Modeling and Simulation of Performance limits in IEEE 802.11 Point Coordination Function

Ali Eyadeh, Mohammad Jarrah, Ahmad Aljumaili

Abstract*: *The IEEE 802.11 standard is based on prevalence of Wireless Local Area Network (WLAN) technology. The performance of Wireless network depends mainly on the network throughput and average delay. Network requirements change according to applications deployed. Thus, the performance limits of IEEE 802.11 WLAN system should be evaluated and analyzed under the fundamental access mechanism for medium access control (MAC) called point coordination function (PCF). In this paper, we study the performance limits of IEEE 802.11n standard in PCF MAC layer through calculating theoretical maximum throughput (TMT) and delay time using an analytical model. Moreover, we develop a simulation model to study the performance limits using OPNET modeler. In the simulation, we examine the effects of packet size and number of stations on the TMT and delay time. Results show that the Delay time and TMT increase as the packet size increases, and as the number of stations increases, the Delay time increases and the TMT decreases.

Index Terms*: *Wireless LAN, point coordination function IEEE 802.11, throughput, OPNET simulator.

I. INTRODUCTION

WLAN is a wireless transfer of data in a specific geographic area for two or more devices using high radio frequency instead of cables [1]. In the late 1990s, Institute of Electrical and Electronics Engineers (IEEE) created the first WLAN standard called IEEE 802.11[2]. The IEEE 802.11 standard consists of physical (PHY) and Medium Access Control (MAC) layers. MAC and PHY layers reside in lower layers of Open Systems Interconnection model.

The physical layer in IEEE 802.11 standard is responsible for the conversion of every packet and sends it to physical layer for transmission on the network. The PHY layer consists of different implementations such as Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), Orthogonal Frequency Division Multiplexing (OFDM), Infrared (IR), etc. [3]. The MAC layer in IEEE 802.11 standard is responsible for channel allocation time procedures, protocol data unit (PDU) addressing, frame formatting, error checking, and fragmentation and reassembly. MAC layer consists of two parts, the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF) [3]. The researchers in IEEE launched many standard versions, including 802.11a, b, g, e, j and n [2]. IEEE 802.11n has made a quantum leap in data transfer on frequency ranging from 20 - 40 MHz channels.

In addition, it is the first version in IEEE 802.11 standard that uses multiple antennas to the data stream. It is considered a Multiple Input Multiple Output (MIMO) (4X4) technology with high data rate of 300 - 600 Mbps operates on 2.4&5 GHz bands [4, 5].

In 2013, researchers increased the data rate approximately to seven Gbps through using 80 -160 MHz channels and developed multiple antennas for data streams with Multi Users (MU)-MIMO from (4×4) to (8×8) technology. This modification is included in IEEE 802.11ac version [6-8].

The capacity (Maximum Throughput) of WLANs is expected to reach their wired counterparts. However, the data rates of WLANs are currently targeted to operate around 20 Mbps due to physical limitations. To support multiple transmissions at the same time, spread spectrum techniques are frequently employed [3].

A. Background

The IEEE 802.11 architecture consists of several components used to provide a wireless network that supports mobility to upper layers. Infrastructure-based IEEE 802.11 standard for basic services set (BSS) is a group of stations controlled by a single coordination function that determined when to allow transfer stations to receive the protocol data unit (PDU) across the wireless medium. Ad hoc network of two stations is shown in Fig. 1(A) and the station (STA) is a device containing an IEEE 802.11 conformant MAC and PHY interface to the wireless medium. An extended form of network that is built with multiple BSSs is shown in Fig. 1(B). The distribution system (DS) is used to interconnect BSSs. An Access Point (AP) station provides access to DS.

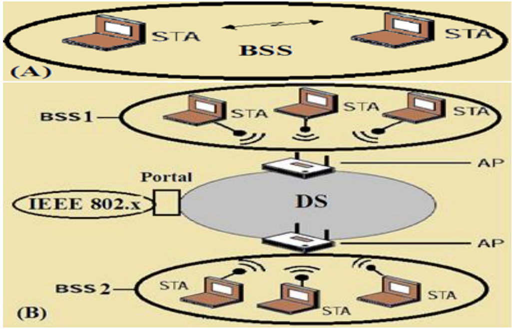

Fig. 1. IEEE 802.11 architecture. (A) ad-hoc network, (B) infrastructure network

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B. Medium Access Control Layer in IEEE 802.11

The MAC sublayer architecture consists of DCF, PCF and their coexistence in IEEE 802.11 LAN. The DCF is a fundamental access method of the IEEE 802.11 MAC, and it is based on carrier sense multiple accesses with collision avoidance (CSMA/CA). In addition, all STAs must support the DCF.

The PCF is a centralized contention-free access method, which is essentially based on infrastructure architecture. DCF and PCF operate alongside within the same BSS. The two-access methods are illustrated in Fig. 2.

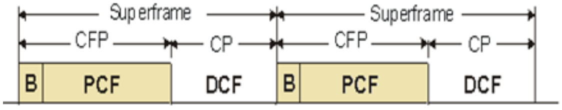

Fig. 2. The super frame of IEEE 802.11 [4].

The PCF is an optional capability that required coexisting with the DCF, which provides contention free (CF) frame transfer. The PCF relies on the point coordinator (PC) to perform polling, enabling polled stations to transmit without contending for the channel [3]. The PCF allows Stations (STAs) to have priority access to the wireless medium as polling methods by coordinating with the STA PC.

It is important to know that the PCF will have priority over DCF. DCF starts after the Distributed Inter Frame Space (DIFS) period. PCF starts after the Point Inter Frame Space (PIFS) period. PIFS time is less than DIFS. PCF divided time into frequent intervals called super frames as shown in Fig. 3 [7, 8]. Super frames are divided into stages, and the first is a stage beacon (B). The Beacon is a management frame that maintains timers in the stations and delivers protocol-related parameters. Then, the remaining stages are (CF-Poll) frame, Data frame, (CF-ACK) frame, and (CF-End) frame. Each stage will wait for a certain time called Short Inter Frame Space (SIFS). If there is more than a frame at a time trying to acknowledge that the (CF-End) be transmitted, STA transferred to the end of the (CF-End + CF-ACK) frame instead. Figure 3 shows the stages of sending data.

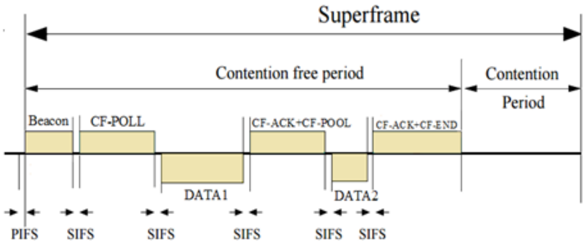

Fig. 3. PC to STA frame transmissions in PCF

II. RELATED WORK

Several researches conducted to increase the throughput by enhancement the speed of the data transfer. Some of these methods were conducted on versions IEEE 802.11 standard in DCF MAC layer. Few tried to improve throughput using PCF MAC layer [9]. Development of throughput differs from one version to another. In [10], the authors calculated the value of throughput in two versions 802.11a and 802.11b standard, in the absence of transmission errors and for various physical layers, data rates, and packet sizes. To calculate throughput, the research used delay per MAC Service Data Unit (MSDU) in DCF MAC layer, which includes a two-part CSMA/CA and RTS/CTS. In this paper, different results were concluded, which helped researchers and designers to establish a control system based on IEEE 802.11 technology.

In [11], the researchers studied impact of packet aggregation on the delay performance of the IEEE 802.11 PCF MAC layer. The purpose of use a packet aggregation to reduce polling overhead of 802.11 PCF and improve the delay performance. The researchers worked to develop the analytical model based on Markovian analysis for evaluating the queuing delay of packets at nodes using 802.11 PCF MAC for medium access and to develop a simulator for the 802.11 PCF MAC to evaluate the results. In [12], an improvement on the performance of the mechanics of DCF and PCF on three versions of IEEE 802.11 standards, including a, b and g is evaluated. The performance is improved through evaluating throughput and delay on the three versions of IEEE 802.11 Standard. The analysis revealed superior throughput performance with low delays for 802.11g standard as compared to 802.11 a/b standard using both DCF and PCF access methods. Finally, comparison is made between DCF and DCF_PCF using version 802. 11g and concluded that lower retransmission attempts, and load is achieved when DCF is using PCF compared to WLAN network using only DCF. In [13], the researchers studied performance of IEEE 802. 11b WLAN system under the fundamental access mechanism for DCF MAC layer through the creation of simulation showing throughput and average delay and impact of the changes on the wireless network in terms of Request to Send/ Clear to Send (RTS/CTS), fragmentation threshold and discuss the best configurations and parameters values in correspondence to network load and topology to get best performance.

In [14], the authors revealed a new analytical model to improve the throughput of the infrastructure of IEEE 802.11 DCF MAC layer in case of hidden terminals. The results of the simulation conducted on a single access point show that this model gives a reasonable approximation of the behavior of this complex system. In [15], the author proposed the efficient modification of the DCF protocol to deal with the problem of MAC performance degradation of the DCF protocol. Simulation results show that the proposed modified DCF protocol significantly enhances the MAC performance. In [16], the authors proposed a distributed scheme for partially saturated heterogeneous IEEE 802.11 DCF networks to achieve the maximum network throughput. The work in [17] is based on DCF in MAC layer of IEEE 802.11 WLAN to control the contention window size for reducing the collision problems and improving the throughput.

III. METHADOLOGY

Different literatures used different statistics in measuring the performance of wireless networks. In this section, the aim is to purify some concepts related to the throughput as they will be used throughout this paper. This paper is divided into two stages.

The first stage is a composition of a mathematical model to measure TMT and delay time. Second stage developed a simulation to evaluate our results using OPNET modeler. OPNET is widely used among specialists in the field of wireless networks [18]. It is used in many competent studies for IEEE 802.11 protocols. Moreover, OPNET provides many solutions in network management such as network operation, planning, research and development.

Fig. 4 shows the main components of the simulated architecture. Five different scenarios are used, ten STAs, twenty STAs, thirty STAs, forty STAs and fifty STAs.

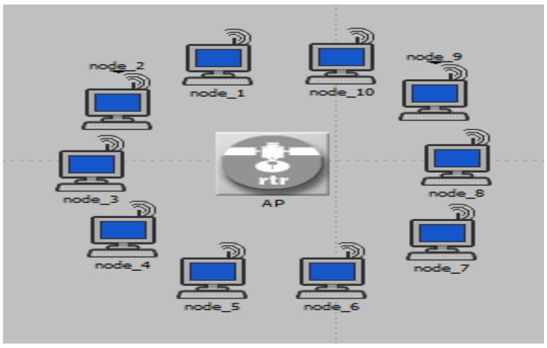

Fig. 4. IEEE 802.11 WLAN architecture

In each case, we calculated the TMT and delay time assuming ideal case.

After that, we compared the results of TMT and delay time with the packet size and number of stations. We used 20MHz frequency on IEEE 802.11n version and 5 GHz band to perform this study.

A. Analytic Model

We used different parameters to measure the performance of wireless network using IEEE 802.11n protocol. The aim of the study is to clarify the impact of the throughput on the wireless network performance by using the analytical model to prove it. In this model, some assumptions for analytical frameworks are made, there is no failure in the transferred data, no interference or collision and no hidden stations.

Notations are defined in Table I and will be used throughout this paper:

TABLE I: NOTATIONS AND DEFINITIONS

Notation	Definition
L_1	Transmission time for the payload in µs
L_2	Time of Point inter frame space =SIFS+SLOT$_{TIME}$
L_3	Time of Beacon
L_4	Time of Short inter frame space
L_5	Time of (CF_ACK + CF_Poll)
L_6	Time of (CF_ACK + CF_End).
$T_{GF\ HT\ PREAMBLE}$	The duration of the preamble in HT- Greenfield format
$T_{HT\text{-}SIG}$	Time of High Throughput - Signal field
T_{SYM}	Time of symbol interval
$T_{HT\text{-}GF\text{-}STF}$	Time of High Throughput – Greenfield - Short Training Field
$T_{HT\text{-}LTF1}$	Time of First High Throughput - Long Training Field
$T_{HT\text{-}LTF}$	Time of High Throughput - Long Training Fields
N_{SYM}	Total number of data symbols in the data portion
S	Signal Extension 0 µs when operating in the 5 GHz band
N_{LTF}	Is equal to number of space-time streams
m_{STBC}	Is equal to 2 when STBC is used, and otherwise 1
N_{ES}	Number of BCC encoders for the Data field
N_{DBPS}	Number of data bits per OFDM symbol
Length	The number of octets in the data portion of the PPDU
N_{Hader}	Size of Hader in bytes

- **Delay Time**

The delay time is the time spent while a packet travels from one node to another. It is a totally different space between the frame, pull back time and transmission time of all frames of control. We calculated the delay time through IEEE 802.11n version to High-Throughput Greenfield frame as shown in Fig. 5.

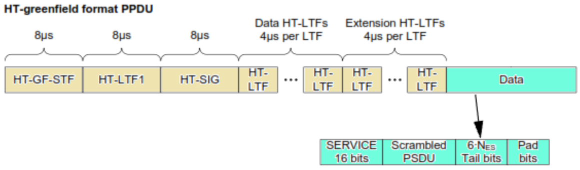

Fig. 5. High-Throughput Greenfield frame of IEEE 802.11n

Equation (1) shows the sum of the High-Throughput Greenfield frame parts, which is equal to the data time (L_1). Equation (2) is the sum of ($T_{GF\_HT\_PREAMBLE}$). Equation (3) is the sum of the parts that produce the total number of data symbols in the data portion (N_{SYM}).

$$L_1 = T_{GF\_HT\_PREAMBLE} + T_{HT-SIG} + T_{SYM} \times N_{SYM} + S \quad (1)$$

$$T_{GF_{HT_{PREAMBLE}}} = T_{HT-GF-STF} + T_{HT-LTF1} + (N_{LTF} - 1) \times T_{HT-LTFs} \quad (2)$$

$$N_{SYM} = m_{STBC} \times \left(\frac{(8 \times length + N_{Hader}) + 16 + 6 \times N_{ES}}{m_{STBC} \times N_{DBPS}} \right) \quad (3)$$

Table II provides the mapping between data rate and N_{DBPS} of 20MHz frequency.

TABLE II. DATA RATE N_{DBPS} 20 MHZ MAPPING

Modulation	R	N_{DBPS}	Data rate (Mb/s)
BPSK	1/2	26	6.5
QPSK	1/2	52	13.0
QPSK	3/4	78	19.5
16-QAM	1/2	104	26.0
16-QAM	3/4	156	39.0
64-QAM	2/3	208	52.0
64-QAM	3/4	234	58.5
64-QAM	5/6	260	65.0

After that, we extracted the data time and we calculated the delay time using (4). We have assumed that the network contains ten stations trying to connect to AP.

Delay Time = $L_2+L_3+5L_4+2L_1+L_5+L_6$ (4)

- **Throughput**

Throughput is the amount of data transferred successfully to another node in a specified period. The objective is to calculate the maximum throughput identifier for faster transfers of IEEE 802.11n in PCF MAC layer. In this calculation, we considered the packets size and data rate. Maximum speed in top layers of any application layer will be less due to the additional overhead in each layer. In other words, Throughput is the amount of data (payload) transferred successfully from one node to another divided by Delay Time, as shown in (5).

$$TMT = \frac{payload}{Delay\ Time} \tag{5}$$

- **Data Rate**

Data rate is the maximum available data that can flow over a channel. Like throughput, data rate also has been measured in bits per second. Data rate, unlike throughput, is the theoretical maximum rate at which data is transmitted including the protocol overhead and checksums. Therefore, the data rate of a network is always greater than the throughput. In this paper, we used 19.5 Mbps data rate to measure TMT and delay time on the IEEE 802.11n version.

IV. RESULTS

First, we have implemented previous equations for each of the five scenarios. Equations (2) and (3) are used to calculate the value of the data time (L_1) which is represented in (1). We calculated the delay time value using (4). We assumed five values of packet sizes and we applied them to QPSK type of modulation. The obtained results were slightly different but close. Additionally, we have used 20MHz frequency to calculate the TMT throughput as in (5) that consists of the payload divided by the delay time. These parameters of packet sizes, 20 MHz frequency, 19.5 Mbps and QPSK modulation are applied to all five scenarios. The following are the results of applying all equations in the first scenario that contains ten STAs try to send data to the AP.

The parameters values for throughput calculation are listed in Table III. Most of values have been taken from the IEEE 802.11n standard [19].

TABLE III: IEEE 802.11N PARAMETERS

Element	IEEE 802.11n value	Element	IEEE 802.11n value
$T_{HT—GF-STF}$	8µs	Length 3	1300 Byte
$T_{HT-LTF1}$	8µs	Length 4	1400 Byte
T_{HT-SIG}	8µs	N_{HADER}	34 Byte
T_{HT-LTF}	4µs	N_{ES}	1
T_{SYM}	3.6µs	L_2	25µs
S	0	L_3	209µs
m_{STBC}	1	L_4	16µs
Length 1	1000 Byte	L_5	362µs
Length 2	1100 Byte	L_6	362µs
Length 3	1200 Byte		

According to (2), (3), and (4):

$$T_{GF\_HT\_PREAMBLE} = 28\ \mu s \tag{6}$$

$$N_{SYM} = 103.28\ \mu s \tag{7}$$

$$L_1 = 407.82\ \mu s \tag{8}$$

$$Delay\ Time = 0.008477154\ sec \tag{9}$$

Finally, the TMT is equal to:

$$TMT = \frac{8 \times 1000}{0.008477154} = 0.943712966\ Mbps \tag{10}$$

The TMT and Delay Time are calculated for the five scenarios; 10, 20, 30, 40, and 50 STAs, and the calculation results are shown in Tables IV, V, VI, VII, and VIII, respectively.

TABLE IV: TRANSMISSION TIME FOR THE TMT AND DELAY TIME PARAMETERS OF IEEE 802.11N FOR OPTIONAL TEN STAS

Packet size (Byte)	L_1 (µs)	Delay Time(sec)	TMT(Mbps)
1000	407.8153846	0.008477154	0.943712966
1100	444.7384615	0.008846385	0.994756659
1200	481.6615385	0.009215615	1.041710141
1300	518.5846154	0.009584846	1.085046106
1400	555.5076923	0.009954077	1.125167114

TABLE V: TRANSMISSION TIME FOR THE TMT AND DELAY TIME PARAMETERS OF IEEE 802.11N FOR OPTIONAL TWENTY STAS

Packet size (Byte)	L_1 (µs)	Delay Time(sec)	TMT(Mbps)
1000	407.83846	0.016149308	0.495377273
1100	444.7384615	0.016887769	0.521087177
1200	481.6615385	0.017626231	0.544642818
1300	518.5846154	0.018364692	0.56630407
1400	555.5076923	0.019103154	0.586290625

TABLE VI: TRANSMISSION TIME FOR THE TMT AND DELAY TIME PARAMETERS OF IEEE 802.11N FOR OPTIONAL THIRTY STAS

Packet size (Byte)	L_1 (µs)	Delay Time(sec)	TMT(Mbps)
1000	407.8153846	0.023821462	0.335831619
1100	444.7384615	0.024929154	0.353000349
1200	481.6615385	0.026036846	0.368708251
1300	518.5846154	0.027144538	0.383134162
1400	555.5076923	0.028252231	0.396428873

TABLE VII: TRANSMISSION TIME FOR THE TMT AND DELAY TIME PARAMETERS OF IEEE 802.11N FOR OPTIONAL FORTY STAS

Packet size (Byte)	L_1 (μs)	Delay Time(sec)	TMT(Mbps)
1000	407.8153846	0.031493615	0.25401974
1100	444.7384615	0.032970538	0.266904952
1200	481.6615385	0.034447462	0.278685267
1300	518.5846154	0.035924385	0.289496956
1400	555.5076923	0.037401308	0.29945477

TABLE VIII: TRANSMISSION TIME FOR TMT AND DELAY TIME PARAMETERS OF IEEE 802.11N FOR OPTIONAL FIFTY STAS

Packet size (Byte)	L_1 (μs)	Delay Time(sec)	TMT(Mbps)
1000	407.8153846	0.039165769	0.204259999
1100	444.7384615	0.041011923	0.214571747
1200	481.6615385	0.042858077	0.223995118
1300	518.5846154	0.044704231	0.232640173
1400	555.5076923	0.046550385	0.240599516

From Tables IV, V, VI, VII and VIII, we noticed that TMT and Delay Time are increased by increasing the packet size for all scenarios.

After completing the theoretical analysis, all scenarios have been simulated. The following figures explain the simulation results.

Fig. 6 shows the Delay Time versus packet size with respect to number of stations. As shown, increases number of stations, increases the delay time for all values of packet size used in the simulation.

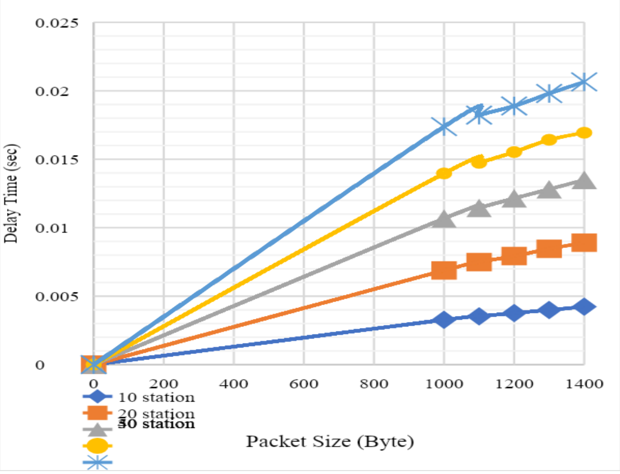

Fig. 6. Delay time versus packet size of 802.11n for different number of stations

Fig. 7 shows the TMT versus packet size for different number of stations. As shown, increases number of stations, decreases the TMT.

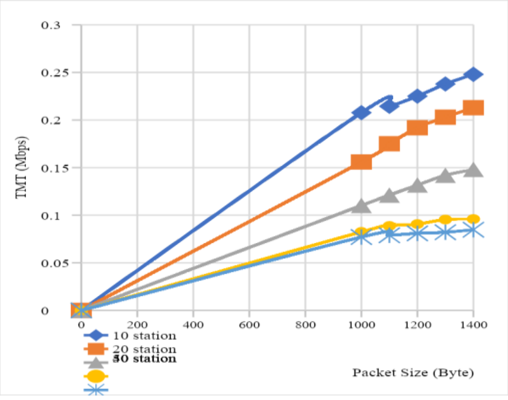

Fig. 7. TMT versus packet size of 802.11n for different number of stations

Fig. 8 shows the Delay Time versus number of stations with respect to packet size. As shown, increases the packet size, increases the delay time.

Fig. 9 shows the TMT versus number of stations with respect to packet size. As shown, increases the packet size, increases the TMT.

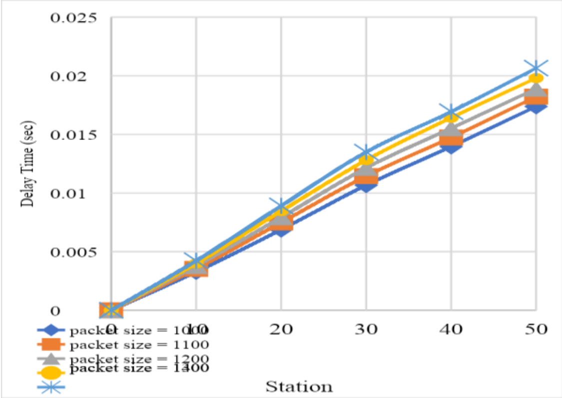

Fig. 8. Delay time versus station of 802.11n for different packet sizes

Most of previous studies that have been mentioned in literature used different complicated equations to calculate the TMT and Delay Time. In this paper, we reduced equations complexity. In addition, we developed a simulation consists different scenarios using OPNET modeler.

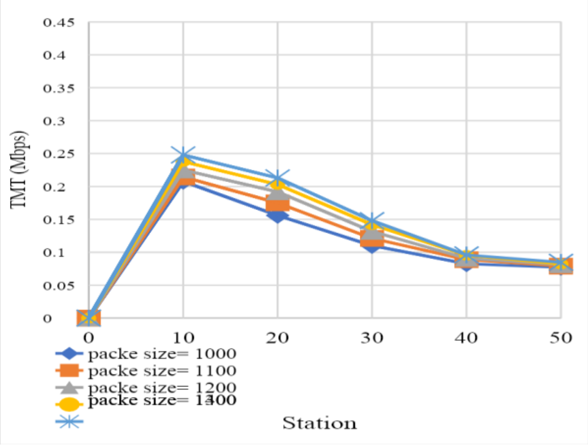

Fig. 9. TMT versus station of 802.11n different packet sizes

The computed results based on our theoretical model show that increases the packet size, increase TMT and delay time. The simulation results are shown in figures 6,7,8 and 9. Figures 6 and 7 show the Delay time and the TMT versus the packet size for different number of stations. The results show that increases number of stations, increases the Delay time and decreases the TMT.

Figures 8 and 9 show the Delay time and the TMT versus number of stations for different values of packet size. As shown, increases the packet size, increases the Delay time and TMT.

V. CONCLUSIONS

Performance analysis of IEEE 802.11n PCF MAC layer Wireless LANs in terms of calculating theoretical maximum throughput (TMT) and delay time was performed. Both analytical and simulation models have been developed to characterize the performance metrics. We have used five different scenarios operating in the 5 GHz band with variable packet size. We have examined the effects of network variables including packet size, number of stations and their impact on the throughput and delay performance. The relationship of TMT and delay time with packet size is studied. The results showed that as the number of stations increases, the delay time increases and the TMT decreases. When examined the relationship of TMT and delay time as a function of the number of stations, we noticed that there is an increase in network performance. The results showed that theoretical and simulation models provide comparable performance. Specifically, the delay time in simulation results is a bit higher than the theoretical analysis while the TMT in the simulation is a bit lower. This is because of the relaxed (ideal) assumptions used in developing the theoretical model.

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