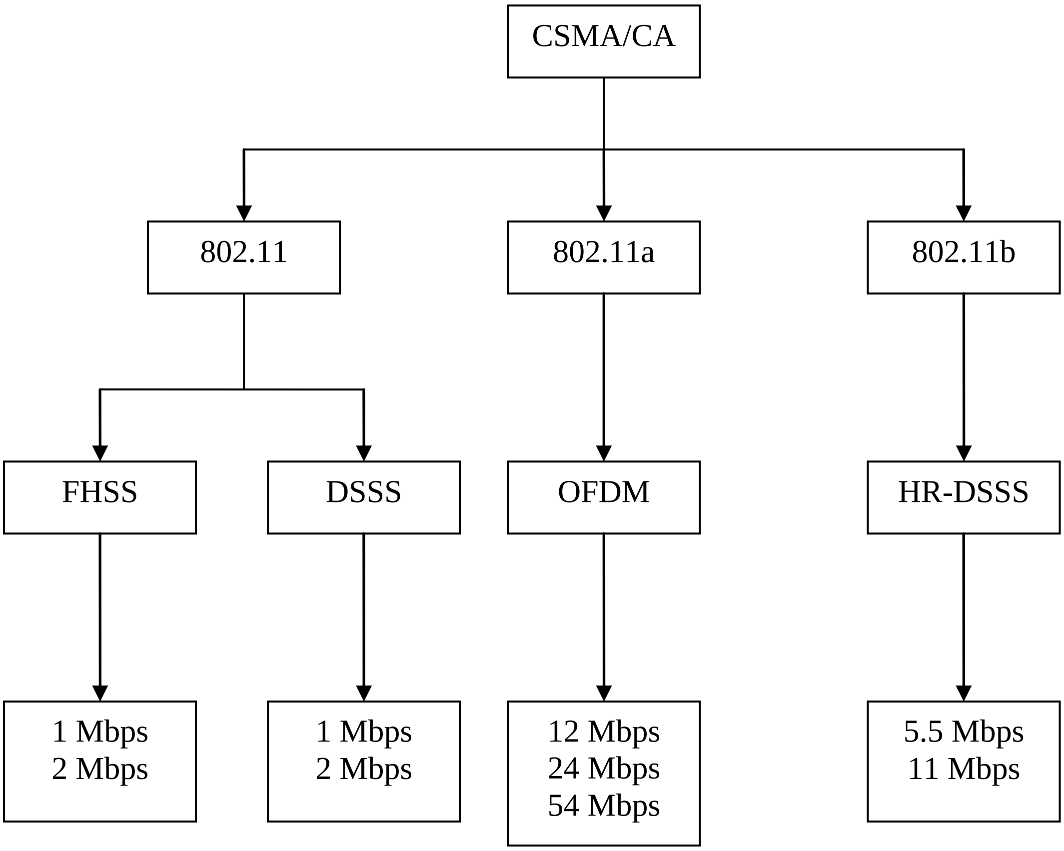

Figure 4: Classification of CSMA/CA for Maximum Throughput

Figure 4 shows the classification of CSMA/CA to compute maximum throughput. Here four classifications are made for three different MAC groups (802.11, 802.11a, 802.11b) according to modulation techniques. Four classifications are Frequency Hopping Spread Spectrum (FHSS) for 1 and 2 Mbps, Direct Sequence Spread Spectrum (DSSS) for 1 and 2 Mbps, Orthogonal Frequency Division Multiplexing (OFDM) for 12, 24 and 54 Mbps, High Rate DSSS (HR-DSSS) for 5.5 and 11 Mbps. Similar Classification made for RTS/CTS which is shown in Figure 5.

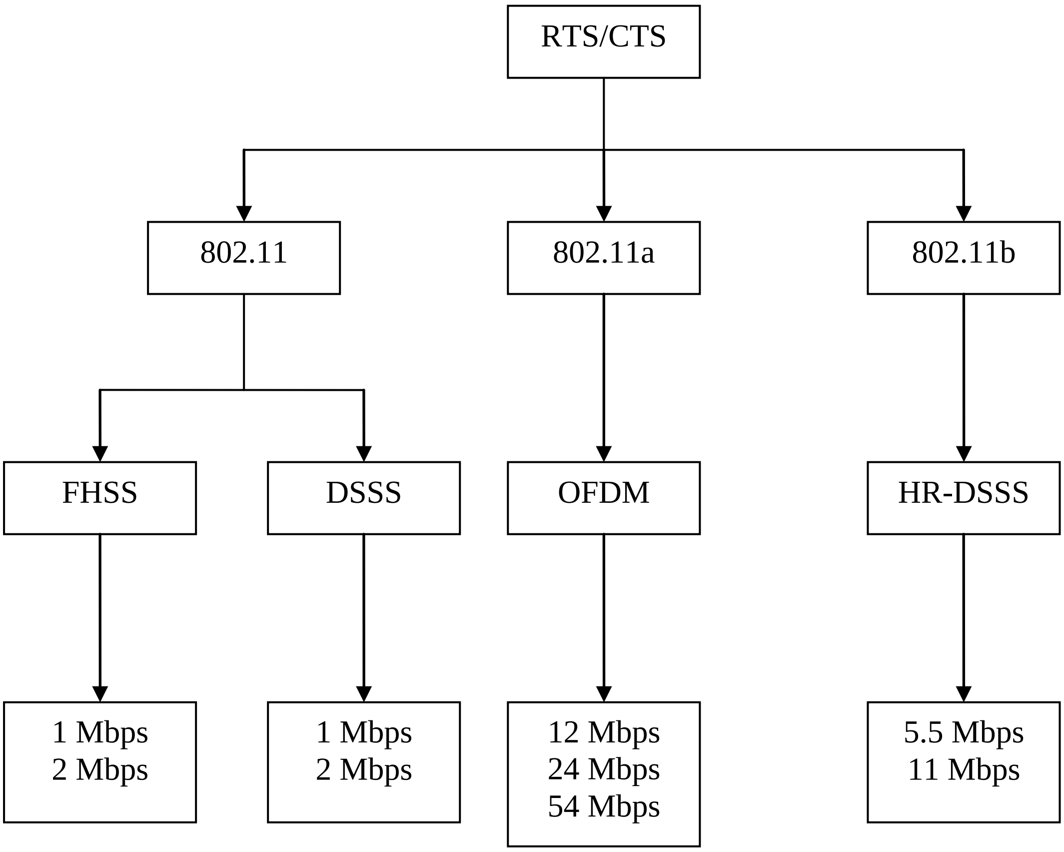

Figure 5: Classification of RTS/CTS for Maximum Throughput

4.2. Overheads at Sublayers

When a higher layer pushes packet down to the MAC layer as an MSDU (MAC Service Data Unit), overheads added at each intermediate layer [8], [14]. To compute maximum throughput we consider overheads added at each sublayers (Figure 6). The IEEE 802.11 covers both Medium Access Control (MAC) and Physical (PHY) layer of OSI reference model [13]. At the bottom of the OSI stack is the PHY (Figure 7). The PHY provides three levels of functionality [14]. First, the PHY layer provides a frame exchange between the MAC and PHY under the control of the physical layer convergence protocol (PLCP) sublayer. Secondly, the PHY uses signal carrier and spread spectrum modulation to transmit data frames over the media under the control of the physical medium dependent (PMD) sublayer. Thirdly, the PHY provides a carrier sense indication back to the MAC to verify activity on the media. At the MAC layer, the MAC header added before MSDU and trailer (FCS) added after MSDU. Similarly, PLCP preamble and PLCP header are attached to the MPDU at the PLCP sublayer. Again, various inter frame spaces are added depending on the type of MPDU.

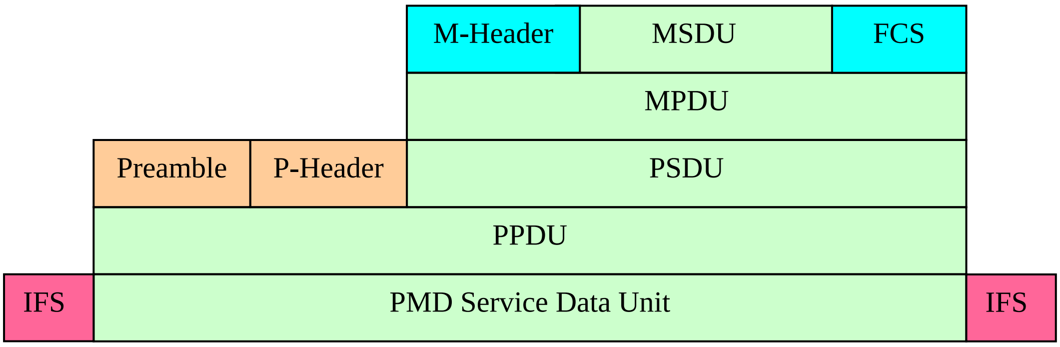

Figure 6: Overheads added at different sublayers

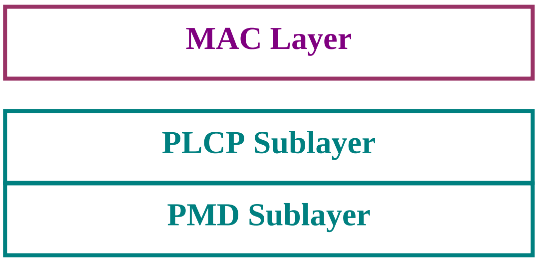

Figure 7: Lower level of OSI reference model

5. Calculation of Maximum Throughput

Maximum throughput can be calculated as follow:

Maximum throughput = MSDU size / Delay per MSDU

Total delay per MSDU is the summation of all the delay components [27], [11].

Delay per MSDU = $(T_{DIFS} + T_{SIFS} + T_{BO} + T_{RTS} + T_{CTS} + T_{ACK} + T_{DATA}) \times 10^{-6}$ second ..…………….…..………(1)

Total delay per MSDU can be simplified to a function of the MSDU size in bytes, x as follow:

Delay per MSDU(x) = $(\alpha x + \beta) \times 10^{-6}$ second ………………………………..(2)

Where, α and β are the parameters of theoretical maximum throughput. Table 1 shows the parameter values for CSMA / CA. Table 2 shows the parameter values for RTS / CTS.

Dividing the number of bits in MSDU (8x) by the delay per MSDU, we can get the maximum throughput.

Maximum throughput = $(8x / \alpha x + \beta) \times 10^{6}$ bit per second …………...………(3)

Table 1: α and β parameters values for CSMA / CA

Modulation	Data Rate (Mbps)	A	β
FHSS	1	8.25	1179.5
	2	4.125	1039.25

DSSS	1	8	1138
	2	4	1002
OFDM	12	0.66667	187
	24	0.33333	170.75
	54	0.14815	159.94
HR-DSSS	5.5	1.45455	915.45
	11	0.72727	890.73

Table 2: α and β parameters values for RTS / CTS

Modulation	Data Rate (Mbps)	A	β
FHSS	1	8.25	1763.5
	2	4.125	1623.25
DSSS	1	8	1814
	2	4	1678
OFDM	12	0.66667	273
	24	0.33333	244.75
	54	0.14815	225.94
HR-DSSS	5.5	1.45455	1591.45
	11	0.72727	1566.73

6. Results and Analysis

6.1. Throughput Analysis

In section 5 theoretical maximum throughput formula for IEEE 802.11 has shown. Here we will describe four figures which are obtained by maximum throughput formula (Equation 3 of section 5). These graphs have been drawn by MATLAB. In these figures comparison of different data rate and spread spectrum technologies is shown. Figure 8 shows the throughput of CSMA/CA for frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS) and 5.5 Mbps high rate DSSS (HR-DSSS).

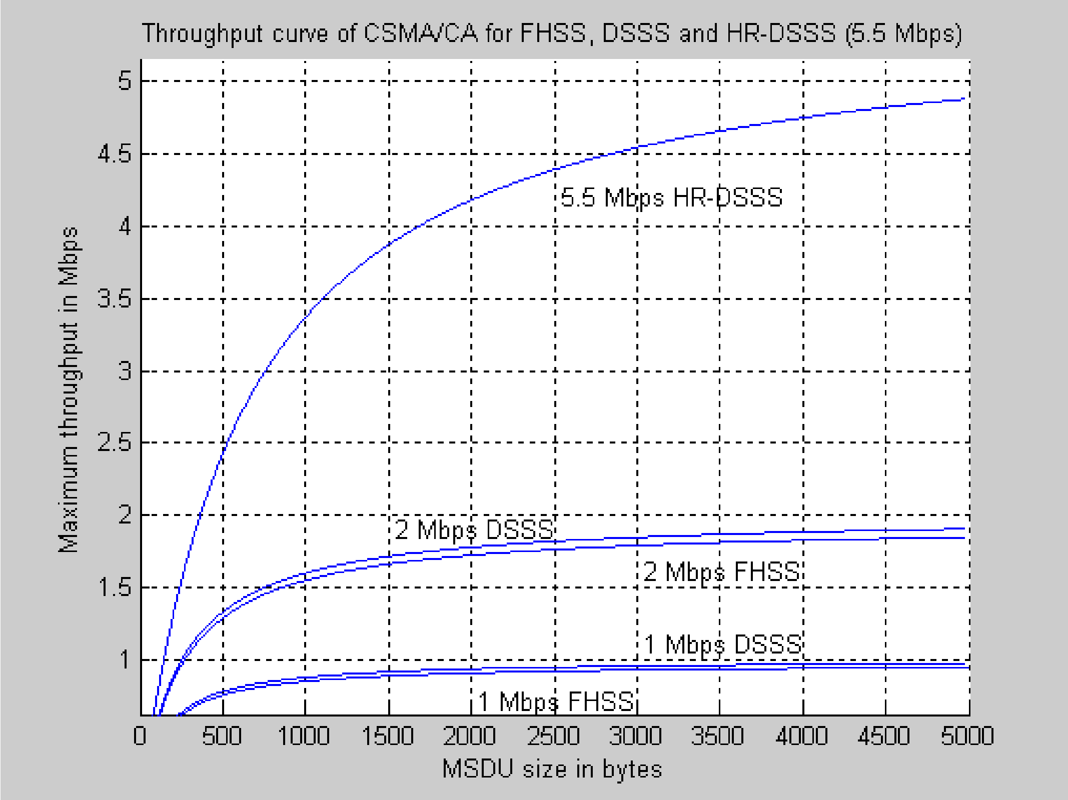

Figure 8: Throughput curve of CSMA/CA for FHSS, DSSS and 5.5 Mbps HR-DSSS

In Figure 8 X-axis represents MAC service data unit (MSDU) size in the number of bytes and Y-axis represents maximum available throughput in Mbps for particular MSDU size. The graph is drawn for maximum MSDU size of 5000 bytes though maximum allowable MSDU size for 802.11, 802.11a and 802.11b is 4095 bytes. It is observed that throughput depends upon MSDU size. As MSDU size increases throughput increases and vice versa. It is also shown that low basic data rate graphs (1, 2 Mbps) saturated earlier than higher basic data rate graphs.

Figure 9 shows the data for high rate DSSS (HR-DSSS) and orthogonal frequency division multiplexing (OFDM) of CSMA/CA. As the graph of figure 8 it is clear that data is saturated towards maximum MSDU size. Figure 9 also shows that throughput of 802.11a (OFDM) saturates earlier than that of 802.11b (HR-DSSS).

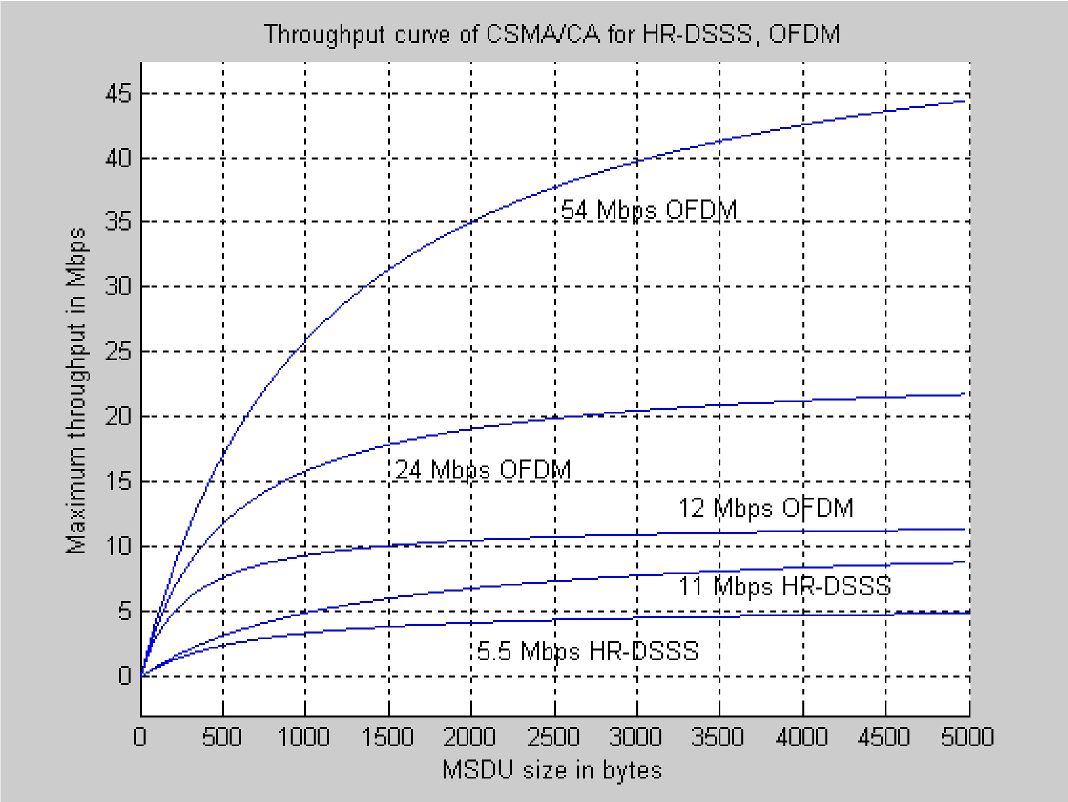

Figure 9: Throughput curve of CSMA/CA for HR-DSSS and OFDM

Figure 10 describes throughput for FHSS, DSSS and 5.5 Mbps HR-DSSS for RTS/CTS. This graph is almost similar to figure 8 but there is a bit difference. That is, maximum throughput a bit higher for a fixed size of MSDU.

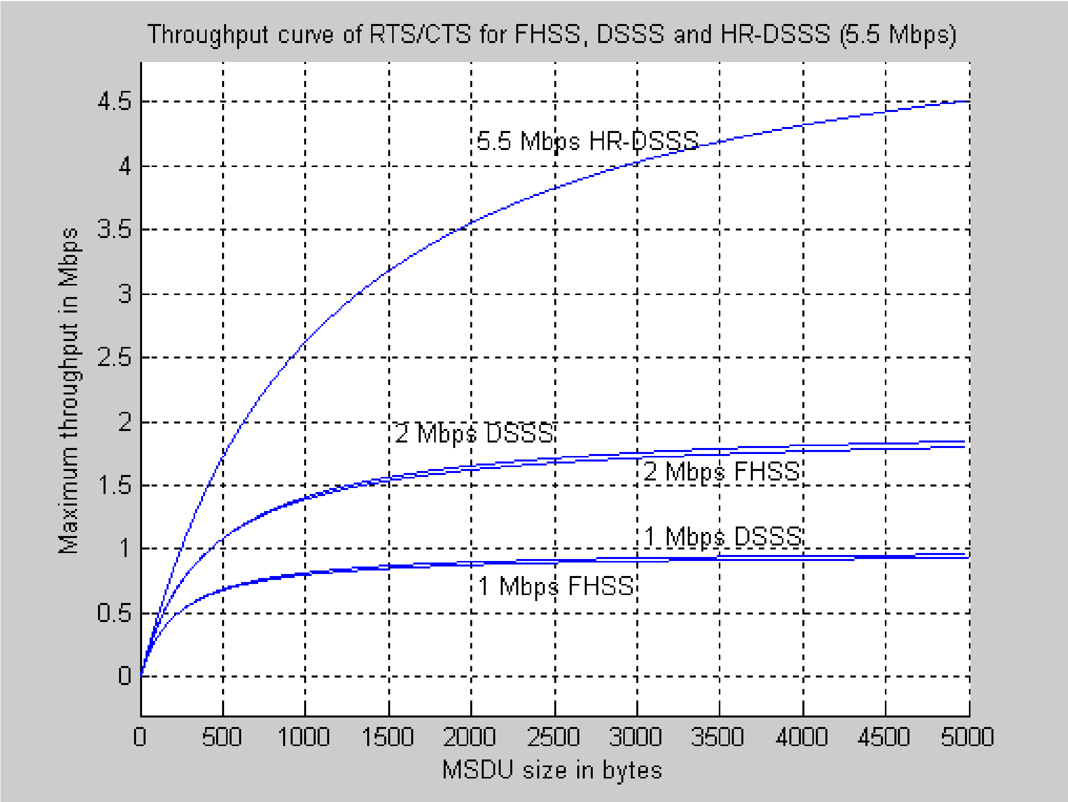

Figure 10: Throughput curve of RTS/CTS for FHSS, DSSS and 5.5 Mbps HR-DSSS

Figure 11 represents throughput curve of RTS/CTS of HR-DSSS and OFDM. It is also examined that maximum throughput of RTS/CTS of 11 Mbps is lower for particular MSDU size than that of CSMA/CA. For instance, when MSDU size is 2000 bytes and CSMA/CA is used 7 Mbps throughput achievable. On the other hand when RTS/CTS is used 5.5 Mbps throughput could be achieved which is lower than CSMA/CA.

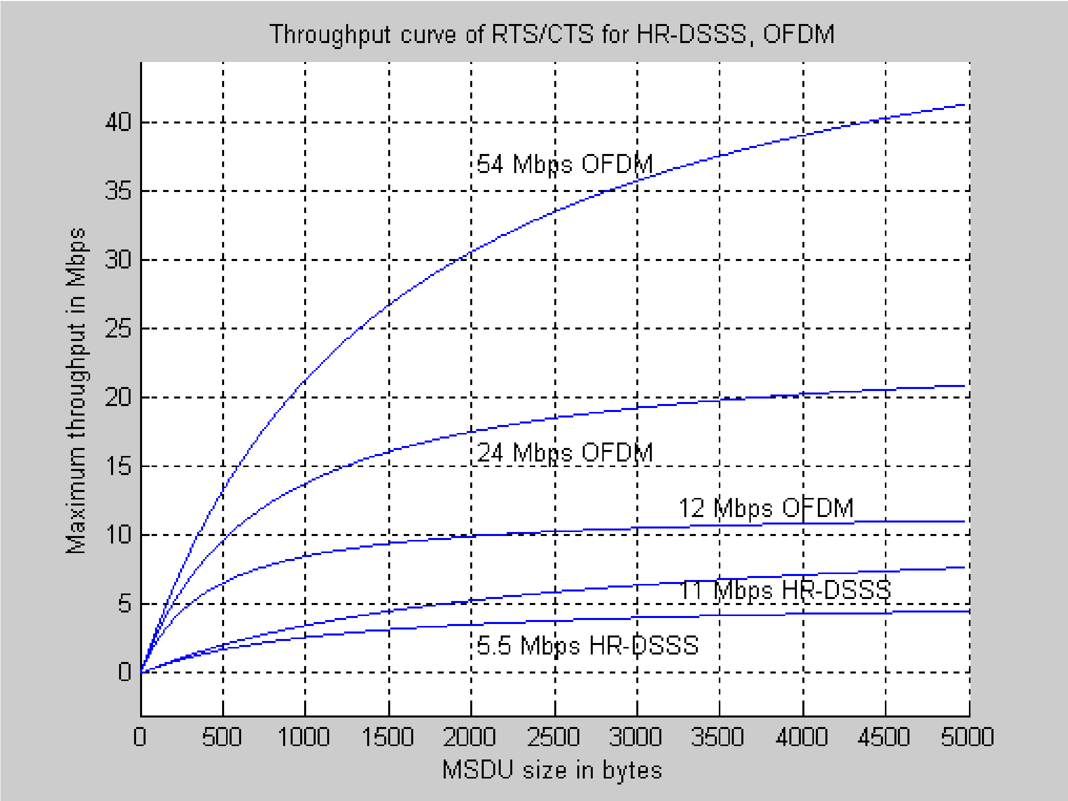

Figure 11: Throughput curve of RTS/CTS for HR-DSSS and OFDM

6.2. Bandwidth Analysis

Bandwidth efficiency is inversely proportional to basic data rate. Bandwidth efficiency can be defined as follow:

Bandwidth efficiency = Maximum throughput / Basic data rate

Figure 12 shows the bandwidth efficiency curve for CSMA/CA of FHSS, DSSS and HR-DSSS (5.5 Mbps). From the curves it is seen that bandwidth efficiency saturates earlier for low basic data rate scheme than that of higher basic data rate scheme. It’s also observed that bandwidth efficiency increases as MSDU size increases and vice versa.

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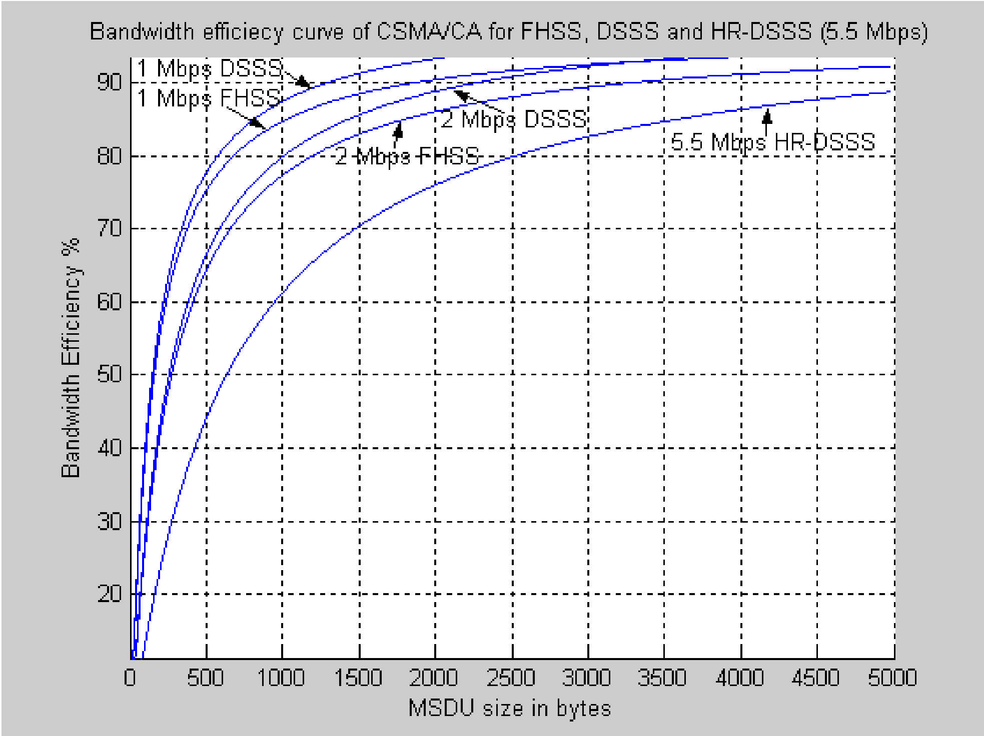

Figure 12: Bandwidth efficiency curve of CSMA/CA for FHSS, DSSS and 5.5 Mbps HR-DSSS

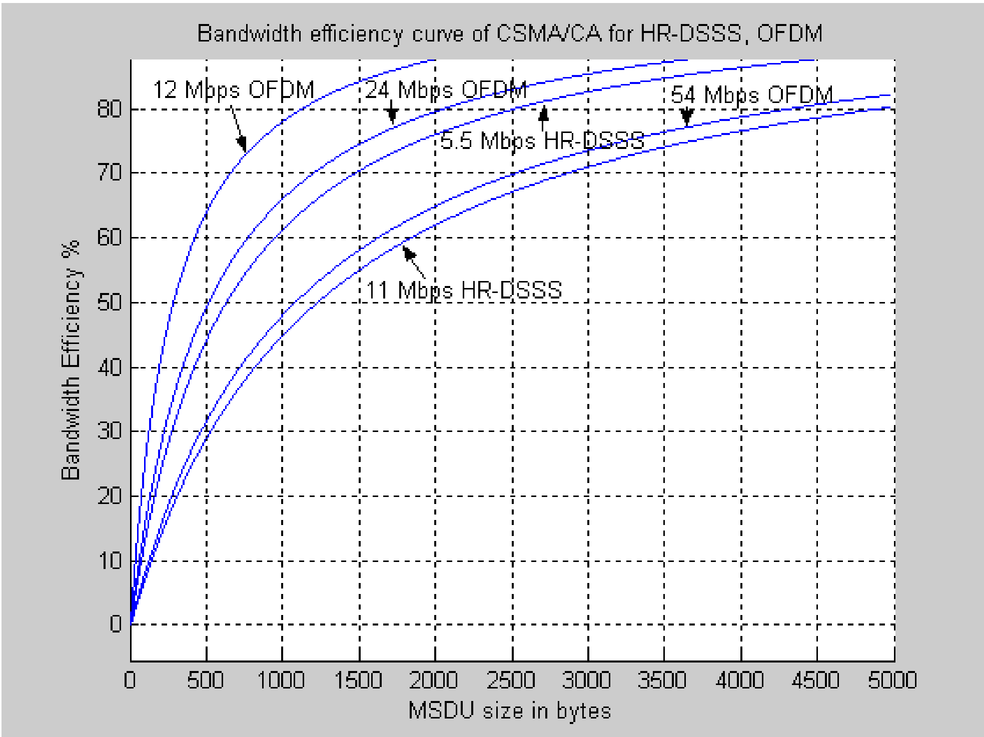

Figure 13: Bandwidth efficiency curve of CSMA/CA for HR-DSSS and OFDM

Figure 13 describes bandwidth efficiency curve of CSMA/CA for HR-DSSS and OFDM. Here we observed that 802.11a (OFDM) has better bandwidth efficiency than that of 802.11b (HR-DSSS). For example, when MSDU size is 1000 bytes; 12 Mbps OFDM has bandwidth efficiency 78% whereas 11 Mbps HR-DSSS has an efficiency of 45%.

Bandwidth efficiency curve of RTS/CTS for FHSS, DSSS and 5.5 Mbps HR-DSSS is shown in figure 14. Again, we see that low basic data rate graphs increasing sharply and saturates earlier as MSDU size increases. 1 Mbps DSSS and 1 Mbps FHSS, 2 Mbps DSSS and 2 Mbps FHSS almost overlap each other. As MSDU size increases DSSS shows a little bit better bandwidth efficiency than that of FHSS.

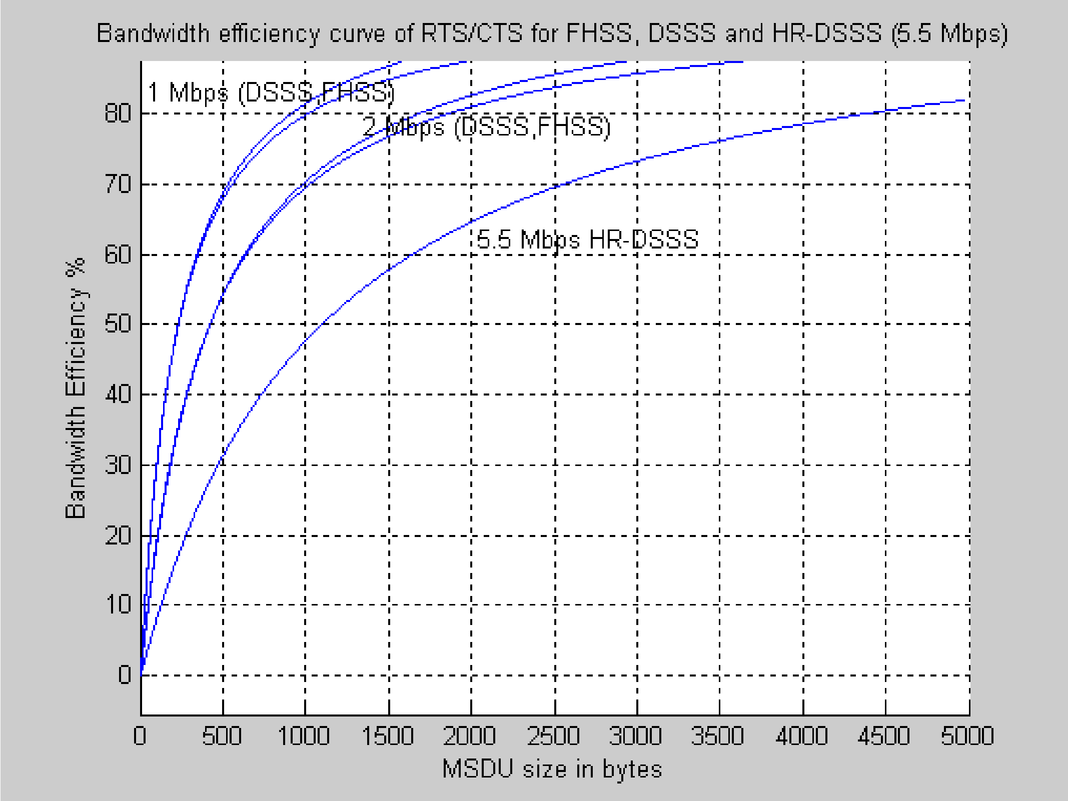

Figure 14: Bandwidth efficiency curve of RTS/CTS for FHSS, DSSS and 5.5 Mbps HR-DSSS

Figure 15 describes bandwidth efficiency curve of RTS/CTS for HR-DSSS and OFDM. Now, we can make another comparison between RTS/CTS and CSMA/CA. Bandwidth efficiency of CSMA/CA always better than that of RTS/CTS. Because CSMA/CA scheme has fewer control frames than RTS/CTS scheme. Consider, 11 Mbps HR-DSSS of RTS/CTS in figure 15 and 11 Mbps HR-DSSS of CSMA/CA in figure 13 for the MSDU size of 2000 bytes. We see, RTS/CTS has a bandwidth efficiency of 48%, whereas, CSMA/CA has an efficiency 62%.

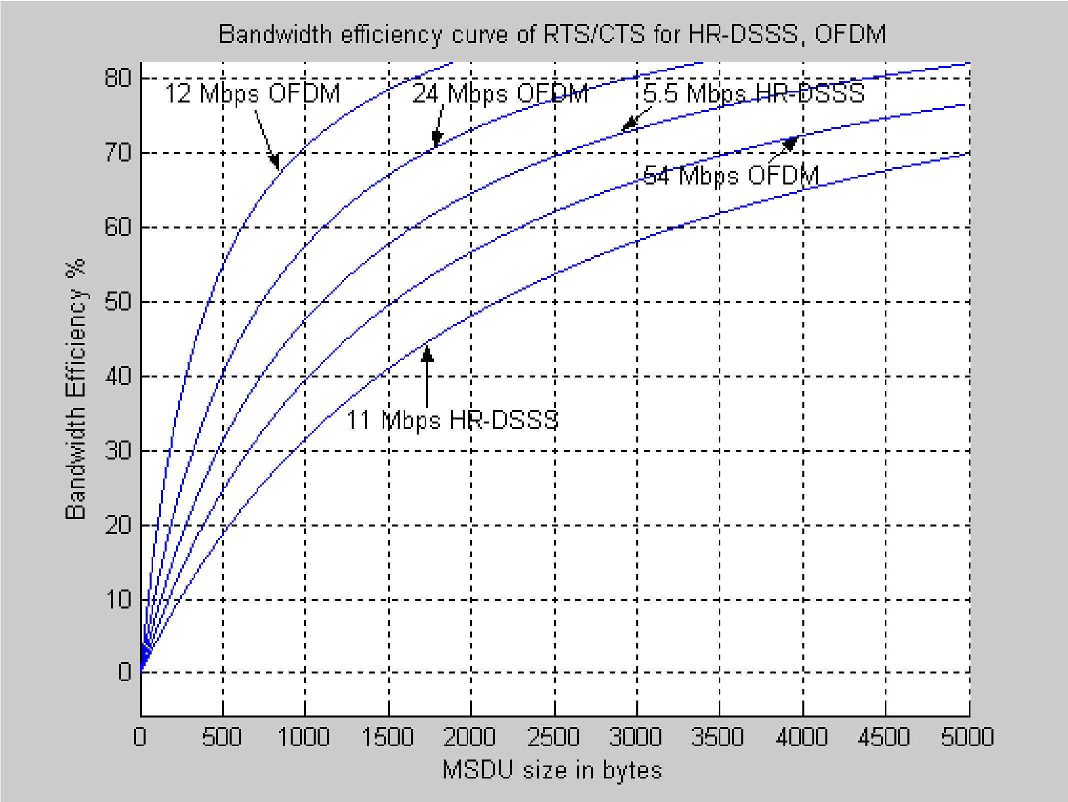

Figure 15: Bandwidth efficiency curve of RTS/CTS for HR-DSSS and OFDM

We can easily analyze the behavior of theoretical maximum throughput (Figure 8–Figure 11) and spectral efficiency (Figure 12–Figure 15) by the graphs described in this section. All of the figures of this section have drawn by MATLAB software version 10.

7. Accomplishments

In section 5 we have derived theoretical maximum throughput formula for IEEE 802.11 MAC. This formula 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. This throughput calculation 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.

Throughput formula can be used in call admission and control procedures for QoS (Quality of Service) schemes to determine accurate upper bounds on available bandwidth. For example, consider ARME [1], and DIME [5] – protocols that aim to provide throughput guarantees in a WLAN 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. As described in [27], maximum throughput calculation is vital in the estimation of the maximum number of voice channels that can be accommodated in a WLAN. Voice and video applications can use the formula to calculate the optimum MSDU size to maximize throughput and, hence, determine the amount of buffering required for a communication link. Throughput formula can be used to validate and check the sanity of network simulators that model IEEE 80.11 protocols.

We have drawn bandwidth efficiency curve of different IEEE 802.11 technologies in section 6.2. The knowledge of the bandwidth efficiency curves (Figure 12 - Figure 15) 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.

An important criterion for designing the layout of a WLAN is provisioning. Extensive traffic modeling and workload analysis have to be carried out to correctly estimate the infrastructure needs of any given location. 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 theoretical maximum throughput of the network. Thus, the ability to accurately measure the link utilization at various locations in order to perform provisioning is extremely useful.

8. Future Work

In this project we already derived the theoretical maximum throughput and corresponding bandwidth efficiency for various IEEE 802.11 (Wi-Fi) technologies. As a consequence, capacity estimation of Wireless Mesh Networks (WMNs) would be an ideal research topic in future.

WMNs have particular topology and traffic patterns compared to conventional wireless local loops or mobile ad hoc networks. This particularity requires completely different approaches for the analysis of capacity. As a prerequisite for the WMN capacity estimation, we derived formulae for the maximum throughput of IEEE 802.11 and the corresponding efficiency. This formula is critical in the capacity analysis of WMNs because it sets the upper limit on achievable throughput of IEEE 802.11 which is the standard that covers MAC and physical layer of the WMNs. Unlike in the case of wired networks such as Ethernet, the maximum throughput of IEEE 802.11 is quite low compared to the basic data rate resulting in low efficiency. In a multiple-node system, the sum of nodal maximum throughputs is defined as the system maximum throughput (SMT). The SMT can be greater than maximum throughput due to reduced backoff time. The maximum throughput and SMT calculation could be very useful for future researchers and system designers.

Since IEEE 802.11 covers only the MAC and physical layer, fairness is not guaranteed at the network layer in multihop or asymmetric topology. Various aspects of the fairness issues could be examined. Competition between internal and external traffic in a user node brings about a unique challenge in WMN fairness implementation. It is needed to identify desirable fairness characteristics in WMN. The capacity analysis might be carried out on the assumption that ideal fairness is guaranteed.

Realization of WMN fairness is quite challenging because careful design of the algorithm is required so that it incorporates the uniqueness of the wireless medium into the fairness issues of WMNs. The fairness implementation can be either centralized or distributed. The details of such design remain to be tackled as a future research.

In the real world where user traffic is highly correlated and frequently appears as a burst of packets over a short time, user bandwidth may be different from the general analysis. Probabilistic modeling of user traffic patterns in WMNs can be a very interesting research topic. The effect of traffic patterns on ad hoc network capacity was examined by Li et al. [17]. The effect in the case of WMNs capacity can be another interesting research topic in the future.

9. Conclusion

The main contribution of this project is the exact calculation of the maximum throughput for a variety of IEEE 802.11 technologies. All of the information for the calculation of these data rates is available in the IEEE standards. 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 providing 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 maximum throughput. To emphasize the importance of the maximum throughput, we have discussed several applications which require knowledge of the maximum throughput if they are to be designed correctly. One of the most important facts of designing the layout of a WLAN is network provisioning. The maximum throughput formula that we have shown can be used to facilitate optimal network provisioning, both for data as well as multimedia applications. This formula is critical in the capacity analysis of WMNs because it sets the upper limit on achievable throughput of the IEEE 802.11.

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