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Achievable Maximum Throughput and Coverage Range of Wireless LANs

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Abstract

It is observed that the data rates specified for the various Wireless LAN (WLAN) standards do not reflect the true throughput available to the user. Also, the carrier sense multiple access with collision avoidance (CSMA/CA) medium access control (MAC) protocol implementation of IEEE 802.11b has good distance coverage scope. This paper addresses these two issues of WLANs and computes the achievable maximum throughput and the range coverage. The computations are performed over the IEEE 802.11b standard, but can be extended to other WLAN standards as well.

Key Words: Achievable maximum throughput, coverage range, data transmission time, throughput, wireless LAN

1. Introduction

After about 10 years of activity the IEEE released the first 802.11 standard **[10]** in 1997 for 1 and 2 Mbps, which support DSSS (Direct Sequence Spread Spectrum), FHSS (Frequency Hopping Spread Spectrum) and DFIR (Diffusion Infrared) physical layers. The 802.11 is a group of specifications developed by IEEE for wireless local area networks. These specifications define an over-the-air interface between a wireless client and a base station (access point), or between two or more wireless clients. After the completion of the first standard, new PHY layers supporting 11 Mbps using CCK (Complementary Code Keying), IEEE 802.11b **[6]** and 54 Mbps using OFDM (Orthogonal Frequency Division Multiplexing) have been defined. To obtain the 11 Mbps data rate, 802.11b uses 8-complex CCK symbol codes with DQPSK (Differential Quadrature Phase Shift Keying) modulation. The symbol rate is 1.375 Msps and the bits/symbol **[15]** is 8. IEEE WLAN standards include 802.11 **[10, 2, 3, 4]** and 802.11b **[6]** both operating at 2.4 GHz, 802.11a **[5]** operating at 5 GHz, and 802.11g **[7]** operating at 2.4 GHz. Of late another IEEE standard, 802.16 **[8]**, is gaining prominence, even though it belongs to the metropolitan area network (MAN).

The IEEE 802.11 standard was the first WLAN standard facing the challenge of organizing a systematic approach for defining a standard for wireless wideband local access. In comparison with the wired LANs, WLANs operate in a difficult medium for communication, and they need to support mobility and security. The wireless medium has serious bandwidth limitations and frequency regulations. It suffers from time and location dependent multi-path fading **[14]**. It is subjected to interference from other WLANs, and other radio and non-radio devices operating in the vicinity of a WLAN **[15]**. Wireless standards need to have provisions to support mobility that is not shared in the other LAN standards. The IEEE 802.11 body had to examine connection management, link reliability and power management - none of which were concerns for the other 802 standards. In addition, WLANs have no physical boundaries and they overlap with each other, and a standardization organization is needed to define provisions for the security of the links.

1.1 Access Methods

Two different approaches can be followed in the implementation of a WLAN, an infrastructure-based approach or an ad hoc networking approach. An infrastructure-based architecture imposes the existence of a centralized controller for each cell, often referred to as the access point (AP). The AP is normally connected to a wired network, thus providing Internet access to the wireless devices. In contrast, an ad hoc network is a peer-to-peer network formed by a set of stations within the range of each other, which dynamically configure themselves to setup a temporary network.

1.1.1 The MAC Sublayer

The overall MAC layer responsibilities are divided between MAC sublayer and MAC layer management sublayer. The responsibilities of the MAC sublayer include definition of access mechanisms and packet formats. The MAC management sublayer defines roaming support, power management and security. The basic access method in IEEE 802.11 MAC protocol is the distributed coordination function (DCF), which is a carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. Besides the DCF, the IEEE 802.11 also incorporates an alternative access method known as the point coordination function (PCF). The optional PCF operates similar to a polling system [12].

The access point in the infrastructure-based WLAN acts as the coordinator for PCF. Infrastructure-based WLAN can be based either on DCF, PCF, or a combination of both. The ad hoc WLAN can only be using the DCF access method. As a solution to a situation called hidden terminal problem [16] - where two "unseen" terminals may cause a collision while transmitting simultaneously to a central node - DCF can also be implemented with request to send/ clear to send (RTS/CTS) signals.

To allow coordination of a number of options for the MAC operations, IEEE 802.11 recommends three interframe spacings (IFSs) between the transmissions of the packets [15]. These IFS periods provide a mechanism for assigning priority, which can be used for implementation of the QoS support for time-bounded or other applications. After completion of each transmission, all terminals having information packets wait for one of the three IFS periods according to the level of priority of their information packet. These inter-framing intervals are DCF-IFS (DIFS) and used for contention data spacing, which has the lowest priority and longest duration. Short IFS (SIFS), used for highest priority packets such as ACK and CTS, has the lowest duration of time. The PCF-IFS (PIFS), designed for PCF operation, has the medium priority rate with duration between DIFS and SIFS. Fig. 1.1 depicts the MAC layer interframe spacing (indicating the relative duration of DIFS, PIFS and SIFS).

1.2 IEEE 802.11 DCF

In DCF, before a station initiates transmission, it senses the channel to determine whether another station is transmitting.

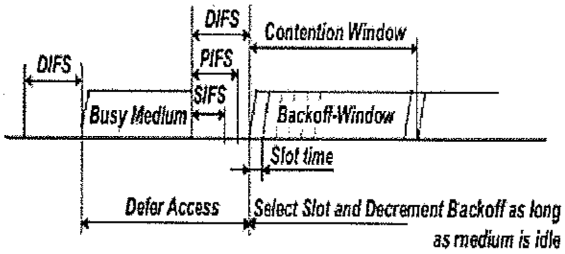

Figure 1.1: MAC layer interframe spacing

If the medium is found to be idle for an interval that exceeds DIFS, the station continues with its transmission. The transmitted packet contains the projected length of the transmission. Each active station stores this information in a local variable named network allocation vector (NAV)

[12]. Therefore, the NAV contains the period of time the channel will remain busy.

In the CSMA/CA protocol, immediate positive acknowledgments are employed to ascertain the successful reception of each packet transmission. Specifically, the receiver after the reception of the data frame waits for a time interval SIFS and then initiates the transmission of an acknowledgment (ACK) frame. Collisions occur when two or more stations transmit at the same time. If an erroneous frame is detected (due to collisions or transmission errors), the channel must remain idle for at least an extended interframe space (EIFS) interval, before the stations reactivate the backoff algorithm to reschedule their transmissions.

To reduce the collision probability, IEEE 802.11 uses a backoff mechanism that guarantees a time spreading of transmissions [12].

1.3 Data Rate and Throughput

The data rate of IEEE 802.11b is 11 Mbps. But, the end user gets a lesser bandwidth. So, the term *throughput* is used to describe the bandwidth available at the end of a protocol layer. It is the maximum fraction of the channel bandwidth used by successfully transmitted messages [12]. Hence, the throughput available to a user is much less than the advertised data rate. There are two reasons for this lowering of throughput. The first one is, as part of the system itself, the overheads such as protocol overheads and delay due to collision avoidance mechanisms. The second cause is due to sources external to the network system, in the form of collisions, noise, etc. Our focus is to determine analytically, the maximum throughput available above the MAC layer. So, we concentrate on the first set of causes for lowering the throughput up to the MAC layer.

1.4 Coverage Range of WLAN

An important parameter while deciding on a particular WLAN strategy is the coverage range. Since the present day WLAN covers the outdoor as well as indoor environments, studies have been carried out to determine the best strategy. Since our work focuses around IEEE 802.11 DCF protocol, a comparison between DCF and PCF with respect to range of coverage is in order. Leung et al. [11] gives a broader picture on this issue. The rest of this paper is organized as follows. Section 2 presents the computation of the AMT of IEEE 802.11b DCF. Section 3 presents the coverage range computation. Performance evaluations and results are discussed in Section 4. The conclusions and future works are discussed in Section 5.

2 Achievable Maximum Throughput

As mentioned in Section 1, the basic access method of IEEE 802.11 is DCF. This Section computes the achievable maximum throughput (AMT) under DCF. The computations are performed for IEEE 802.11b. Consider a single station transmitting a data frame. Neglecting the propagation time, the overall transmission time is composed of the transmission time and a constant overhead. The overhead is due to DIFS for idle channel detection, the PLCP (Physical Layer Convergence Protocol) header and preamble transmission time per frame, SIFS duration between data frame and ACK frame and the ACK transmission time. Note that the PLCP header time has to be accounted twice, once for the data frame and then for the ACK frame. The MPDU (MAC layer Protocol Data Unit) consists of the Data, the MAC header and CRC bytes. For PLCP, we have two options between long PLCP preamble and short PLCP preamble. The preamble is always transmitted at 1 Mbps [13].

The long preamble consists of 128 SYNC bits and 16 delimiter bits, requiring 144 μs transmission time. The

PLCP header is 48 bits in size and for a long preamble; the header is also transmitted at 1 Mbps, requiring 48 µs. So a total of 192 µs is required to transmit a long preamble. The short preamble consists of 56 SYNC bits and 16 delimiter bits, requiring 72 µs transmission time. The PLCP header is 48 bits in size and for a short preamble the header is transmitted at 2 Mbps, requiring 24 µs. So a total of 96 µs is required to transmit a short preamble. According to IEEE 802.11 specifications, SIFS takes 10 µs and DIFS takes 50 µs.

At the MAC layer, the data units handled are frames. So we shall consider the data as part of fixed sized frames. A frame consists of frame headers and CRC bytes, in addition to the data. The throughput is defined as

Definition 2.1 Throughput, TP = $\dfrac{8 * D}{TT}$ Mbps, where D is the size of data in bytes and TT is the total transmission time.

The total transmission time consists of frame transmission time and overheads, and is computed as

$$TT = TFR + TOH \qquad (2.1)$$

where TFR is the frame transmission time and TOH is the overhead time. As per the specifications for a DCF environment, the MAC header size is 24 bytes. As usual, CRC is 4 bytes. The MAC frame size is calculated as

$$MP = MAC\ header\ size + Data\ size + CRC\ size \quad (2.2)$$

where MP is the MPDU (the MAC frame) size. Hence,

$$MP = 24 + D + 4 = 28 + D\ bytes \qquad (2.3)$$

Now, TFR is calculated as

$$TFR = MP*8/11 = (28+D)*8/11$$

i.e., $TFR = (224 + 8 * D)/11\ \mu s$ (2.4)

The overhead time (TOH) is calculated as

$$TOH = DIFS\square + 2 * P\square + SIFS\square + \frac{acksize * 8}{ackrate} \qquad (2.5)$$

where P is the PLCP duration, *acksize* is the size of the ACK frame and *ackrate* is the rate at which the ACK frame is transmitted and it may be taken as equal to data rate (= 11 Mbps). Also, $acksize = 14$ bytes and $DIFS = 50\ \mu s$ and $SIFS = 10\ \mu s$. Hence,

$$TOH = 60 + 112/11 + 2 * P \qquad (2.6)$$

where,

$$P = \begin{cases} 192\,\mu s & for\ long\ PLCP\ preamble \\ 96\,\mu s & for\ short\ PLCP\ preamble \end{cases}$$

Using [illegible]

$$TT = (224 + 8 * D)/11 + 60 + 112/11 + 2 * P$$

i.e., $TT = (336 + 8 * D)/11 + 60 + 2 * P$ (2.7)

Theorem 2.1 *The throughput, TP of a WLAN is equal to the value*

$$\frac{8 * \mathrm{D}}{(336 + 8 * \mathrm{D})/11 + 60 + 2 * \mathrm{P}}\ \mathrm{Mbps}$$

Proof *The proof directly follows from equations 2.1 to 2.7.* □

Corollary 2.1

$$TP = \begin{cases} \frac{8*D}{(336+8*D)/11+252}\ Mbps \\ \qquad for\ short\ PLCP\ preamble \\ \frac{8*D}{(336+8*D)/11+444}\ Mbps \\ \qquad for\ long\ PLCP\ preamble \end{cases}$$

Proof *It is obtained from Theorem 2.1 by substituting* P *= 96* µs *and* P *= 192* µs *for short PLCP preamble and long PLCP preamble respectively.* ?

Corollary 2.2 *For the standard data frame of size 1500 bytes, the achievable maximum throughput,*

$$AMT = \begin{cases} 7.67\ Mbps \\ \qquad for\ long\ PLCP\ preamble \\ 8.74\ Mbps \\ \qquad for\ short\ PLCP\ preamble \end{cases}$$

Proof *It follows from Theorem 2.1 with data size,* D = 1500 *bytes.*??

The AMT for transmitting one frame of size 1500 bytes with no contention with short PLCP preamble is 8.74 Mbps. For the short PLCP preamble case, the equation for AMT can be written as

$$AMT = \frac{8 * D}{282.5454 + D * 0.7272} Mbps \qquad (2.8)$$

This shows that 282.55 μs is accounted for overheads. Also, total time for transmitting the 1500 bytes including overheads

$$\begin{aligned} TT &= 282.5454 + 1500 * 0.7272 \\ &= 282.5454 + 1090.90 = 1373.46\ \mu s \end{aligned} \qquad (2.9)$$

In the ideal scenario where every frame is of fixed size, say 1500 bytes, the above analysis is valid for a single transmitter and a single receiver. In case of multiple nodes, the total throughput should be ideally 7.67 or 8.74 (for long or short PLCP). It can happen only if the multiple nodes do not try to transmit at the same time. This computation means that, against the industry claim of 11 Mbps at best we can have 8.74 Mbps with packet size of 1500 bytes. It comes to 79.45% effective throughput. The throughput loss of 20.55% is attributed to the MAC overheads contributed by SIFS and DIFS delays, MAC header and CRC bytes in MPDU, PLCP transmission time and ACK frame transmission time.

2.1 The Effect of Collisions on Throughput

An AMT of 8.74 Mbps means that 728 data packets are received per second. Even if the number of stations is increased, altogether there could be a maximum of 728 frame transmissions only. But since multiple stations sense the channel as idle simultaneously and if they release the frames on to the channel, collision is bound to occur. Since there is no way the sender knew that a collision has occurred, until at least the completion the frame transmission, the entire bandwidth for the frame is wasted. So, the impetus is on avoiding collisions. Another paper [17] by the same authors addresses these issues.

3 Maximum Range of WLAN Nodes

Here the maximum possible separations between WLAN nodes are computed. We are addressing only the MAC layer timing issues. Radio wave propagation issues such as radiated power, transmission impairments, etc. are not addressed.

Theorem 3.1 *The coverage range, R of a wireless LAN node is given by the inequality* R < 0.15 * IFS km, *where IFS is the interframe space in* μs.

Proof *The speed of light (and also of RF signals) = 299792458 m/s = 299.8 m/*μs. *An ACK should start in such a way to be received within the IFS duration at the end of DATA transmission, i.e. the time between the release of the last bit of data and start of the receipt of the ACK is IFS. Within this time, the entire data should reach the destination, get processed, ACK transmitted and the sender should start receiving the ACK. Let R be the distance between the nodes. Time required for a bit to cover R + R = 2R is 2R/299.8* μs. *Since we have only IFS for this,*

$$2R/299.8 + p \leq IFS \qquad (3.1)$$

*where p is the time taken by the receiver for processing the frame before ACK is released. Since, the frame processing time by the receiver is beyond the scope of this discussion and also because the value of p is relatively much smaller than other parameters in the inequality, we can safely exclude p from further discussion On solving, we get, R < 0.15 * IFS km.* □

The IEEE 802.11b standard value of interframe space between data and ACK frames (SIFS) is 10 μs. Using this value, we get R < 1.5 km. However, in the DCF scenario, since other nodes will start the contention only after DIFS, the commencement of the ACK receipt may be delayed up to $DIFS = 50\ \mu s$.

Thus, we have $R < 7.5\ km$.

Similarly, for PCF, (PIFS = 30µs) $R < 4.5\ km$.

Corollary 3.1 *In IEEE 802.11b, DCF has better coverage range than PCF.*

Proof *From Theorem 3.1, going strictly by the standard, the maximum range possible is 1.5 km and if we wait for the ACK up to DIFS (the interframe space for DCF), the upper limit of range can be extended to 7.5 km. If we employ PCF (with interframe spacing PCF= 30* µs*) this is 4.5 km. These calculations show that DCF has the best coverage distance with an upper limit of 7.5 km.*

Hence we can infer that DCF is more appropriate for outdoor WLAN. Note that our study considered only the MAC layer timing issues and we have not addressed the radio wave propagation issues.

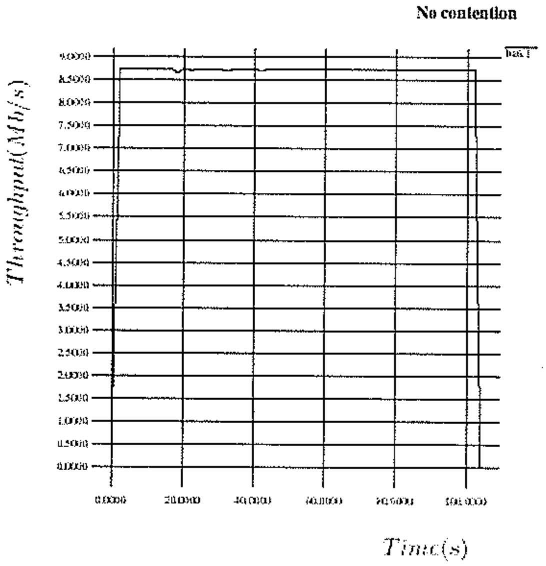

Figure 4.1 : Throughput simulation: One sender and one receiver.

4. Testing and Results

The experimentation of the WLAN for throughput was carried out using network simulator NS-2.27 [9]. For the experimental setup, we have taken a pair of nodes. The pair consists of a transmitter and a receiver. The transmitter generates constant bit rate (CBR) traffic and it is attached to a UDP server. The receiver acts as the UDP client. The packet size is taken as 1500 bytes. The 802.11b parameter values are taken as per the standard i.e., DIFS = 50 µs, SIFS = 10 µs, and one packet is produced every millisecond i.e., the CBR source is generating data at 12 Mbps. To calculate the throughput, data packets received during one-second intervals are counted. Multiply this count by the number of bits per packet (8*1500) to get the throughput in bits per second. **Figure 4.1** depicts the simulation result obtained. This result is plotted using xgraph [1], a general-purpose 2-D plotter. The plot shows that with just one pair of nodes a throughput equal to AMT is achievable.

5. Conclusion and Future Research

We have computed the achievable maximum throughput (AMT) possible with IEEE 802.11b DCF protocol and verified it through simulation. With just a single transmitter and a single receiver, a carried out the coverage range computations for IEEE 802.11b DCF and PCF. We are able to conclude that DCF has better range of coverage than PCF. Future works include extension of our techniques to other standards like 802.11b PCF, 802.11g, 802.16 etc. If carried out on a real wireless network, these observations may be useful in fine-tuning the parameters to improve the performance of the existing WLANs. The effect of collision avoidance backoff delay on throughput may further be investigated. Also the radio wave propagation issues are to be analyzed in detail before making a final conclusion and recommendation on coverage range issues.

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