

Saturation Throughput and Delay Performance Evaluation of the IEEE 802.11g/n for a Wireless Lossy Channel

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Abstract Non-ideal channel conditions degrade the performance of wireless networks due to the occurrence of frame errors. Most of the well-known works compute the saturation throughput and packet delay for the IEEE 802.11 Distributed Coordination Function (DCF) protocol with the assumption that transmission is carried out via an ideal channel (i.e., no channel bit errors or hidden stations), and/or the errors exist only in data packets. Besides, there are no considerations for transmission errors in the control frames (i.e., Request to Send (RTS), Clear to Send (CTS), and Acknowledgement (ACK)). Considering the transmission errors in the control frames adds complexity to the existing analysis for the wireless networks. In this paper, an analytical model to evaluate the Medium Access Control (MAC) layer saturation throughput and packet delay of the IEEE 802.11g and IEEE 802.11n protocols in the presence of both collisions and transmission errors in a non-ideal wireless channel is provided. The derived analytical expressions reveal that the saturation throughput and packet delay are affected by the network size (n), packet size, minimum backoff window size (W_{min}), maximum backoff stage (m), and bit error rate (BER). These results are important for protocol optimization and network planning in wireless networks.

Index Terms— IEEE 802.n, WLAN performance, Noise Channel, Throughput, Delay, DCF

I. INTRODUCTION

The non-ideal channel conditions leads to frames error that degrade the performance of the IEEE 802.11 wireless networks. The throughput performance of the Medium Access Control (MAC) layer in the IEEE 802.11 can be improved using combination several frames before transmission [1]. An analytical model that calculates the probability of frame error in MAC service data scheme is proposed in [2]. The scheme uses Distributed Coordination Function (DCF) and the High Throughput Physical Layer (HT-PHY). Another analytical model for the 802.11 multi-radio network using the uniform random interface selection strategy applied is presented in [3]. In that work [3], the authors assumed that the transmission is always under ideal channel conditions, a limited number of stations exist in the same collision domain, and the packet transmitted collision probability for each node is independent.

Bencini and Fantacci in [4] have proposed an analytical model for a single-hop multi-interface IEEE 802.11 DCF mesh network. In that model the

nodes utilize the Uniform Random Interface Selection (URIS) policy in order to select the transmitting channel. Similar to [3], the model is derived based on the assumption that transmission is under ideal channel conditions, number of nodes are finite.

In [5], the analytical network model that considers the effect of packet errors in various MAC protocols is presented. In another model [6], the authors have considered the errors exist in data frames to calculate the throughput, packet drop probability, and average packet delay. Li et al. [7] have introduced an analytical model to estimate the performance of the IEEE 802.11 DCF protocol that ignores the present of transmission errors in the control frames. Similarly, the works are also available in [2], [5]-[13] that ignore the transmission errors in the control frames (i.e., RTS, CTS, and ACK).

Authors in [9] have presented a method for estimation the saturation throughput in non-ideal channel based on the concept of virtual slot. They assumed that collisions only occur during the RTS frame and ignore the hidden node effect, such as in the analysis of [14]. In the IEEE 802.11n, the frame aggregation process can be performed either by the

MAC Protocol Data Unit Aggregation (AMPDU) or the MAC Service Data Unit Aggregation (AMSDU) [15], [16], [17]. The frame aggregation increases throughput of the MAC layer in case the ideal channel conditions is considered. However, a larger collected frame causes each node to wait longer, prior its next chance for channel access [18]. Therefore, there exist a tradeoff between the delay and throughput. Other MAC mechanisms in the IEEE 802.11n that offer the frame aggregation service are the block acknowledgement, bidirectional data transmission, and uni-directional data transmission that presented in [19]. In [19], the authors have proposed an analytical model to estimate the throughput of the IEEE 802.11n protocol.

In [20], an analytical model based on generalized two dimensional Markov chain is developed for the IEEE 802.11 DCF under ideal transmission channel. The authors [20] have considered several assumptions such as, the system have the unsaturated traffic, retry limits, backoff freezing, and the limited buffer size. A unified analytical model for IEEE 802.11 MAC protocol for the ad-hoc network in unsaturated conditions with heterogenous traffic flows is developed in [21]. The analytical model considers the impacts of channel access parameters, traffic rate and buffer size on the 802.11 DCF performances. Similar work can be found in [22], where the authors analyzed the throughput of the IEEE 802.11 protocol in the non-saturated traffic conditions by considering the imperfect channel sensing.

The hidden node problem does not eliminate by use the RTS/CTS mechanism in wireless multihop networks [23], [24]. Considering the non-ideal channel and hidden node problems adds complexity to the existing analysis for multihop networks. Moreover, ignoring the hidden nodes effect and assuming ideal channel conditions (i.e., no link errors) in the analysis model cannot completely or accurately validate the network. Therefore, building an accurate mathematical model for the network performance evaluation is still an open issue. Consequently, this serves as the main motivation of this work.

In this paper, the non-ideal channel conditions and hidden nodes collision are considered in the analysis to evaluate the network performance. The analytical proposed model can be used to accurately estimate the saturation throughput and packet delay for the IEEE 802.11g and IEEE 802.11n standard protocols. The exact relationship between the saturation throughput and delay with various channel conditions, such as the number of contending nodes, packet size, maximum backoff stage (m), and (W_{min}) with different BER values are introduced.

The outline of this paper is structured as follows. Section 2 presents the proposed analytical model. Section 3 discusses the analytical simulation results. Finally, section 4 concludes the paper.

II. ANALYTICAL MODEL

The proposed analytical model to evaluate the MAC layer saturation throughput and packet delay of the IEEE 802.11g/n protocols is presented in this section. The analysis assumes that the presence of both collisions and transmission errors in a non-ideal wireless channel. Fig. 1 shows the hidden node problem when a node cannot hear other node because it is located outside the transmission range. Node A is assumed located inside the transmission range of Nodes B and C. Node C is located outside the transmission range of node B. Node B is hidden node within node C. If nodes B and C transmit to A at the same time, then collision will be occur.

In this paper, two types of collisions in the RTS/CTS method may happen. The first collision can happen if two RTS frames transmit at the same time from B and C to A (i.e., RTS_b and RTS_c) as show in Fig. 1. The second collision, it can happen during CTS frame transmission, as the following scenario. After B sends the RTS_b frame to A, considering C did not hear B, and C sends a RTS_c frame to A simultaneous that A sends a CTS_a frame to node B, as the request to RTS_b frame. More details for hidden nodes problems can be found in [24]. In this paper, several additional necessary assumptions are made for the analytical model as follows: i) The RTS/CTS access method is applied. ii) A limited number of nodes operate in the saturated conditions exists. iii) Timeouts of ACK and CTS frames are

contemplated. iv) Hidden node problem is deliberated. v) Multi-hop wireless communication. vi) RTS and CTS frames collision occurs because the hidden node. vii) The error probabilities of RTS, CTS, ACK and data frames are deliberated. The difference between analysis in this paper with the previous works in [1]-[4], [8]-[14], [17]-[23], and [25]-[29] are the additional assumptions numbered as (vi) and (vii). For this reason, it is not possible (not fair) to compare with previous models.

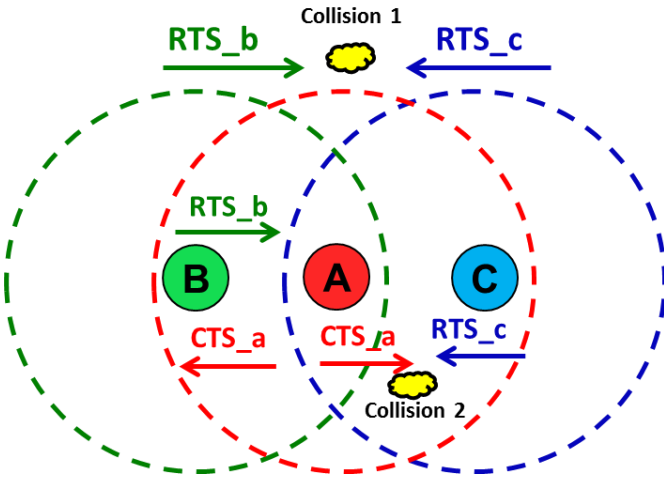


Fig. 1 RTS and CTS frames collision because the hidden node problem.

In this work, the mathematical model is developed using MATLAB software by taking into consider both transmission errors of the IEEE 802.11g/n, and hidden nodes. The performance model calculates saturation throughput and packet delay for RTS/CTS scheme for non-ideal channel.

A. Virtual Time Slots

Based on the non-ideal channel conditions and hidden nodes collision problem that are considered in the analysis assumption, a mathematical model for the virtual time slot parameter is derived below. Seven kinds of virtual time slots, as shown in Fig. 2, is used to compute saturation throughput and packet delay of the IEEE 802.11g/n for a non-ideal wireless channel. The virtual time slots for the RTS/CTS are given as follows:

1. Empty time slots (T_E) defined as:

$$T_E = \sigma \quad (1)$$

σ indicates the time slot duration needed by any node to detect the channel transmission if it is busy or not. The value of σ is = 9 μ sec. It depends on the characteristics of the physical and MAC layers.

2. Collision time slots: If the hidden node problem is considered, a collision might happen within the RTS and CTS. The parameters T_{RTSC} and T_{CTSC} indicate the average time that the channel is sensed busy due to frame collision during the RTS and CTS transmission, respectively, that can be expressed as follows:

$$T_{RTSC} = T_{RTS} + DIFS + \delta \quad (2)$$

$$T_{CTSC} = T_{RTS} + SIFS + \delta + T_{CTS} + DIFS + \delta \quad (3)$$

Where, *SIFS* is the “short inter frame space time”, and *DIFS* is the “distributed inter frame space time”. The parameters T_{RTS} , T_{CTS} are the durations of the RTS, CTS frames, respectively and the δ is the channel propagation delay (1 μ sec).

The collision time slots T_C is defined as,

$$T_C = T_{RTSC} + T_{CTSC} \quad (4)$$

3. The RTS error time slot (T_{ERTS}): When an error happens in RTS transmission, it can be defined as follows:

$$T_{ERTS} = T_{RTS} + T_{EIFS} + \sigma \quad (5)$$

Where, T_{RTS} is the transmission time of the RTS frame and the T_{EIFS} is the extended inter frame space time that given by Eq. (6)

$$T_{EIFS} = SIFS + \delta + T_{CTS} + DIFS + \delta \quad (6)$$

If an error occurs in RTS and CTS control frames transmission, the source node waits for the end of the CTS timeout timer (*SIFS* + *CTS*), whereas other nodes wait for the time extended inter

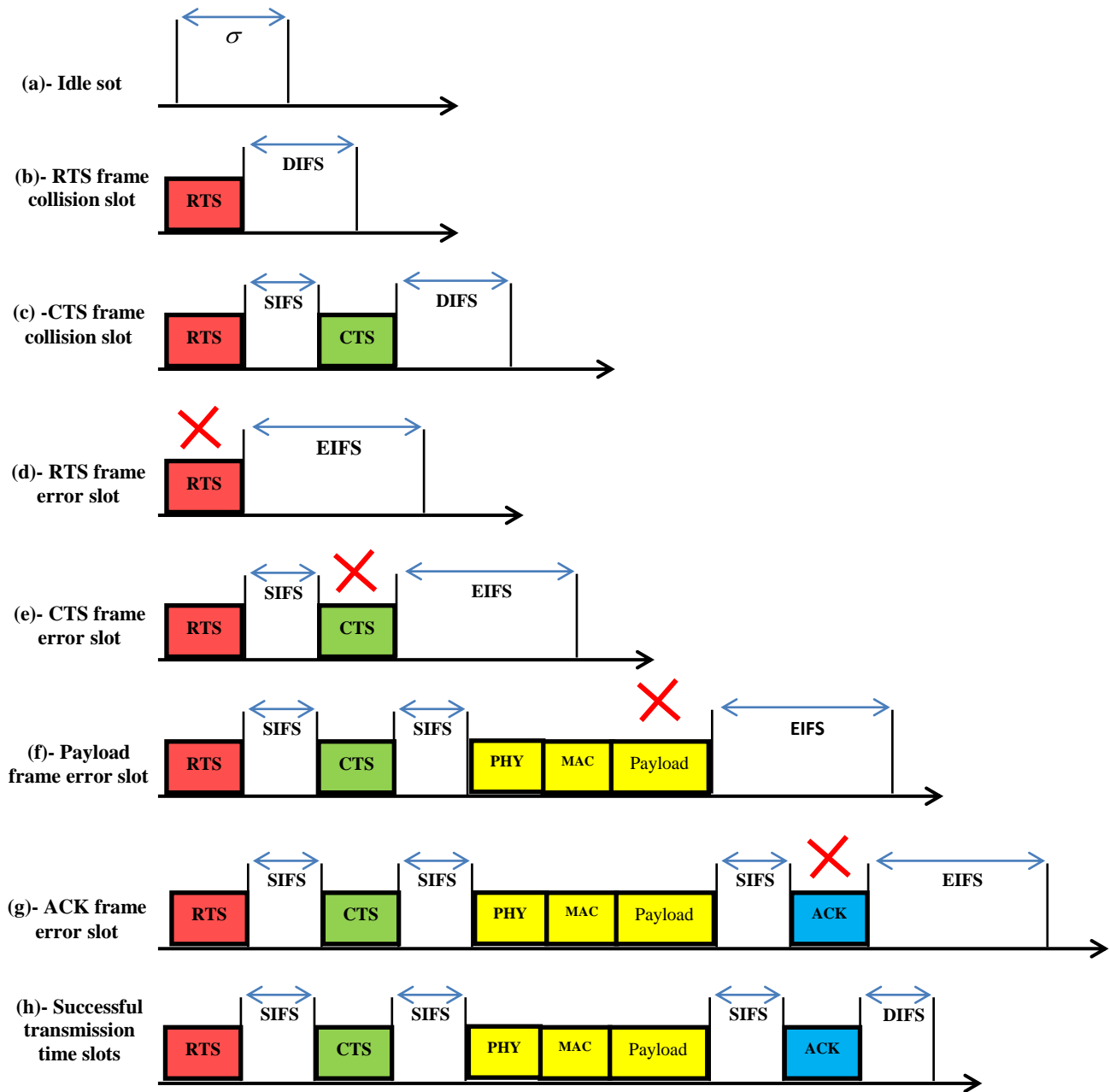


Fig. 2 RTS/CTS virtual time slots

frame space (T_{EIFS}) interval to resume backoff. The length of the T_{EIFS} interval is the same as that of the CTS timeout timer and $DIFS$ combined.

4. The CTS error time slot (T_{ECTS}), when an error occurs in CTS frame transmission, it can be expressed as:

$$T_{ECTS} = T_{RTS} + SIFS + \delta + T_{CTS} + T_{EIFS} + \sigma \quad (7)$$

Where, T_{CTS} is the transmission time of CTS frame.

5. The error time slot in data frame T_{EDATA} , when an error occurs in transmitting a payload frame, is given by the following:

$$T_{EDATA} = T_{RTS} + SIFS + \delta + T_{CTS} + SIFS + \delta + T_{PHY} + T_{MAC} + T_{PL} + T_{EIFS} + \sigma \quad (8)$$

Where, T_{PHY} is the time duration of the Physical headers, T_{MAC} is the time duration of MAC headers and T_{PL} is the time duration of packet payload.

A node that receives incorrect data frames waits for (T_{EIFS}) interval to resume backoff. Meanwhile, the transmitting node waits for the expiration of the ACK timeout timers ($SIFS+ACK$), whereas other nodes wait for the time extended inter frame space (T_{EIFS}) interval to resume backoff.

6. The ACK error time slot: When an error occurs in transmitting an ACK control frame it can be expressed as:

$$T_{EACK} = T_{RTS} + \delta + SIFS + T_{CTS} + SIFS + \delta + T_{PHY} + T_{MAC} + T_{PL} + SIFS + \delta + T_{ACK} + T_{EIFS} + \sigma \quad (9)$$

Where, T_{ACK} is the transmission time of the ACK frame. In case of ACK error time slot, the no error in the RTS, CTS and data frames is assumed.

7. Finally, T_{ST} denotes the successful transmission of time slots which can be expressed as:

$$T_{ST} = T_{RTS} + \delta + SIFS + T_{CTS} + \delta + SIFS + T_{PHY} + T_{MAC} + T_{PL} + \delta + SIFS + T_{ACK} + \delta + DIFS + \sigma \quad (10)$$

The virtual time slots that is expressed in Eq. (2) and Eq. (3) are considered due to the assumptions (vi) that assumed a collision might happen in RTS and CTS frames. On the other hand, the virtual time slots that is expressed in Eqs. (5, 7, 8 and 9) are considered due to the assumptions (vii) when the error probabilities might happen during the transmission of the RTS, CTS, ACK and data frames are assumed.

B. Packet Transmission, Conditional Collision and Frame Error Probabilities

To compute the saturation throughput and packet delay, the packet transmission, conditional collision and frame error probabilities are necessary defined.

Based in [14], the packet transmission probability (τ) in a randomly chosen slot time is given as:

$$\tau = \frac{2}{1 + W_{min} + W_{min} P \frac{(2P)^m - 1}{2P - 1}} \quad (11)$$

Where, (W_{min}) is the minimum backoff window size, (m) is the maximum number of retransmissions or the maximum backoff stage and P is the unsuccessful transmission probability. When the transmission considers both the collisions and transmission errors within a time slot as assumed, P can be expressed as

$$P = 1 - (1 - P_c)(1 - P_e) \quad (12)$$

The (P_c) is the conditional collision probability defined as the probability of at least one of the ($n-1$) remaining nodes transmit within the same time slot. Additionally, the parameter (P_c) can be expressed as;

$$P_c = 1 - (1 - \tau)^{n-1} \quad (13)$$

Where (n) is the number of nodes. The frame error probability (P_e) is the error probability with the condition that there is a successful RTS/CTS transmission within the time slot as expressed as:

$$P_e = 1 - (1 - \beta)^{RTS+CTS+PHY+MAC+PL+ACK} \quad (14)$$

Where β is the bit error rate and PL is the packet payload size. Equations (11) and (12) represent a non-linear system with two variables (τ) and (P). This non-linear system has a unique solution and can be solved utilizing numerical methods based on Eqs. (13) and (14).

C. Saturation Throughput and Successful Transmission Probability

After, the packet transmission (τ), conditional collision (P_c) and frame error (P_e) probabilities is defined in the prior subsection. In this subsection, and based on the packet transmission probability (τ), another probabilities to compute the saturation

throughput are needed to define, these probabilities will be used to compute the delay packet (D). These probabilities define as the follows; probability of at least one node transmission (P_{TR}), probability of the idle channel (P_{id}), probability of a successful transmission on channel (P_{ST}), probability that at least one node transmission is successful (P_S), collision probability (P_{col}), error probability of transmitting RTS frame (P_{ERTS}), error probability of transmitting CTS frame (P_{ECTS}), error probability of transmitting ACK frame (P_{EACK}), the error probability of transmitting a data packet (P_{EDATA}), and the successful transmission probability (P_{ST}).

The saturation throughput is defined as the ratio;

$$S_{TH} = \frac{\text{Expected}[\text{payload transmitted in a virtual slot}]}{\text{Expected}[\text{length of a virtual slot}]}$$

Assuming that P_{TR} is the probability of at least one transmission happen in the considered time slot, it can be expressed as the following:

$$P_{TR} = 1 - (1 - \tau)^n \quad (15)$$

P_{id} is the probability of the idle channel.

$$P_{id} = 1 - P_{TR} = (1 - \tau)^n \quad (16)$$

The successful transmission probability on a channel (P_{ST}) is defined as the probability that at least one node transmit on the channel [14].

$$P_{ST} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (17)$$

Where, P_S is the probability that at least one node transmission is successful in a given time slot on the channel and the probability that other $n-1$ nodes remain silent. From Eq. (15) and Eq. (17), the P_S is expressed as follows:

$$\begin{aligned} P_S &= P_{TR}P_{ST} \\ P_S &= n\tau(1-\tau)^{n-1} \end{aligned} \quad (18)$$

The collision probability defines as follows:

$$P_{col} = 1 - P_S - P_{id} \quad (19)$$

After substituting both Eq. (16) and Eq. (18) into Eq. (19),

$$P_{col} = 1 - n\tau(1-\tau)^{n-1} - (1-\tau)^n \quad (20)$$

The error probability of transmitting a RTS frame in error express as;

$$P_{ERTS} = P_S(1-\beta)^{RTS} \quad (21)$$

The error probability of transmitting a CTS frame in error is expressed as;

$$P_{ECTS} = P_S(1-\beta)^{RTS}(1-(1-\beta)^{CTS}) \quad (22)$$

The error probability of transmitting a data packet in error is expressed as;

$$P_{EDATA} = P_S(1-\beta)^{RTS+CTS}(1-(1-\beta)^{PHY+MAC+PL}) \quad (23)$$

The error probability of transmitting an ACK frame in error is expressed as;

$$P_{EACK} = P_S(1-\beta)^{RTS+CTS+PHY+MAC+PL}(1-(1-\beta)^{ACK}) \quad (24)$$

A successful transmission probability is expressed as follows:

$$P_{ST} = P_S(1-\beta)^{RTS+CTS+PHY+MAC+PL+ACK} \quad (25)$$

Therefore, combining all Eqs. (1, 4, 5, 7, 8, 9, 10, 19, 20, 21, 22, 23, 24, and 25). The system saturation throughput (S_{TH}) can be expressed as Eq. (26).

$$S_{TH} = \frac{P_{ST}PL}{P_{id}T_E + P_{col}T_C + P_{ERTS}T_{ERTS} + P_{ECTS}T_{ECTS} + P_{EDATA}T_{EDATA} + P_{EACK}T_{EACK} + P_{ST}T_{ST}} \quad (26)$$

D. Delay of Packet Transmission

The delay is defined, (due to the proposed assumption numbered as (vi) and (vii)), to be the duration of a successful packet transmission (T_{ST}) as shown in Fig. 2 (h), duration of the wasted time due to error transmissions (T_{ERTS} , T_{ECTS} , T_{EDATA} , T_{EACK}) as shown in Fig. 2 (d, e, f, and g), empty time slots (T_E) as shown in Fig. 2 (a) and collisions (T_{RTSC} , T_{CTSC}) as shown in Fig. 2 (b and c).

The delay (D) for a successfully transmitted packet is defined as the product of the average length of time slot (L_{slot}) with the average number of time slots for successful packet transmission (N_{slot}) [30] as follows

$$D = L_{slot} \times N_{slot} \quad (27)$$

Where,

$$N_{slot} = d_i \times q_i \quad (28)$$

d_i signify the time slots number during the packets are delayed in each m , whereas q_i signify the probability of reaching the m . The d_i and q_i parameters are expressed as Eq. (29) and Eq. (30) [24]:

$$d_i = \frac{W_i + 1}{2}, \quad i \in [0, m] \quad (29)$$

$$q_i = \begin{cases} P^i, & i \in [0, m-1] \\ \frac{P^i}{1-P}, & i = m \end{cases} \quad (30)$$

After substituting both Eq. (29) and Eq. (30) into Eq. (28),

$$N_{slot} = \sum_{i=0}^m \frac{W_i + 1}{2} \times \frac{(P^i - P^{m+1})}{1 - P^{m+1}} \quad (31)$$

After, a number of mathematical manipulations on Eq. (31), N_{slot} can be written as;

$$N_{slot} = \frac{(1-2P)(1+W) + WP(1-(2P)^m)}{2(1-2P)(1-P)} \quad (32)$$

where, the average length of a slot time (L_{slot}), can be expressed as sum the multiplication all the virtual slot times that assumed with their probabilities.

$$L_{slot} = P_{id}T_E + P_{col}T_C + P_{ERTS}T_{ERTS} + P_{ECTS}T_{ECTS} + P_{EDATA}T_{EDATA} + P_{EACK}T_{EACK} + P_{ST}T_{ST} \quad (33)$$

III. DISCUSSION THE NUMERICAL RESULTS

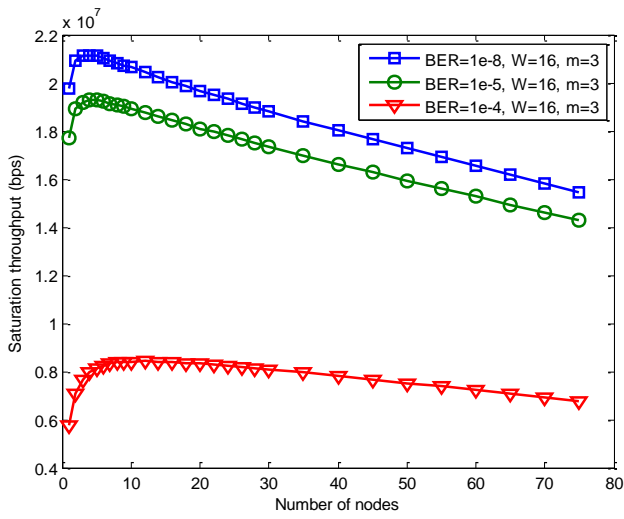
The numerical results of the proposed analytical model for the IEEE 802.11g and IEEE 802.11n protocols are presented in this section. Table 1 shows the network parameters values that used for the analysis [31].

Table I. Physical and MAC Layers System Parameters

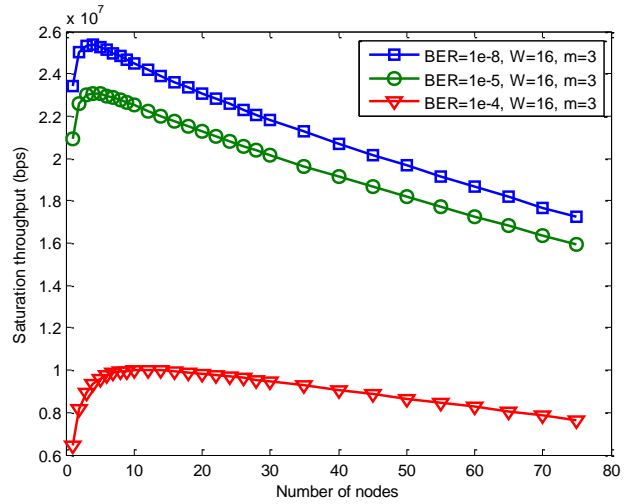
Parameter	IEEE 802.11g	IEEE 802.11n
Packet payload	1023 Bytes	1023 Bytes
MAC header	272 bits	272 bits
PHY header	20 μ sec	20 μ sec
ACK Size	112 bits	112 bits
CTS Size	112 bits	112 bits
RTS Size	160 bits	160 bits
DIFS	28 μ sec	34 μ sec
SIFS	10 μ sec	16 μ sec
Slot time (σ)	9 μ sec	9 μ sec
W_{min} (units of Slot)	15	15
W_{max} (units of Slot)	1023	1023
Channel propagation delay (δ)	1 μ sec	1 μ sec
Channel bit rate	54 Mbps	54*k Mbps, (k=2,3,..)
L_{Tail}	6 bits	6 bits
$L_{Service}$	16 bits	16 bits
T_{Sym} "symbol duration"	4 μ sec	4 μ sec
T_{Ex}	6 μ sec	6 μ sec
T_{NDS} Data bits per OFDM symbol	216	216*k, (k=2, 3,..)

The figures below show the results that obtained for the analysis of the protocols in terms of saturation throughput and packet delay. In this analysis, the effect of BER, number of nodes in the network (n), packet size (PL), maximum backoff stage (m), and minimum backoff windows (W_{min}) on the saturation throughput and packet delay are studied.

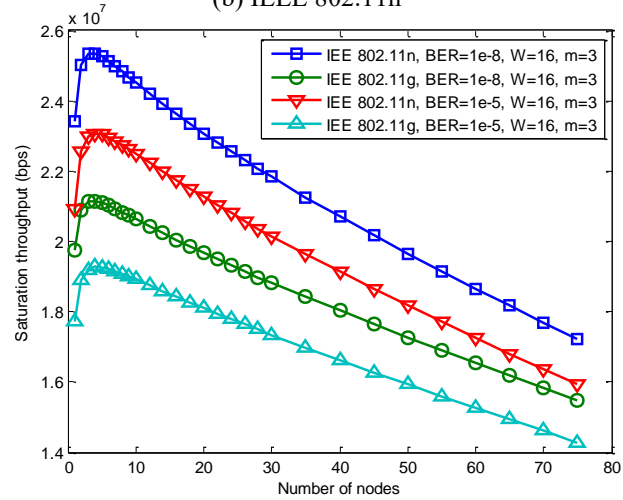
Fig. 3 (a, b, c) present the saturation throughput versus n for different BER values (1e-5 and 1e-8) with $W_{min} = 16$ and $m = 3$. The analysis in Fig. 3a uses the IEEE 802.11g protocol, and Fig. 3b uses the IEEE 802.11n protocol respectively. Fig. 3c compares the saturation throughput performance between IEEE 802.11g, IEEE 802.11n protocols respectively. These figures show the evident that when the number of nodes increase the saturation throughput decreases.



(a) IEEE 802.11g



(b) IEEE 802.11n



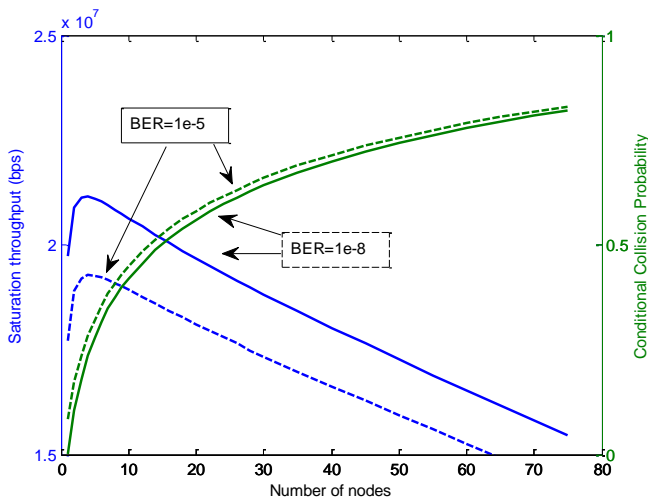
(c) IEEE 802.11g/n

Fig. 3 (a, b, c) demonstrate the effects of number of nodes on the saturation throughput performance. In addition, Fig. 3c shows the throughput performance of the IEEE 802.11n is better than IEEE 802.11g protocols at different BER.

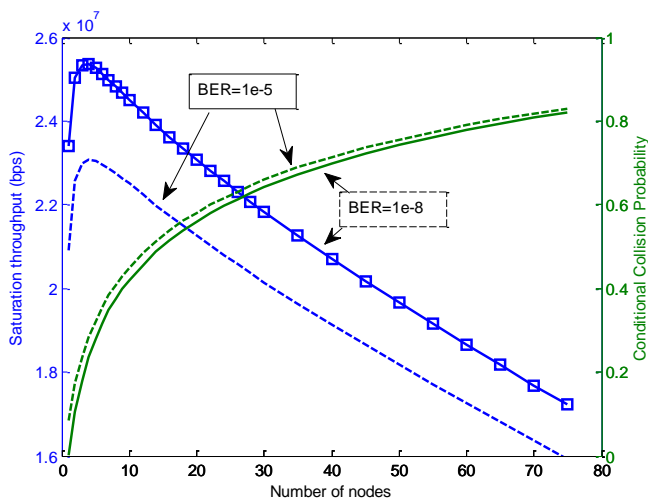
Accordingly, increased the number of nodes leads to the increased the collision probability that leads to decrease the packet transmission probability (τ). Thus, this causes the probability of successful transmission (P_{ST}) to decrease, which results the saturation throughput decreases.

Fig. 3 (a, b, c) Saturation throughput versus number of nodes at different BER

Fig. 4a and Fig. 4b show the plot of saturation throughput and conditional collision probability against the number of nodes. The analysis in Fig. 4a uses for IEEE 802.11g and Fig. 4b uses the IEEE 802.11n. In both figures the analysis uses the BER = 1e-8 and 1e-5 and $W_{min} = 16, m = 3$. The figures clearly show that saturation throughput and conditional collision probability is highly dependent on the number of contenting nodes. Saturation throughput decreases and conditional collision probability increased. This means that when the network size grows, more nodes try to transmit, this leads to more packet collisions happened at different BER.



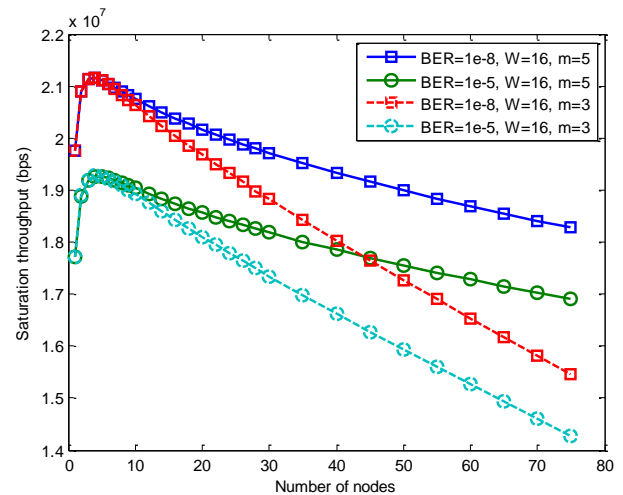
(a) IEEE 802.11g



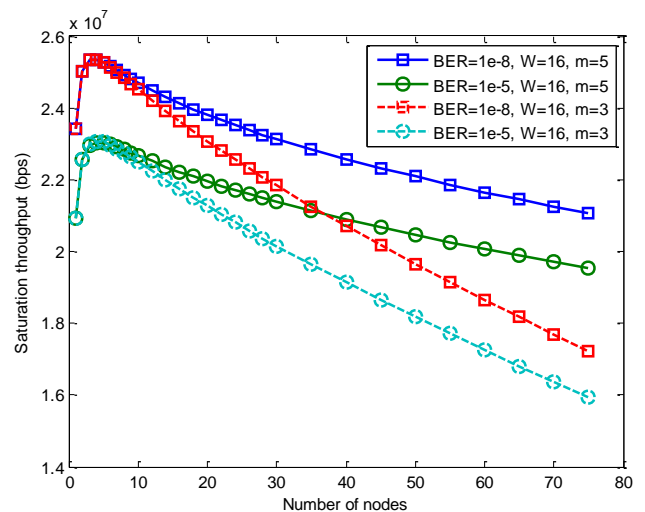
(b) IEEE 802.11n

Fig. 4 (a, b) Saturation throughput and conditional collision probability versus number of nodes at different BER

Fig. 5a and Fig. 5b present the saturation throughput against number of nodes with $W_{min} = 16, m = 3$ and 5 at different BER values (1e-5 and 1e-8). The analysis in Fig. 5a uses the IEEE 802.11g, and Fig. 5b uses the IEEE 802.11n protocols respectively. The aim of this analysis is to examination the effect of minimum backoff stage (m) in the saturation throughput at the same BER and W_{min} values. The figures show that the performance of saturation throughput when $m = 5$ is better than $m = 3$ at same BER and W_{min} , especially as the number of nodes increases. The figures also illustrate that the number of nodes affects the throughput performance.



(a) IEEE 802.11g



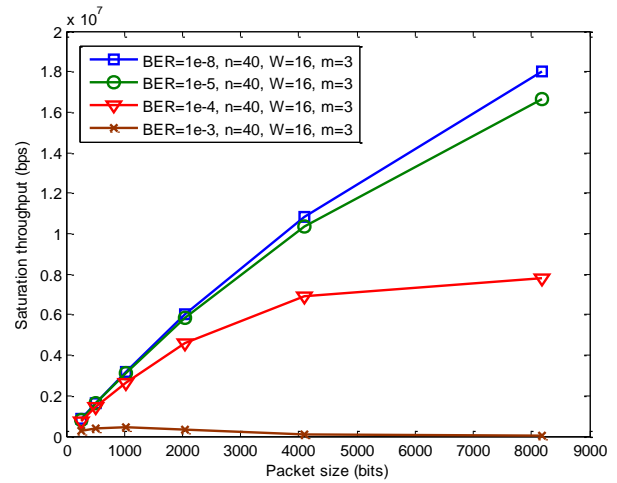
(b) IEEE 802.11n

Fig. 5 (a, b) Saturation throughput versus number of nodes at different BER and m

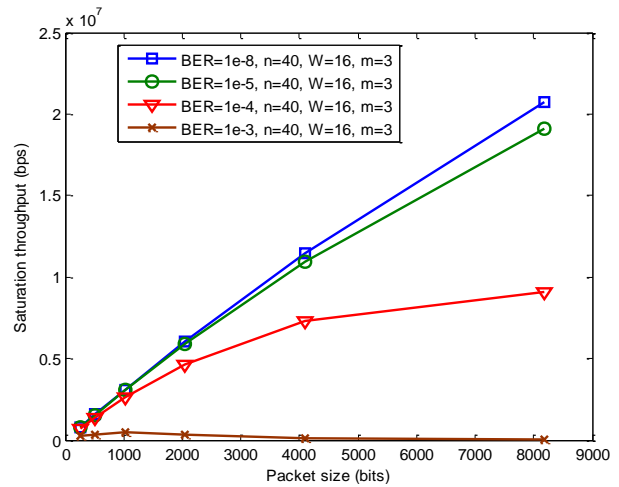
The higher the number of nodes in the network results higher number of packet collisions.

Fig. 6a to Fig. 6c illustrate the performance of saturation throughput versus the packet size at a fixed network size (40 nodes) at different BER values (1e-3, 1e-4, 1e-5, and 1e-8) with $W_{min} = 16$ and $m = 3$. The analysis in Fig. 6a uses the IEEE 802.11g, and in Fig. 6b uses the IEEE 802.11n protocols. The analysis in Fig. 6c shows the comparison of the saturation throughput performances between the IEEE 802.11g and IEEE 802.11n. Fig. 6a and Fig. 6b show that the throughput improves as packet size increased but the performance when the BER = 1e-5 and 1e-8 is better than that at BER = 1e-4 and 1e-3, due to the fact the number of transmissions error increased. The saturation throughput performance using the IEEE 802.11n protocol is still better than IEEE 802.11g protocol as shown in Fig. 6c. This is because the fact that increasing packet size (PL) leads to an increased in the successful transmission time slots (T_{ST}), accordingly increases in throughput (S_{TH}).

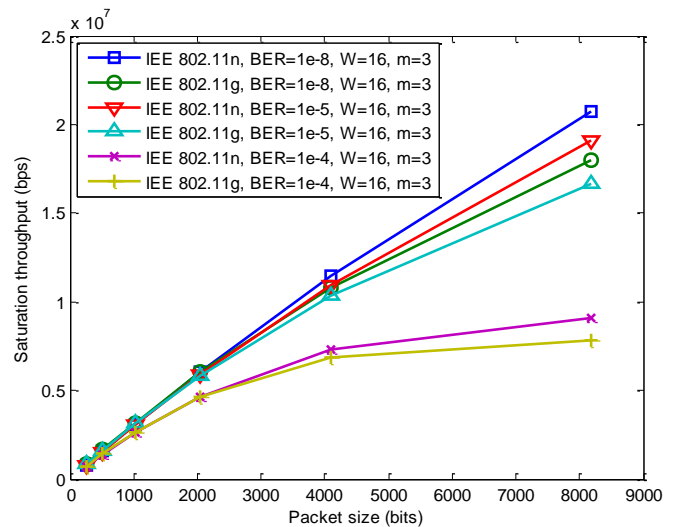
Fig. 7a and Fig. 7b illustrate the performance of packet delay versus packet size at different values of BER (1e-4, 1e-5 and 1e-8), $n = 40$, $m = 3$ and $W_{min} = 16$. The analysis in Fig. 6a uses the IEEE 802.11g and Fig. 7b uses the IEEE 802.11n protocols. Fig. 7a and Fig. 7b show that the packet delay gradually increases as the packet size increased. This is because the fact that increasing packet size (PL) leads to the increased the average length of a slot time (transmission time). As the channel conditions becomes poor (e.g., BER=1e-4), the figures show the delay rapidly increases with respect to the packet size. The packet delay increases due to the transmission error increased. Also, the number of retries to deliver the packet data increases which means that the packet delay increased. Fig. 7c presents the delay performance comparison for using the IEEE 802.11n and IEEE 802.11g protocols respectively. The figure demonstrates that the performance of the IEEE 802.11n is better than the IEEE 802.11g protocol. The delay of the IEEE 802.11n is less than the delay of the IEEE 802.11g protocol at the same BER, network size, m , and W_{min} .



(a) IEEE 802.11g

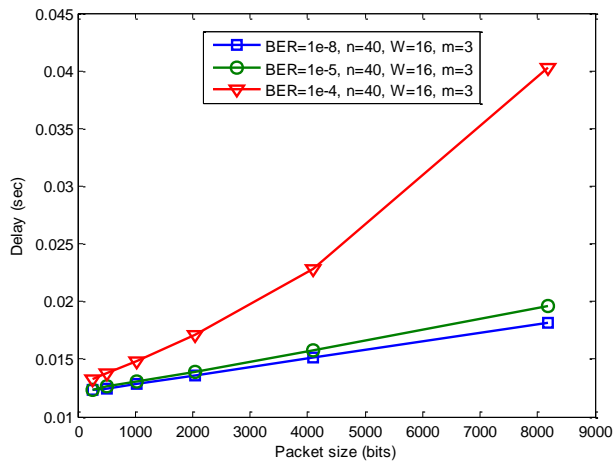


(b) IEEE 802.11n

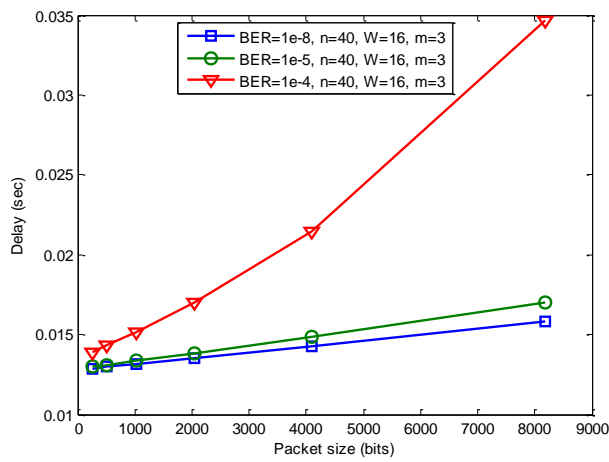


(c) IEEE 802.11g/n

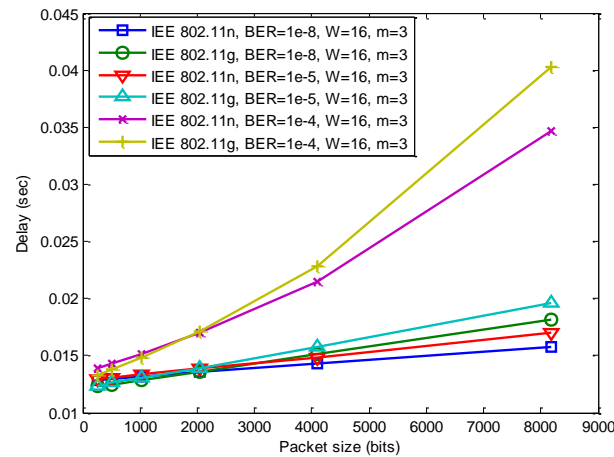
Fig. 6 (a, b, c) Saturation throughput versus packet size at different BER



(a) IEEE 802.11g



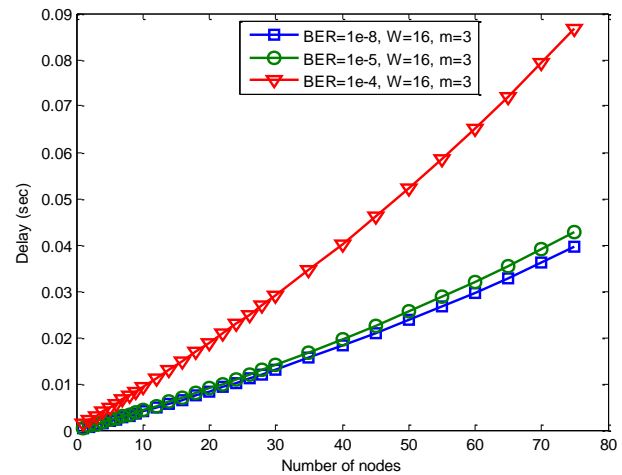
(b) IEEE 802.11n



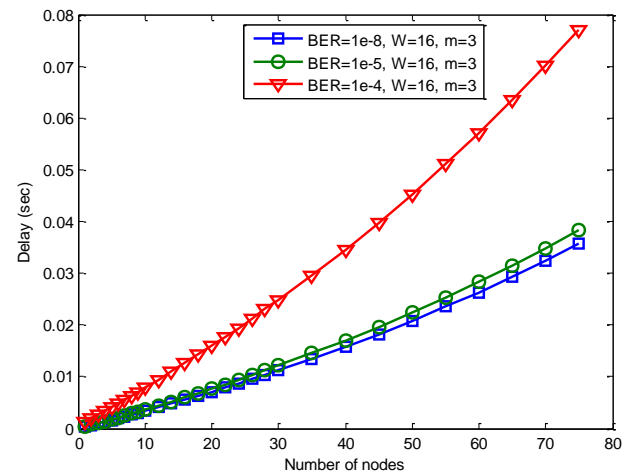
(c) IEEE 802.11g/n

Fig. 7 (a, b, c) Delay versus packet size at different BER

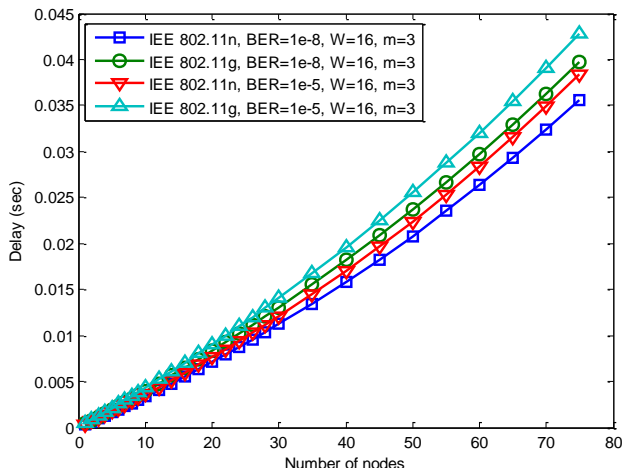
Fig. 8a to Fig. 8c demonstrate the effect of the number of nodes versus the packet delay at different values of BER ($1e-4$, $1e-5$ and $1e-8$), $n = 40$, $m = 3$ and $W_{min} = 16$. The analysis in Fig. 8a uses the IEEE 802.11g and Fig. 8b uses the IEEE 802.11n protocols, respectively. The figures show that the delay increases dramatically as the number of nodes increased. This is due to the collision probability that increased as the number of nodes increased as illustrated in Fig. 4. Furthermore, the delay is sensitive on network size. The increased in the number of contenting nodes causes more collisions to happen. This results in continuous packet retransmissions and therefore generate additional delay. The delay for the IEEE 802.11n protocol is less than the delay of the IEEE 802.11g protocol at the same BER and network size.



(a) IEEE 802.11g



(b) IEEE 802.11n



(c) IEEE 802.11g/n

Fig. 8 (a, b, c) Delay versus number of nodes at different BER

Finally, to explain and show the differences between the ideal channel (BER = 0) and non-ideal channel (BER = 1e-5), a comparison results for saturation throughput versus number of nodes for IEEE 802.11g and IEEE 802.11n is shown in Fig. 9. Fig. 9 demonstrates the BER effect the performance of saturation throughput. The ideal channel condition provides higher throughput in comparison to the throughput obtained when using the non-ideal channel.

Fig. 10 shows the saturation throughput versus packet size at BER = 0 and 1e-4 for IEEE 802.11g and IEEE 802.11n. Fig. 10 illustrates that the throughput obtained at BER = 0 is higher than at BER = 1e-4. Figures 9 and 10 represent the difference in network performance in the case of the ideal channel and the non-ideal channel.

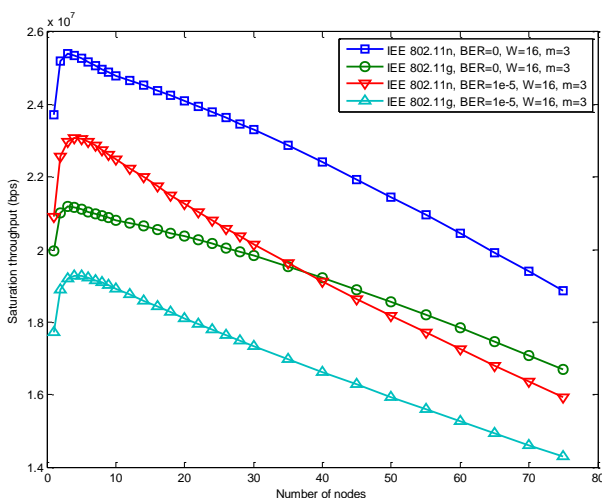


Fig. 9 Saturation throughput versus number of nodes for ideal channel (BER = 0) and non-ideal channel (BER = 1e-5)

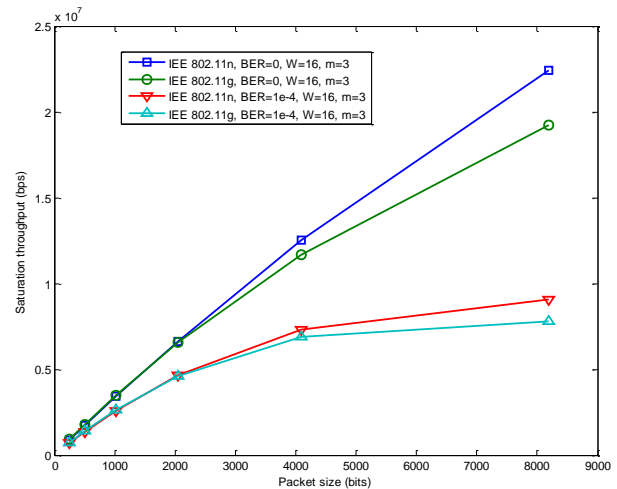


Fig. 10 Saturation throughput versus packet size at BER = 0 and 1e-4

IV. CONCLUSION

This paper presents an analytical model to analyze the protocols performance and compute the saturation throughput and packet delay for IEEE 802.11g and IEEE 802.11n at a non-ideal channel conditions. Because of the non-ideal wireless channel, the error happens during the sending RTS, CTS and ACK control frames as well as the data frame is assumed. The impact of transmission errors, number of nodes, packet size, minimum contention window size, and maximum number of backoff stages is introduced in the analytical model. According to the results of the analytical model, the channel conditions are one of the critical parameters that can effect on the saturation throughput and packet delay performance of the WLANs.

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