A New Performance Evaluation Model for IEEE 802.11DCF

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ABSTRACT: *Modeling and performance analysis of the media access control layer are extremely significant. Therefore, the performance evaluation helps a researcher in discovering the inherent cause of many problems, and may even suggest possible solutions. This is why much of the research work aimed to achieve an accurate evaluation. However, a lot of work does not consider the main difference between the busy probability and the collision probability in analytical mathematical models. Some of them consider both probabilities to be the same or ignore the busy probability and consider only the collision probability, which is not accurate. This paper proposes a new performance evaluation by creating a new mathematical model to compute a packet transmission probability for IEEE 802.11 DCF. Therefore, we enhance Bianchi's model by adding a new state to represent the busy probability in the mathematical model, which helps to achieve the highest accuracy performance evaluation of IEEE 802.11 DCF.*

Keywords: IEEE 802.11 Standard, Performance Analysis, Backoff Algorithm, Busy Probability and Collision Probability

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1. Introduction

The IEEE 802.11 (WLANs) standard still presents many challenges, most of them related to the Media Access Control (MAC) layer. The mechanism for accessing the media is based on two types of MAC mechanisms. Basic type is called the distributed coordination function (DCF) that represents the primary MAC mechanism for IEEE 802.11[1]. The DCF is based on the Listening Before Transmit (LBT) mechanism to detect whether a channel is idle or busy so as to avoid a collision [2]. The secondary part of DCF is called four-way hand-shaking technique or known as request to send/clear to send (RTS/CTS) mechanism. This mechanism helps the protocol reduce a collision by reserving the transmission media channel when the channel becomes idle [1] and also avoid the hidden station problem.

The DCF uses a control frame called acknowledgment (ACK) frame. This helps the sender station to detect whether a data frame has been successfully received or resulted in a collision. The optional type for MAC is called point coordination function (PCF). The MAC in PCF is centralized and able to avoid collision by using point inter frame space duration (PIFS) rather than distribution inter frame space duration (DIFS) [2]. In this paper, we focus on the basic mechanism (DCF) rather than the optional mechanism (PCF).

In DCF, the sender station first listens to the channel until it becomes idle for at least a DIFS. After that the station generates the back-off timer between intervals (0, W_i-1). If the channel remains idle, the back-off timer will decrement to zero and then the station can transmit. Otherwise, the channel becomes busy during the back-off timer process, and then the station would freeze the back-off timer until the channel becomes idle again[2]. After each successful transmission, the station must receive an ACK frame after a short inter frame space duration (SIFS). In cases when the sender station does not receive an ACK, it will detect that a collision has occurred, and will need to repeat the transmission [3].

The remaining part of the paper is organized as follows- Section 2 summarizes and evaluates number of popular related work; Section 3 presents a new mathematical model by considering busy probability through the analytical model; Section 4 presents and analyses the simulation results in comparison with Bianchi's model; Section 5 concludes our proposal.

2. Related Work

The famous performance analytical model for IEEE 802.11 DCF under saturation traffic is the Bianchi model [1]. It is based on the bi-dimensional Markov chain ($b_{i,k}$) to describe the behaviour of single station [4], where is the back-off stage and is the back-off timer [1]. There are several different ways to propose or extend the analytical model. For instance, in [5], the authors proposed a new analytical performance model under non-saturation traffic by using Equilibrium Point Analysis (EPA). This method is applicable only to a system in EP. Therefore, it is not suitable for the general case and is difficult to extend. In [6], the authors proposed the analytical model for IEEE 802.11 DCF by using virtual slot time under saturation traffic. However, the authors assumed all stations can hear each other. Therefore, this method did not consider a hidden station. On the other hand, many researchers pay great attention to enhance the protocol. Such as in [7], work was shown on an enhancement protocol to propose a performance analytical model for IEEE 802.11e by using mean value analysis (MVA). This method provides less computation overhead than the Markov chain. In [8], the authors proposed a unified performance analytical model for IEEE802.11e-EDCA. This model was based on extending their work to both Bianchi's model that was based on Markov chain [1] and the Tay's model based on the mean value analysis [9]. The authors suggested that their work considered both analysis methods in the same model which reduces the complexity for the analytical model of a protocol. Our review of the extant literature suggests that most researchers have extended Bianchi's model so as to improve the quality of service (QoS) for wireless network protocol. Therefore, in [10] the authors argued that the assumption where the collision probability and the busy probability are similar is not valid. Therefore, considering the difference helps to achieve the most accurate prediction of throughput and access delay. Some researchers, such as in [11], mentioned the difference between the collision and the busy probabilities in their model diagram, but without considering it in a mathematical analysis.

However, Bianchi's model is built on many assumptions. One of them assumed that the analytical model is based only on a collision probability during the frozen period, which we need to improve. In this paper we extend Bianchi's model by proposing the busy probability. Therefore, we modify Bianchi's model to cover all the possible transmission probabilities during the back-off process, by introducing a new state ($b_{i,k}$) which considers a busy probability. Our modification considers the busy probability at all possible stages, where $i \in (0, m)$ but k must be greater than zero because if $k = 0$, then a transmission has occurred.

In Bianchi's model we replace the assumption that the stations have only conditional collision probability with a packet transmission on the channel. Therefore, we consider the difference between a busy probability and a collision probability (P_b, P_c) during the back-off process as shown in figure 1.

Thus, we consider the station when it wants to transmit but sensed the channel is busy for some reason. We are of the view that we cannot ignore any probability or assume that both have the same process.

3. Throughput Analysis

First, we obtain a new formula to compute the packet transmission probability (τ) in a given slot time. The new formula includes all the possible states in the back-off process ($b_{i,k}$). Then we use τ to compute the saturation throughput (S), and compare the result with Bianchi's model.

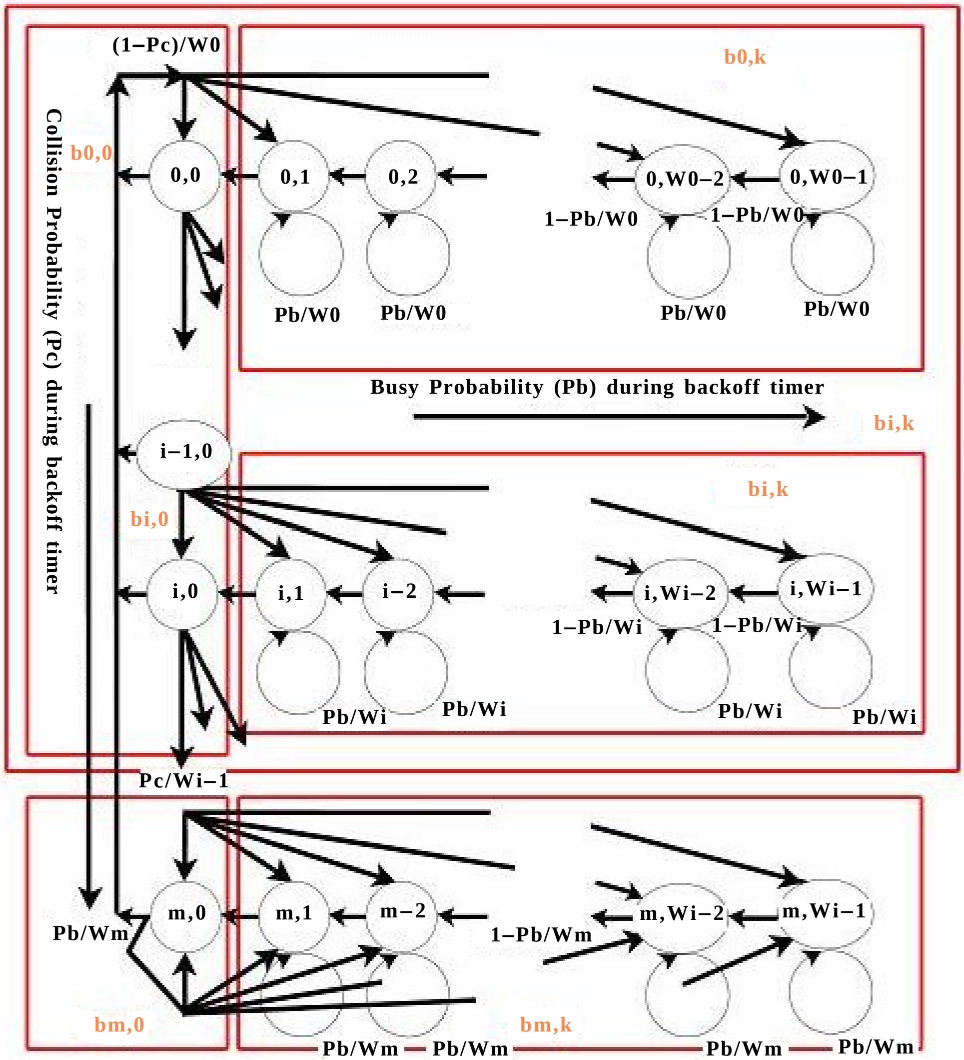

Figure 1. Markov chain for representing our model

3.1 Packet Transmission Probability

We consider the discrete-time Markov chain (i, k), whose nonzero transition probabilities are as described in table (1) below where:

$$P(i_1, k_1 \mid i_0, k_0) := p(s_{i+1} = i_1, b_{i+1} = k_1 \mid s_t = i_0, b_t = k_0).$$

The stationary probabilities (if they exist)

$$b_{i,k} = \lim t \to \infty \quad p\{s(t) = i, b(t) = k\}$$

satisfy the forward Kolmogorov equation:

$$b_{i,k} = \sum_{j=0}^{m} \sum_{\ell=0}^{W_j - 1} P(i, k \mid j, \ell)\, b_{j,\ell} \qquad \forall k \in (0, W_i - 1), i \in (0, m)$$

Where: $P(i, k \mid j, \ell) := p(s_{t+1} = i, b_{t+1} = k \mid s_t = j, b_t = \ell)$, are the transition probabilities. As we have seen from figure (1), we can divide the calculation process into several states:

$$(b_{0,k}, b_{i,k}, b_{m,0}, b_{m,k}, b_{0,0})$$

Equations	Conditional	Description
$P[(i,k)\mid(i,k+1)] = 1 - p_b / W_i$	$k \in (0,\ W_i - 2),\ i \in (0,\ m).$	The back-off counter is decremented at the beginning of each slot time[1].
$P[(0,k)\mid(i,0)] = (1-p_b)/W_0$	$k \in (0,\ W_0 - 1),\ i \in (0,\ m).$	Successful transmission and the station is ready to transmit again with the back-off stage zero[1].
$P[(i,k)\mid(i,k)] = p_b / W_i$	$k \in (1,\ W_i - 1),\ i \in (0,\ m).$	Frozen period and busy channel occurred at back-off counter $k > 0$.
$P[(i,k)\mid(i-1,0)] = p_c / W_i$	$k \in (0,\ W_i - 1),\ i \in (1,\ m).$	Unsuccessful transmission and collision occurred at back off stage i and the back-off stage increases to retransmit a frame[1].
$P[(m,k)\mid(m,0)] = p_c / W_m$	$k \in (0,\ W_m - 1),\ i = m.$	Unsuccessful transmission and the collision is still active untill the back-off stage reaches the value m[1].

[1] We use the same assumption in [1] but with introducing the busy probability into account.

Table 1. Description for Equations

As a result of deriving the formulae for these states, we can compute τ. For the network depicted in the model diagram in figure (1), we have:

$$b_{i,W_{i-1}} = b_{i,W_{i-1}} \frac{p_b}{W_i} + b_{i-1,0} \frac{p_c}{W_i} \quad \forall i \in (1,\ m-1) \tag{1}$$

From (1), (3), and (4) in table (1) we can derive the probability for transmission, collision and busy in one equation:

$$b_{i,k} = b_{i,k} \frac{p_b}{W_i} + b_{i,k+1}\left(1 - \frac{p_b}{W_i}\right) + b_{i-1,0} \frac{p_c}{W_i} \quad \forall k \in (1, W_i - 2), k \in (1, m-1) \tag{2}$$

We can consider (2) as the following:

$$b_{i,k} = b_{i,k+1} + b_{i-1,0} \frac{\frac{p_c}{W_i}}{1 - \frac{P_b}{W_i}}$$

With considering the Contention Window (W) through the equation, then

$$b_{i,k} = b_{i,W_{i-1}} + (W_i - 1 - k)\, b_{i-1,0} \frac{\frac{p_c}{W_i}}{1 - \frac{P_b}{W_i}}$$

We can consider(1) as the following:

$$b_{i,W_{i-1}} = b_{i-1,0} \frac{\frac{p_c}{W_i}}{1 - \frac{P_b}{W_i}}$$

On the other hand,

$$b_{i,k} = b_{i-1,0}(W_i - k)\frac{\frac{p_c}{W_i}}{1-\frac{P_b}{W_i}} \quad \forall k \in (1, W_i - 1), i \in (1, m-1) \tag{3}$$

Further, from a zero stage in the model diagram in figure (1), we can consider the back-off procedure as follows:

$$b_{0,k} = b_{0,k}\frac{p_b}{W_0} + b_{0,k+1}(1-\frac{p_b}{W_0}) + \frac{1-p_c}{W_0}\sum_{j=0}^{m} b_{j,0} \quad \forall k \in (0, W_0 - 2) \tag{4}$$

And

$$b_{0,W_{0-1}} = b_{0,W_{0-1}}\frac{p_b}{W_0} + \frac{1-p_c}{W_0}\sum_{j=0}^{m} b_{j,0} \tag{5}$$

Equation (4) can be defined as:

$$b_{0,k} = b_{0,k+1} + b_{i-1,0}\frac{\frac{(1-p_c)}{W_0}}{1-\frac{P_b}{W_0}}\sum_{j=0}^{m} b_{j,0}$$

Consequently,

$$b_{0,k} = b_{0,W_{0-1}} + (W_0 - 1 - k)\frac{\frac{(1-p_c)}{W_0}}{1-\frac{P_b}{W_0}}\sum_{j=0}^{m} b_{j,0}$$

From (5),

$$b_{0,W_{0-1}} = \frac{\frac{(1-p_c)}{W_0}}{1-\frac{P_b}{W_0}}\sum_{j=0}^{m} b_{j,0}$$

We can work horizontally in the back-off counter direction (i) and vertically in the back-off stage direction (k) to obtain all states for $b_{i,k}$ as shown in figures 1 and 2.

$$b_{0,k} = (W_0 - k)\frac{\frac{(1-p_c)}{W_0}}{1-\frac{P_b}{W_i}}\sum_{j=0}^{m} b_{j,0} \quad \forall k \in (1, W_0 - 1) \tag{6}$$

$$b_{0,0} = b_{0,1}(1-\frac{p_b}{W_0}) + \frac{1-p_c}{W_0}\sum_{j=0}^{m} b_{j,0} \tag{7}$$

$$b_{i,0} = b_{i,1}(1-\frac{p_b}{W_i}) + b_{i-1,0}\frac{p_c}{W_i} \quad \forall i \in (1, m-1) \tag{8}$$

Where k = 1, then:

$$b_{0,0} = (W_0 - 1)\frac{1-p_c}{W_0}\sum_{j=0}^{m} b_{j,0} + \frac{1-p_c}{W_0}\sum_{j=0}^{m} b_{j,0} = (1-p_c)\sum_{j=0}^{m} b_{j,0}$$

Therefore,

$$\sum_{j=0}^{m} b_{j,0} = b_{0,0}\frac{1}{1-p_c} \tag{9}$$

Now, we are in a position to derive the mathematical equations for all the parts in the model diagram.

First, we can consider (6) as follows:

$$b_{0,k} = b_{0,0} \frac{1}{1-\frac{p_b}{W_0}} (1 - k / W_0) \; \forall k \in (1, W_0 - 1) \tag{10}$$

However, (3) where $k = 1$,

$$b_{i,k} = b_{i-1,0} (W_i - 1) \frac{\frac{p_c}{W_i}}{1-\frac{P_b}{W_i}}$$

From (8) we can consider:

$$b_{i,0} = b_{i-1,0} (W_i - 1) \frac{p_c}{W_i} + b_{i-1,0} \frac{p_c}{W_i} = p_c b_{i-1,0}$$

Second, we can compute:

$$b_{i,0} = p_c^i b_{0,0} \quad \forall i \in (0, m-1) \tag{11}$$

Third, we can compute $b_{i,k}$ from (3) as follows:

$$b_{i,k} = b_{0,0}\, p_c^{i-1} (W_i - k) \frac{\frac{p_c}{W_i}}{1-\frac{p_b}{W_i}} = b_{0,0} \frac{p_c^i}{1-\frac{p_b}{W_i}} (1 - k / W_i)$$

Where

$$\forall k \in (1, W_0 - 1), i \in (1, m-1) \tag{12}$$

When (i) achieve the final back-off stage (m), as a consequence

$$b_{m,k} = b_{m,k} \frac{p_b}{W_m} + b_{m,k+1} (1 - \frac{p_b}{W_m}) + b_{m-1,0} \frac{p_c}{W_m} + b_{m,0} \frac{p_c}{W_m} \; \forall k \in (1, W_m - 2) \tag{13}$$

$$b_{m, W_{m-1}} = b_{m-1,0} \frac{p_c}{W_m} + b_{m, W_{m-1}} \frac{p_b}{W_m} + b_{m,0} \frac{p_c}{W_m} \tag{14}$$

$$b_{m,0} = b_{m-1,0} \frac{p_c}{W_m} + b_{m,1} (1 - \frac{p_b}{W_m}) + b_{m,0} \frac{p_c}{W_m} \quad b_{m-1,0} = p_c^{m-1} b_{0,0} \tag{15}$$

Same as (11), however (13) denotes:

$$b_{m,k} = b_{m,k+1} + \frac{1}{1-\frac{p_b}{W_m}} (b_{0,0} \frac{p_c^m}{W_m} + b_{m,0} \frac{p_c}{W_m})$$

As a result of considerng W in the equation instead of k,

$$b_{m,k} = b_{m, W_{m-1}} + (W_m - 1 - k) \frac{1}{1-\frac{p_b}{W_m}} (b_{0,0} \frac{p_c^m}{W_m} + b_{m,0} \frac{p_c}{W_m})$$

and (14),

$$b_{m, W_{m-1}} = \frac{1}{1-\frac{p_b}{W_m}} (b_{0,0} \frac{p_c^m}{W_m} + b_{m,0} \frac{p_c}{W_m})$$

$$b_{m,k} = (W_m - 1)\frac{1}{1-\frac{p_b}{W_m}}\left(b_{0,0}\frac{p_c^m}{W_m} + b_{m,0}\frac{p_c}{W_m}\right) \forall k \in (1, W_m - 1) \tag{16}$$

While the back-off counter $k = 1$, then (16) is represented as:

$$b_{m,1} = (W_m - 1)\frac{1}{1-\frac{p_b}{W_m}}\left(b_{0,0}\frac{p_c^m}{W_m} + b_{m,0}\frac{p_c}{W_m}\right)$$

And from (15), we can obtain:

$$b_{m,0} = b_{0,0}\frac{p_c^m}{W_m} + b_{m,1}\left(1-\frac{p_b}{W_m}\right) + b_{m,0}\frac{p_c}{W_m} = b_{0,0}\frac{p_c^m}{W_m} + (W_m - 1)\left(b_{0,0}\frac{p_c^m}{W_m} + b_{m,0}\frac{p_c}{W_m}\right) + b_{m,0}\frac{p_c}{W_m}$$

$$= b_{0,0}\, p_c^m + b_{m,0}\, p_c$$

Fourth,we can compute:

$$b_{m,0} = b_{0,0}\frac{p_c^m}{1-p_c} \tag{17}$$

Fifth,from (16) we can compute:

$$b_{m,k} = b_{0,0}(1 - k/W_m)\frac{1}{1-\frac{p_b}{W_m}}\frac{p_c^m}{1-p_c} \forall k \in (1, W_m - 1) \tag{18}$$

The only unknown quantity is, $b_{0,0}$ which can be found from the normalization condition:

$$1 = \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} = \sum_{k=1}^{W_0-1} b_{0,k} + \sum_{i=1}^{m-1}\sum_{k=1}^{W_i-1} b_{i,k} + \sum_{i=1}^{m-1} b_{i,0} + b_{m,0} + \sum_{k=1}^{W_i-1} b_{m,k}$$

$$= b_{0,0}\left(\sum_{k=1}^{W_0-1}\frac{1}{1-\frac{p_b}{W_0}}(1-k/W_0) + \sum_{i=1}^{m-1} p_c^i + \sum_{i=1}^{m-1}\sum_{k=0}^{W_i-1}\frac{p_c^i}{1-\frac{p_b}{W_i}}(1-k/W_i) + \frac{p_c^m}{1-p_c} + \right.$$

$$\left.\sum_{k=1}^{W_m-1}(1-k/W_m)\frac{1}{1-\frac{p_b}{W_m}} - \frac{p_c^m}{1-p_c}\right)$$

Where we have used (10), (11), (12), (17) and (18). We note that:

$$\sum_{k=0}^{W_i-1}(1-k/W_i) = W_i - 1 - \frac{1}{W}\sum_{k=1}^{W_i-1} k = W_i - 1 - \frac{1}{W_i}\frac{(W_i-1)W_i}{2} = \frac{W_i-1}{2}$$

Finally, we can compute:

$$b_{0,0} = \left(\sum_{i=1}^{m-1} p_c^i + \sum_{i=0}^{m-1}\frac{p_c^i}{1-\frac{p_b}{W_i}}\frac{W_i-1}{2} + \frac{p_c^m}{1-p_c} + \frac{1}{1-\frac{p_b}{W_m}}\frac{p_c^m}{1-p_c}\frac{W_m-1}{2}\right)^{-1}$$

Once $b_{0,0}$ is found, all the stationary probabilities are obtained through formulae (10), (11), (12), (17), and (18). Therefore, the packet transmission probability can be computed from the following formula:

$$\tau = \sum_{i=0}^{m} b_{i,0}$$

$$= b_{0,0}\left(\sum_{i=0}^{m-1} p_c^i + \frac{p_c^m}{1-p_c}\right) = b_{0,0}\left(\frac{1-p_c^m}{1-p_c} + \frac{p_c^m}{1-p_c}\right) = b_{0,0}\,\frac{1}{1-p_c}\,.$$

3.2 Throughput

Now, we have already computed τ from the previous section. Therefore, we can evaluate the saturation throughput with the same formula in Bianchi's model as follows:

$$S = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\,\sigma + P_{tr} P_s T_S + P_{tr}(1-P_S)\,T_C} \tag{19}$$

4. Model Evaluation

To evaluate the accuracy of our proposed new model we used a MATLAB program to check the mathematical analysis. Therefore, we confirmed that the total calculation of transmission probabilities packet is an equal one to prove (20).

$$\sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = 1 \tag{20}$$

We then use τ to compute for IEEE 802.11 DCF. The analysis calculation was done based on the system parameters for the basic access mechanism in bits, and in 50 µs slot time units. We also use random values between (0, 1) for the busy probability (P_b) and the collision probability (P_c) values as shown in Table 2 and figure 2.

P_b	P_c	τ	***S where*: (*W* = 32, *m* = 3)**			
			$n = 10$	$n = 20$	$n = 30$	$n = 50$
0.3	0.2	0.0462	0.72	0.58	0.45	0.25
0.3	0.3	0.0384	0.74	0.62	0.5	0.32
0.3	0.4	0.0310	0.76	0.67	0.58	0.39
0.3	0.5	0.0246	0.8	0.71	0.62	0.48
0.3	0.6	0.0194	0.81	0.75	0.66	0.55
0.3	0.65	0.0172	0.82	0.76	0.69	0.58
simulation result			0.73	0.67	0.63	0.58

Table 2. Efect of the busy Probaility and the collision Probability on Throughput

As we have seen from table 2, we confirm that *S* depends on the number of stations in the network which is same as Bianchi's model. The experiment shows that large number of stations will produce lower throughput and vice versa as shown in figure 2. In this case, we agree with Bianchi's model about the relationship between the throughput and the number of stations, but we also note that the busy probability makes changing in the throughput.

To validate the model, we have implemented simulation program and compare the results with Bianchi's simulation. This simulation runs over the same parameters and assumption for Bianchi's model as described in Table 3.

Figure 3 shows that the proposed model simulation has slightly less throughput over small network and slightly high throughput over large network by comparing with Bianchi's model simulation. The simulation considers the busy probability is constant has EIFS duration. This duration is the time delay in seconds which a station will face in case of busy channel. The results show that the busy probability will reduce the collision probability, and therefore our model will lead to increase the throughput over large network. Thus it is important to consider any parameter which can act on the performance for IEEE 802.11 DCF protocol. On the

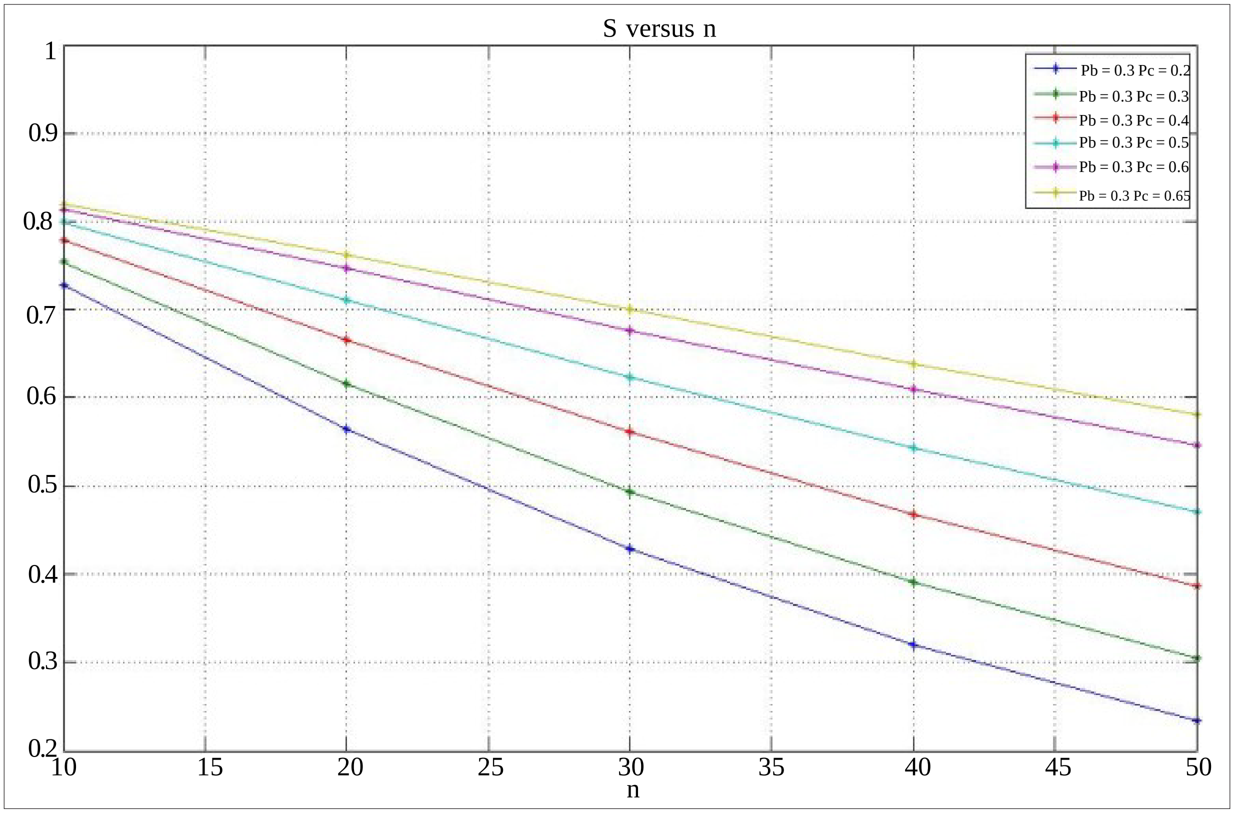

Figure 2. Analytical results under random values of probabilities (*Pb*, *Pc*)

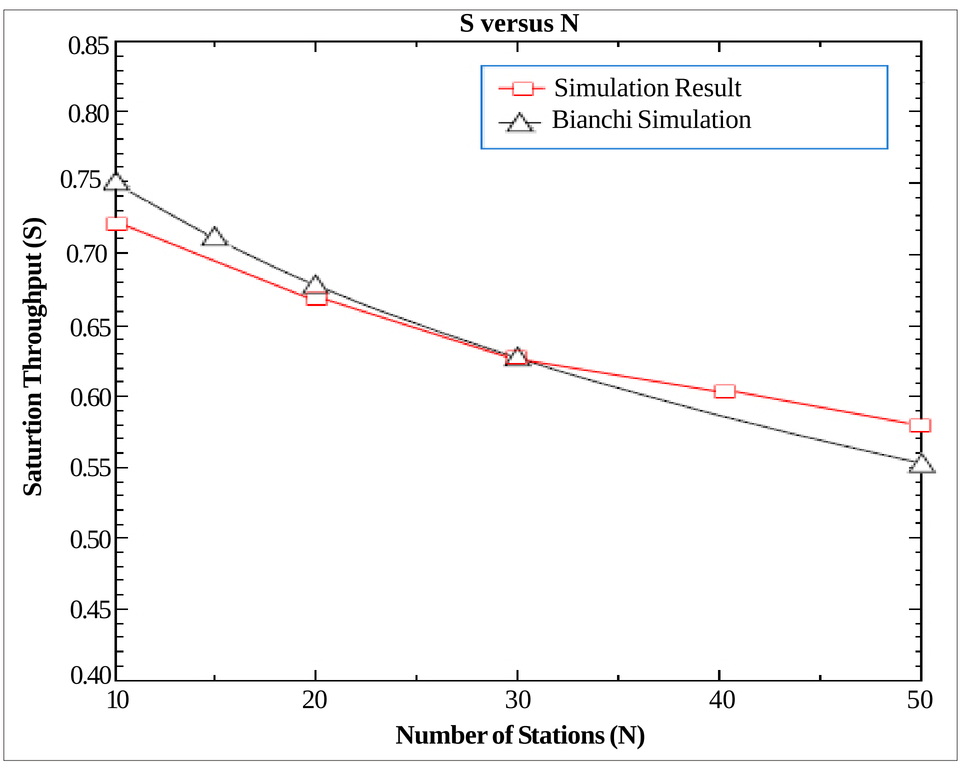

Figure 3. Saturation Throughput: Proposed model simulation versus Bianchi's model simulation ($m = 3$, $W = 32$, $n = 50$)

Parameter	Value
SIFS	28 μs
DIFS	128 μs
EIFS	DIFS+SIFS+ACK
PHYSICAL SLOT	50μs
PHYSICAL HEADER	128 bits
MAC HEADER	272 bits
ACK	112bits+PHY HEADER
DATA PACKET	8184 bits
NETWORK NODES (n)	50 nodes
CHANNEL BIT RATE	1 Mbit/s
PROPAGATION DELAY	1 μs

Table 3. System Parameters

other hand, we cannot ignore busy probability or assume it to be the same as collision probability. In addition, if we aim to achieve the best evaluation accuracy, we will need to consider all the possible states for the back-off mechanism.

5. Conclusion

We have seen from the CSMA/CA mechanism for IEEE 802.11 DCF that there is a difference between the busy probability and the collision probability. The difference between probabilities needs to consider in the analysis of a mathematical model for calculating a packet transmission probability (τ). In this paper, we propose a simple new mathematical analytical model for computing Ä to cover all the possible transmission probabilities for a packet during the back-off mechanism. We achieved this by adding a new probability to Bianchi's model to represent busy state. This enabled us to achieve the most accurate prediction of performance evaluation of IEEE 802.11 DCF. The accuracy of evaluation was validated through a MATLAB simulation program and the results were then compared with those achieved by Bianchi's model. Possible future extensions of our model could provide a new estimation for MAC packet delay distribution or creating a new average packet delay model.

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