International Journal of Automation and Computing
7(1), February 2010, 95-104
DOI: 10.1007/s11633-010-0095-6

Nonsaturation Throughput Enhancement of IEEE 802.11b Distributed Coordination Function for Heterogeneous Traffic under Noisy Environment

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Abstract: In this paper, we propose a mechanism named modified backoff (MB) mechanism to decrease the channel idle time in IEEE 802.11 distributed coordination function (DCF). In the noisy channel, when signal-to-noise ratio (SNR) is low, applying this mechanism in DCF greatly improves the throughput and lowers the channel idle time. This paper presents an analytical model for the performance study of IEEE 802.11 MB-DCF for nonsaturated heterogeneous traffic in the presence of transmission errors. First, we introduce the MB-DCF and compare its performance to IEEE 802.11 DCF with binary exponential backoff (BEB). The IEEE 802.11 DCF with BEB mechanism suffers from more channel idle time under low SNR. The MB-DCF ensures high throughput and low packet delay by reducing the channel idle time under the low traffic in the network. However, to the best of the authors′ knowledge, there are no previous works that enhance the performance of the DCF under imperfect wireless channel. We show through analysis that the proposed mechanism greatly outperforms the original IEEE 802.11 DCF in the imperfect channel condition. The effectiveness of physical and link layer parameters on throughput performance is explored. We also present a throughput investigation of the heterogeneous traffic for different radio conditions.

Keywords: IEEE 802.11, medium access control (MAC), distributed coordination function (DCF), nonsaturated traffic, heterogeneous traffic, signal-to-noise ratio (SNR), binary exponential backoff (BEB).

1 Introduction

The IEEE 802.11 standard specifies wireless local area networks (WLANs). In the recent years, WLANs are becoming widely spread in wireless and mobile networks. In order to allow multiple users to access a common channel, the IEEE 802.11 standard has defined two medium access coordination functions: the contention-based distributed coordination function (DCF) and the contention-free based point coordination function (PCF). The implementation of DCF in IEEE 802.11 compliant devices is mandatory, while provision of PCF is optional. DCF supports basic access mechanism and request-to-send/clear-to-send (RTS/CTS) mechanism. DCF is an access scheme based on the contention principle using carrier sense multiple access/collision avoidance (CSMA/CA). PCF mechanism is proposed for the time bounded traffic.

IEEE 802.11 standard[1] uses binary exponential backoff (BEB) algorithm in DCF. Most of the researchers are attracted towards DCF for their simplicity and flexibility. In DCF, contention window size is increased by using BEB algorithm. The station will decrease the contention window size by one whenever one idle slot time elapses. It will freeze this counter when the channel is sensed being busy. If the contention window size reaches zero, it can transmit the packet. If the transmitted packet collides, the station will assume that the channel is busy, then double the contention window and select a new backoff time for retransmission.

Most of the previous analytical works are based on the discrete Markov chain model and take into consideration the saturation throughput. Bianchi[2] proposed a two-dimensional Markov chain model to calculate the saturation throughput performance considering infinite number of packet retransmissions. IEEE 802.11 DCF is generally in nonsaturated traffic condition. In particular, Malone et al.[3,4] modeled DCF for nonsaturated case and heterogeneous traffic. In this model, post backoff is considered in the nonsaturation throughput analysis. In [5], we extended the work of [6] and presented the nonsaturation throughput analysis for heterogeneous traffic. The throughput of the DCF[7] is investigated under the heterogeneous traffic. In [8], Bianchi′s model is extended to the case of finite loads. In this paper, the state transition from post backoff stage to the other backoff stage is not clearly explained. There are some works[6,9] on finite load models for IEEE 802.11 DCF. A new idle state is introduced in the Markov chain model and the performance of the DCF for the nonsaturated traffic is presented.

Bianchi′s Markov chain model was used to analyze the saturation throughput with the ideal channel condition[10]. In [11], an empty queue state was introduced to model the IEEE 802.11 medium access control (MAC) protocol with queue length used as the third dimension in the Markov chain model. In [12], Bianchi′s Markov model was extended for the nonsaturation under homogeneous traffic in the presence of transmission errors. Minooei and Nojumi[13] investigated the enhancement of the IEEE 802.11 DCF MAC protocol to increase its performance when it is utilized in WLANs and the channel error was not considered. In [14 − 17], the performance of the MAC layer was analyzed with the transmission errors considered. The performance of the MAC

Manuscript received March 11, 2009; revised April 21, 2009

protocol[18] was presented for multihop network. Senthilkumar and Krishnan[19] presented the performance of the multihop network for string topology. Several schemes[20,21] were proposed to enhance the performance of the IEEE 802.11 DCF under saturated condition. In the proposed schemes, the resetting of the contention window $CW_{\min}$ is adjusted after successful transmission. Yin et al.[22] has investigated the performance of the IEEE 802.11 DCF in the presence of transmission error. The optimal packet size is obtained in the error-prone channel. An MAC protocol[23] was proposed for fast collision recovery for IEEE 802.11 DCF. In this paper, we extend the previous works by looking at the important issues, namely, nonsaturation, heterogeneity, and radio channel. In [24], the packet drop probability and the delay analysis were presented for wireless networks.

In case of erroneous retransmission, the contention window size is doubled in the existing IEEE 802.11 DCF. In this paper, we propose a notion that instead of doubling the contention window in the case of erroneous packet retransmission, the backoff counter selects a counter value from the same contention window. If collision occurs, the contention window is doubled to reduce the collision in the network. In the case of transmission error, the contention window needs not be doubled for the erroneous packet retransmission.

The rest of this paper is organized as follows. Section 2 provides the radio channel model and the analysis of the probability of error for different modulation schemes. Section 3 analyzes the nonsaturation throughput of the IEEE 802.11 DCF for heterogeneous traffic. Section 4 presents the numerical results for nonsaturated of MB-DCF. In this section, the performance of the MB-DCF is compared with the performance of the IEEE 802.11 MAC. Section 5 provides the throughput efficiency for variable packet lengths. Section 6 concludes this paper.

2 Radio channel model and analysis

The physical layer of the IEEE 802.11 standard is based on the spread spectrum technology. This technology is specified by frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). The modulation scheme used in the FHSS is frequency shift keying (FSK), whereas the DSSS uses complementary code keying (CCK). The CCK encoding 4 and 8 bits on one CCK symbol, which supports the data rates 5.5 and 11 Mbps.

We determine the probability P_e that an unsuccessful transmission occurs due to transmission errors. Let P_b be the probability of bit error. We assume that the transmission error occurs only in the data frame and not in the control frames like RTS, CTS, and acknowledgment (ACK). The expression for P_e is obtained as[16]

$$P_e = 1 - (1 - P_b^1)^{PHY}(1 - P_b^2)^{(MAC+DATA)} \tag{1}$$

where PHY is the length of the physical header, $DATA$ is the length of the packet payload, and MAC is the length of the MAC header. The path loss calculation is used to find the mean signal strength at a certain receiver distance. The mean received power P_r at a distance d meters from the transmitter is given by[13]

$$P_r = P_t d^{-\alpha} \tag{2}$$

where P_t is the transmitter power and α is the path loss exponent. The path loss P_L (dBm) can be expressed as

$$P_L(\mathrm{dBm}) = 10 \cdot \alpha \cdot \lg(d).$$

The path loss exponent α varies from 2 to 4. Then,

$$P_r\,(\mathrm{dBm}) = P_t\,(\mathrm{dBm}) - P_L\,(\mathrm{dBm}). \tag{3}$$

Let N_0 be the noise power. The received signal-to-noise power ratio at a distance d is given by

$$SNR\,(\mathrm{dB}) = P_r\,(\mathrm{dBm}) - N_0\,(\mathrm{dBm}). \tag{4}$$

The noise power N_0 can be calculated by

$$N_0 = KT_0B$$

where K is the Boltzmann$'$s constant, B is the equivalent bandwidth, and T_0 is the absolute temperature. The signal-to-noise ratio (SNR) is represented by the ratio of the energy per chip to the power spectral density of the noise. Let E_b/N_0 be the signal-to-noise ratio per bit.

$$\frac{E_b}{N_0} = 10\lg(\frac{V}{M}) + SNR\,(\mathrm{dB}) \tag{5}$$

where V and M are listed in Table 1.

Table 1 Different modulation schemes and rates

Modulation	V (chips/symbol)	M (bits/symbol)
DBPSK @ 1 Mbps	11	1
CCK @ 11 Mbps	8	8

The bit error rate (BER) of the modulation scheme depends on the SNR. The probabilities of bit error for different modulation schemes in an additive white Gaussian channel (AWGN) are different. For differential binary phase shift keying (DBPSK) modulation scheme, the BER can be calculated by[25,26]

$$P_b^1 = \frac{1}{2}\exp\left(-\frac{E_b}{N_0}\right). \tag{6}$$

For CCK modulation scheme, the BER can be calculated by[25,26]

$$P_b^2 = 1 - \frac{1}{\sqrt{2\pi}}\int_{-y}^{\infty}\left(\frac{1}{\sqrt{2\pi}}\int_{-(v+y)}^{(v+y)} \mathrm{e}^{\frac{x^2}{2}}\mathrm{d}x\right)^{\frac{M}{2}-1} \mathrm{e}^{-\frac{v^2}{2}}\mathrm{d}v \tag{7}$$

where $y = \sqrt{2E_b/N_0}$ and $M = 8$.

3 Throughput analysis of modified IEEE 802.11 DCF

In this section, we propose a Markov model for MB-DCF scheme in the presence of transmission errors. This section presents the performance of the homogeneous and heterogeneous traffic model. From the per-station Markov model, the probability for a station attempting transmission can be computed.

3.1 Markov model for MB-DCF

Following the Markov model presented in [2], each station is modeled by a pair of stochastic processes $b(t)$ and $s(t)$. Let $b(t)$ be the stochastic process representing the backoff time counter. If a station finds an idle slot time, backoff counter decreases the counter one at the beginning of each idle slot time. When the channel is sensed being busy, a station stops the decrement and freezes the backoff counter.

Let $s(t)$ be the stochastic process that is representing the backoff stage $(0, 1, \cdots, m)$ of the station. Let m be the maximum backoff stage. For mathematical convenience, short notations (i, k) are used for representing the stochastic processes $s(t)$ and $b(t)$, respectively. The backoff stage i starts at zero in the first attempt to transmit and it increases by one every time in case of collision, up to maximum value m. Initially, a station selects a counter value randomly from the contention window size $(0, W_0 - 1)$. The contention window size is doubled for every attempt, where $W_i = 2^i W_0$ is the range of contention window size for i-th attempt. The station attempts to transmit when the backoff counter reaches zero. After successful transmission, the counter value is randomly chosen from the minimum contention window and initiates the new transmission.

At the maximum backoff stage, the packet is not discarded as per the Markov model in [2]. Per-station quantities in the Markov model are q, the probability of at least one packet awaiting transmission at the start of a counter decrement; m, the maximum backoff stage; p_{col}, the probability of collision; b, the stationary probability of the state in Markov chain; and τ, the probability that the station transmits in a slot. Markov chain′s evolution is not real time, so the estimation of throughput requires an estimate of the average state duration. The collision probability p is a constant value. A two-dimensional discrete time Markov chain is depicted in Fig. 1.

In this section, we proposed Markov model for modified DCF to improve the throughput under nonsaturated traffic conditions in the presence of transmission errors. To distinguish the packet collision from the transmission errors in the absence of hidden terminals, we consider that the packet transmission is based on the four- way handshaking mechanism. A station follows the BEB algorithm in case of packet collision. In case of transmission errors, the station selects a counter value from the same contention window, i.e., it does not double the contention window size. To reduce the packet collision, the contention window is doubled for every attempt. Therefore, the contention window needs not be doubled in the case of retransmission due to the transmission errors.

If the backoff counter reaches zero, the station can transmit a packet. Whether it has a packet in a queue after a successful transmission, it selects a counter value from the window $(0, W_0 - 1)$ in stage 0. The backoff stage is increased for each retransmission.

The transition probabilities under our assumptions are

$$\begin{aligned}
&P\,(i, k/i, k+1) = 1, \quad k \in [0, W_i - 1), \quad \forall i \in [0, m] \\
&P\,(0, k/i, 0) = \frac{q\,(1 - P_{eq})}{W_0}, \quad k \in [0, W_0 - 1], \quad \forall i \in [0, m] \\
&P\,(i, k/i-1, 0) = \frac{P_{col}}{W_i}, \quad k \in [0, W_i - 1], \quad \forall i \in [1, m] \\
&P\,(i, k/i, 0) = \frac{P_e\,(1 - P_{col})}{W_i}, \quad k \in [0, W_i - 1), \quad \forall i \in [0, m) \\
&P\,(m, k/m, 0) = \frac{P_e\,(1 - P_{col})}{W_m} + \frac{P_{col}}{W_m}. \qquad (8)
\end{aligned}$$

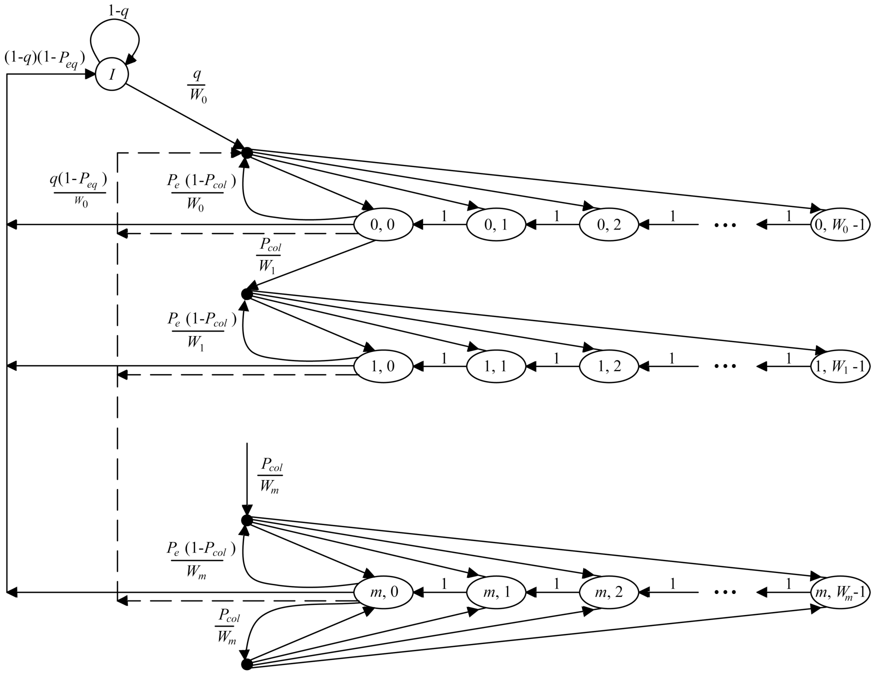

Fig. 1 Modified Markov model considering the effects of channel errors

If there is no packet in a buffer after a successful transmission, the station is waiting in the idle state I until a new packet arrives.

$$\begin{aligned} P\left(I/i,0\right) &= \left(1-q\right)\,\left(1-P_{eq}\right), \quad \forall i \in [0,m]. \\ P\left(0,k/I\right) &= \frac{q}{W_0} \\ P\left(I/I\right) &= 1-q. \end{aligned} \tag{9}$$

All the stationary probabilities in the given Markov model can be expressed as a function of the value $b(0,0)$ and the conditional collision probability. The expression for the $b(0,0)$ can be obtained from this normalization equation.

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b\left(i,k\right) + b\left(I\right). \tag{10}$$

When a packet collision occurs at backoff stage i, the backoff stage increases and the new initial backoff value is randomly chosen in the range $[0, W_{i+1}]$. If transmission error occurs at the backoff stage i again, the backoff value is chosen from the range $[0, W_i]$.

$$b\left(i,0\right) = P_{col} b\left(i-1,0\right) + P_e\left(1-P_{col}\right)\,b\left(i,0\right), \quad \forall i \in (0,m) \tag{11}$$

$$b\left(i,0\right) = P_r^i\, b\left(0,0\right), \quad \forall i \in (0,m) \tag{12}$$

where

$$P_{eq} = P_e + P_{col} - P_e P_{col} \tag{13}$$

$$P_r = \frac{P_{col}}{1-P_{eq}+P_{col}} \tag{14}$$

$$b\left(m,0\right) = \frac{P_{col}}{1-P_{eq}} b\left(m-1,0\right). \tag{15}$$

From the normalization equation, the expression for $b(0,0)$ can be found. The expression for $b(0,0)$ is given in (16). The probability of a station attempting transmission in a random slot time is expressed as

$$\begin{aligned} \tau &= \sum_{i=0}^{m} b\left(i,0\right) \\ \tau &= \frac{b\left(0,0\right)\,P_{col}}{\left(1-P_{eq}\right)\,P_r}. \end{aligned} \tag{17}$$

Upon substituting (16) in (17), the expression for transmission probability (τ) can be obtained and is given by (18). The transmission probability[12] of a nonsaturated station using the currently existing DCF is given in (19). Interested readers can refer to [12] to understand the nonsaturation Markov model and the derivation for the transmission probability of a station. Our computed throughput is compared with that of throughput computed from (19) in Section 4. By letting $P_e = 0$ and $q \to 1$, our model reduces to that of Bianchi model[2]. In this case, the station is in saturation. With the station parameters for each station, the transmission probability and the collision probability can be computed.

3.2 Throughput model for nonsaturated homogeneous traffic

We consider n identical nodes, each being able to sense other nodes′ transmission. A collision with a neighboring node occurs only if any of the $(n-1)$ stations also transmit in the same time slot. In our analysis, we consider the Poisson process for packet arrival in the network. In the Poisson process, the packet arrival rate is λ packets/s.

Let P_{tr} be the probability that at least one transmission occurs in a randomly chosen slot time. Let P_s be the probability that an outgoing transmission is without collision.

$$P_{tr} = 1-\left(1-\tau\right)^n \tag{20}$$

$$P_s = n\tau \frac{\left(1-\tau\right)^{n-1}}{P_{tr}}. \tag{21}$$

Let P_{col} be the probability that packet collides with other packet transmission.

$$P_{col} = 1-\left(1-\tau\right)^{n-1}. \tag{22}$$

The nonsaturated throughput for homogeneous traffic can be derived as

$$S = \frac{P_{tr} P_s \left(1-P_e\right) PACKET}{E\left(slot\right)} \tag{23}$$

where

$$\begin{aligned} E\left(slot\right) = {} & \left(1-P_{tr}\right)\sigma + P_{tr} P_s \left(1-P_e\right) T_s + \\ & P_{tr}\left(1-P_s\right) T_c + P_{tr} P_s P_e T_e \end{aligned}$$

where $E(slot)$ is the average duration of the generic slot, σ is the idle slot time, T_s is the successful packet transmission time, T_c is the unsuccessful packet transmission time due to packet collision, $PACKET$ is the transmission time of the physical header, MAC header, and data payload, and T_e is the unsuccessful packet transmission time due to transmission errors.

$$\begin{aligned} T_s = {} & \text{DIFS} + \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \\ & \text{PACKET} + \text{SIFS} + \delta + \text{ACK} + \delta \\ T_e = {} & \text{DIFS} + \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + \\ & \text{PACKET} + \text{ACK Timeout} \\ T_c = {} & \text{DIFS} + \text{RTS} + \text{CTS Timeout.} \end{aligned}$$

$$b\left(0,0\right) = \frac{2\,\left(1-2P_r\right)\,\left(1-P_{eq}\right)\,\left(1-P_r\right) q}{qW_0\left(1-P_{eq}-P_{col}\left(2P_r\right)^m\right)\,\left(1-P_r\right) + \left[q+2\,\left(1-q\right)\,\left(1-P_{eq}\right)\right]\left(1-P_{eq}\right)\,\left(1-2P_r\right)} \tag{16}$$

$$\tau = \frac{2\,\left(1-2P_r\right)\,\left(1-P_r\right)\,q\,P_{col}}{P_r\left\{qW_0\left(1-P_{eq}-P_{col}\left(2P_r\right)^m\right)\,\left(1-P_r\right) + \left[q+2\left(1-q\right)\left(1-P_{eq}\right)\right]\,\left(1-P_{eq}\right)\,\left(1-2P_r\right)\right\}} \tag{18}$$

$$\tau = \frac{2\left(1-2P_{eq}\right) q}{q\left\{\left(W_0+1\right)\left(1-2P_{eq}\right) + W_0 P_{eq}\left(1-\left(2P_{eq}\right)^m\right)\right\} + 2\left(1-q\right)\left(1-P_{eq}\right)\left(1-2P_{eq}\right)}. \tag{19}$$

where DIFS represents the DCF inter frame space, SIFS represents short inter frame space, and δ represents propagation delay.

3.3 Throughput model for nonsaturated heterogeneous traffic

In this heterogeneous traffic network model, we consider that the stations having same packet arrival rate are grouped together. Suppose there are k different groups within the network. Let there be n_i stations in group i with arrival rate λ_i. The total number of stations from each group is $\sum_{i=1}^{k} n_i = n$. For $k = 1$, all the stations in the network are having same arrival rates, i.e., $n_i = n$. The aggregate mean packet arrival rate can be expressed as the sum of arrival rates of all the groups.

The probability of at least one transmission in a time slot is expressed as

$$p_{tr} = 1 - \prod_{j=1}^{k} (1 - \tau_j)^{n_j}. \tag{24}$$

The probability that no station is transmitting in the arbitrary slot time is expressed as

$$P_{idle} = \prod_{j=1}^{k} (1 - \tau_j)^{n_j} = 1 - p_{tr}. \tag{25}$$

A collision occurs, if anyone of the station in any group is transmitting in the same time slot. Each station in group i transmits with probability τ_i. Then, the collision probability is expressed as

$$p_i = 1 - (1 - \tau_i)^{n_i - 1} \prod_{\substack{j = 1 \\ j \neq i}}^{k} (1 - \tau_j)^{n_j}. \tag{26}$$

Putting together (23)–(25), and (18), the nonlinear equations can be solved using numerical methods and the values of τ, p, q, and P_{idle} can be obtained.

Let P_{si} be the probability that the transmission from group i is successful in the same group and let P_{sj} be the probability that the transmission from group i is successful in all other groups in the network.

$$P_{si} = n_i \tau_i (1 - \tau_i)^{n_i - 1} \tag{27}$$

$$P_{sj} = \prod_{\substack{j = 1 \\ j \neq i}}^{k} (1 - \tau_j)^{n_j}. \tag{28}$$

Let P_s be the successful probability of packet transmission from any group given that at least one transmission in the network.

$$P_s = \sum_{i=1}^{k} \frac{P_{si} P_{sj}}{P_{tr}}. \tag{29}$$

The nonsaturation throughput of the DCF can be derived as

$$S = \frac{P_{tr} P_s (1 - P_e)\ PACKET}{E\,(slot)}. \tag{30}$$

3.4 Heterogeneous network model for different radio conditions

In the previous section, we present the network model for different packet arrival rates based on the Poisson process. In this section, we consider the different radio conditions for the nodes in the network. The network consists of heterogeneous users with different radio conditions that can be characterized into some classes. Suppose there are p different classes and k different groups in the network. Let there be n_{ij} stations in the group j of class i. The total number of stations in the network is $n = \sum_{i=1}^{p} \sum_{j=1}^{k} n_{ij}$. The probability of at least one transmission in a time slot is expressed as

$$p_{tr} = 1 - \prod_{h=1}^{p} \prod_{g=1}^{k} (1 - \tau_{hg})^{n_{hg}}. \tag{31}$$

The probability that no station is transmitting in the random arbitrary slot time is expressed as

$$P_{idle} = \prod_{h=1}^{p} \prod_{g=1}^{k} (1 - \tau_{hg})^{n_{hg}} = 1 - p_{tr}. \tag{32}$$

A collision occurs, if anyone of the station in any group is transmitting in the same time slot. Each station in group j of class i transmits with probability τ_{ij}. Then, the collision probability is expressed as

$$p_{ij} = 1 - (1 - \tau_{ij})^{n_{ij} - 1} \prod_{\substack{g = 1 \\ g \neq j}}^{k} (1 - \tau_{ig})^{n_{ig}}. \prod_{\substack{h = 1 \\ h \neq i}}^{p} \prod_{g=1}^{k} (1 - \tau_{hg})^{n_{hg}}. \tag{33}$$

Let $P_{s1(ij)}$ be the probability that the transmission from group j of class i is successful in the same class. Let $P_{s2(ij)}$ be the probability that the transmission from group j of class i is successful in all other classes in the network.

$$P_{s1(ij)} = n_{ij} \tau_{ij} (1 - \tau_{ij})^{n_{ij} - 1} . \prod_{\substack{g = 1 \\ g \neq j}}^{k} (1 - \tau_{ig})^{n_{ig}} \tag{34}$$

$$P_{s2(ij)} = \prod_{\substack{h = 1 \\ h \neq i}}^{p} \prod_{g=1}^{k} (1 - \tau_{hg})^{n_{hg}}. \tag{35}$$

Let P_s be the successful probability of packet transmission from any group given that at least one transmission in the network.

$$P_s = \sum_{h=1}^{p} \sum_{g=1}^{k} \frac{P_{s1(ij)} P_{s2(ij)}}{P_{tr}}. \tag{36}$$

The nonsaturation throughput of the DCF can be derived as

$$S = \frac{P_{tr}\, P_s\ (1 - P_e)\ PACKET}{E\,(slot)}. \tag{37}$$

3.5 Modeling offered load and estimation of probability *q*

In our analysis, we consider Poisson process for packet arrival. The aggregate mean packet arrival rate is denoted by λ and is measured in packets/s. The time between two packet arrivals is defined as inter-arrival time. To compute the transmission probability τ, we need a probability q, which is the probability of having at least one packet to be transmitted in the buffer. The probability q can be expressed as

$$q_i = 1 - \mathrm{e}^{-\lambda_i E(slot)}. \tag{38}$$

MAC layer receives a packet from upper layer during the average slot time that can be used to calculate the probability q. The probability for k packet arrivals during the time interval T in the Poisson process is given by

$$P(k,T) = \frac{(\lambda T)^k \, \mathrm{e}^{-\lambda T}}{k!}. \tag{39}$$

The probability for at least one packet in a queue can be obtained as

$$q_i = 1 - P\left(0, E\left(slot\right)\right) = 1 - \mathrm{e}^{-\lambda_i E(slot)}. \tag{40}$$

The probability $P\left(0, E\left(slot\right)\right)$ is the probability for zero packet arrival during the expected time per slot.

4 Model verification

We first consider the same arrival rate for all the nodes in the network and then consider the heterogeneous settings. In our analysis, we consider three different packet arrival rates in the heterogeneous network. Each station in the network has one of the three arrival rates. Table 2 lists the values of station parameters used in the theoretical analysis and simulation using ns-2[27]. This section focuses on comparison of the analytical results of MB-DCF with the IEEE 802.11 DCF.

Table 2 Parameter settings used

Parameters	Values
Mac header	24 bytes
PHY header	16 bytes
Payload	1 024 bytes
ACK	14 bytes
RTS	20 bytes
CTS	14 bytes
Propagation delay (δ)	1 μs
σ	20 μs
SIFS	10 μs
DIFS	50 μs
ACK timeout	300 μs
CTS timeout	300 μs
Data rate	11 Mbps

In this section, we present numerical results that show the impact of transmission errors on the system capacity. When the distance increases, it decreases the received power, P_r. Here, the throughput of the MB-DCF is compared with the throughput of the IEEE 802.11 DCF in the presence of transmission errors. Fig. 2 shows the throughput prediction for a station with $P_e = 0.01$. The predicted throughput is plotted against number of stations for two different arrival rates.

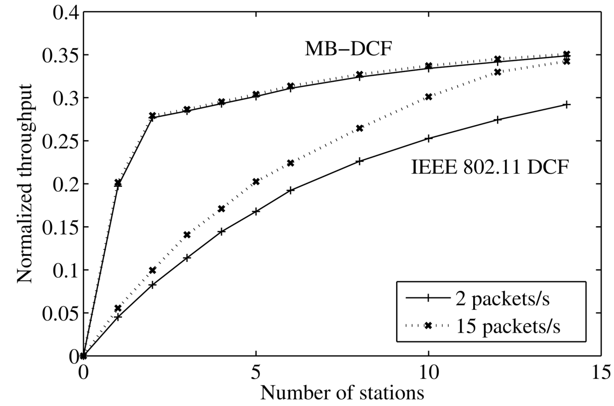

Fig. 2 Number of stations versus normalized throughput for $P_e = 0.01$

Fig. 3 shows that the predicted normalized throughput against the packet arrival rate with $P_e = 0.0001$ for two different numbers of stations. If the total offered load increases, the normalized per-station throughput stays in a constant value. Fig. 3 demonstrates that throughput increases gradually as the number of stations increases.

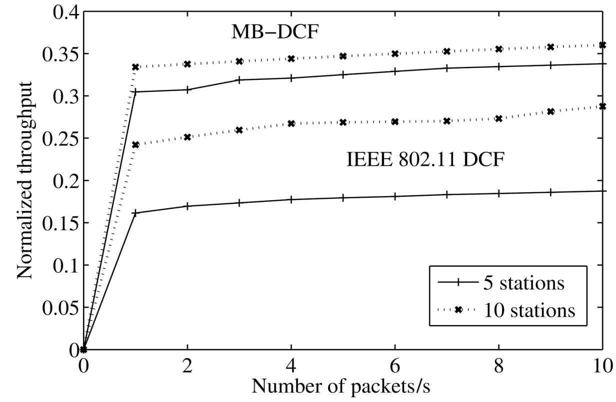

Fig. 3 Packet arrival rate versus normalized throughput for $P_e = 0.0001$

Fig. 4 shows that the predicted normalized throughput against the SNR. In the case of transmission errors, a station selects the counter value from the same contention window instead of doubling the contention window. When the probability of error increases, a larger number of stations select the counter value from the same contention window and then the contention in the network is increased. Hence, the performance of the modified method is degraded. This is justified in Fig. 4.

When the probability of error is high, under the circumstances of a smaller number of stations and low traffic, the proposed modified method will lead to a more efficient channel allocation and will give better throughput performance than the presently existing IEEE 802.11 DCF. The resulting transmission probability (τ) values are reported in Table 3 for low traffic ($\lambda = 10$ packets/s) and $P_e = 0.01$. For a smaller number of stations (up to 15 stations), the MB-DCF efficiently allocates the channel and it will lead to a better throughput result.

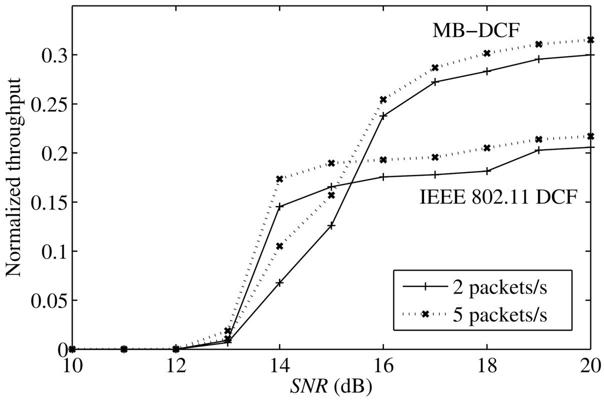

Fig. 4 SNR versus normalized throughput for $n = 5$

Table 3 Comparison for MB-DCF versus DCF with $P_e = 0.01$ and $\lambda = 10$ packets/s

n	Transmission probability (τ)	
	MB-DCF	DCF
2	0.0105	0.0022
4	0.0060	0.0022
8	0.0040	0.0024
10	0.0036	0.0026
15	0.0029	0.0029
20	0.0025	0.0035

Fig. 5 shows the throughput prediction for a station in each group, with $n_1 = 10$, $n_2 = 8$, and $n_3 = 5$. The predicted per-station throughput is plotted against normalized offered load for a station in each group. Fig. 6 illustrates the collision probability as a function of packet arrival rate for three different groups. The packet arrival rate of the group II is 1/2 of that of the group I, and group III is 1/4 of that of the group I.

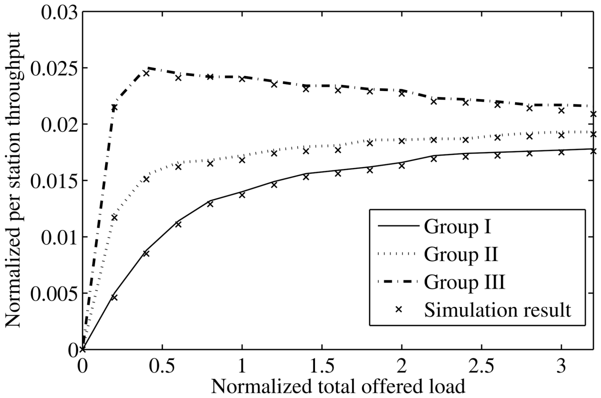

Fig. 5 Normalized per-station throughput versus the normalized offered load

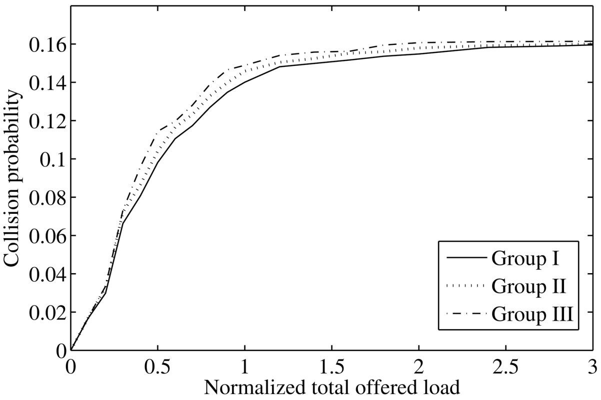

Fig. 6 Collision probability versus the normalized offered load

The predicted throughput closely matches with the simulated throughput. When the packet arrival rate increases, the transmission probability τ also increases and it remains constant. Upon comparing the curves in Figs. 5 and 6, the collision probability and the throughput remains constant beyond a certain offered load. The collision probabilities of a station in each group are very close but not same. A station in group I sees 9 other group I stations, 8 group II stations, and 5 group III stations. Fig. 7 depicts the throughput prediction for a station in class 1, with $n_1 = 10$, $n_2 = 8$, and $n_3 = 5$. The predicted per-station throughput is plotted against SNR for a station in class 1. Fig. 8 shows the throughput prediction for a station in class 2, with $n_1 = 8$, $n_2 = 6$, and $n_3 = 4$. The SNR value of class 2 is 1 dB above the SNR value of class 1. We observe that the per-station throughput of the class 2 is slightly higher than that of class 1.

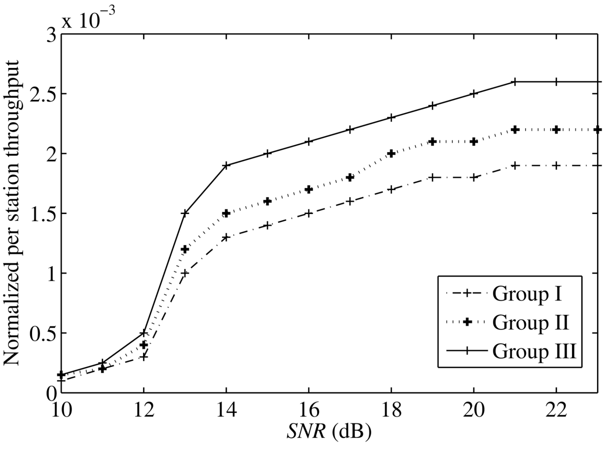

Fig. 7 Normalized throughput versus SNR for class 1 stations

Figs. 9 and 10 show predicted collision probabilities against SNR for class 1 and class 2 stations. Although same radio conditions are considered for each group in a class, the collision probability in each group is not same due to uneven in number of stations in each group. Figs. 11 and 12 present the results of examining the impact of the probability of error in the physical layer performance for each group in class 1 and class 2, respectively. The group throughput of the group in class 2 is slightly greater than that of class 1. The per-station throughput for the station in class 2 is greater than that of class 1, which is due to uneven number of stations in each group in different classes. The result shows that the increase in SNR above a certain value does not improve the performance significantly.

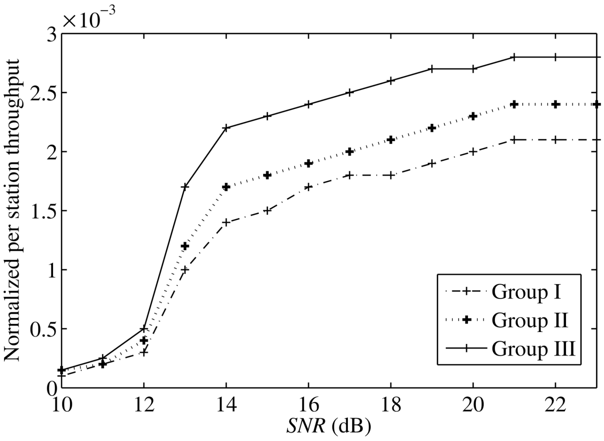

Fig. 8 Normalized throughput versus SNR for class 2 stations

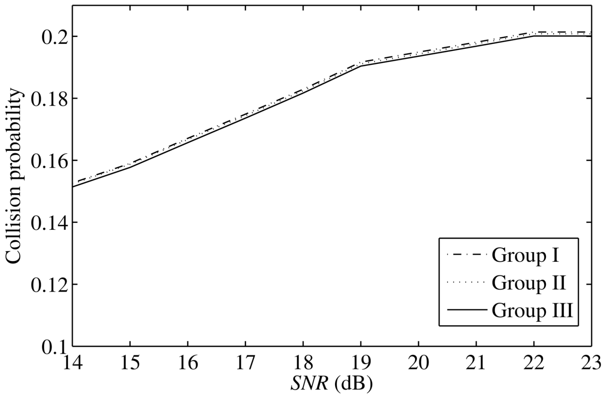

Fig. 9 Collision probability versus SNR for class 1 stations

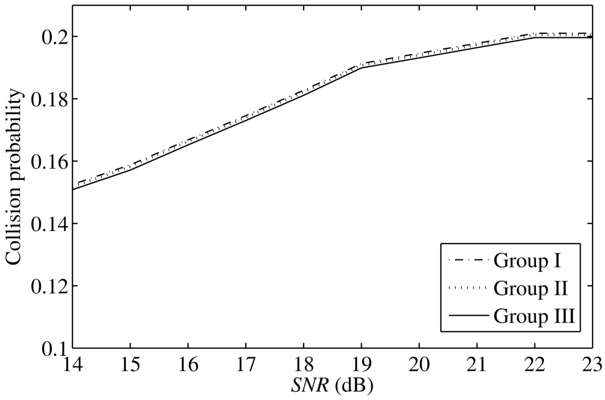

Fig. 10 Collision probability versus SNR for class 2 stations

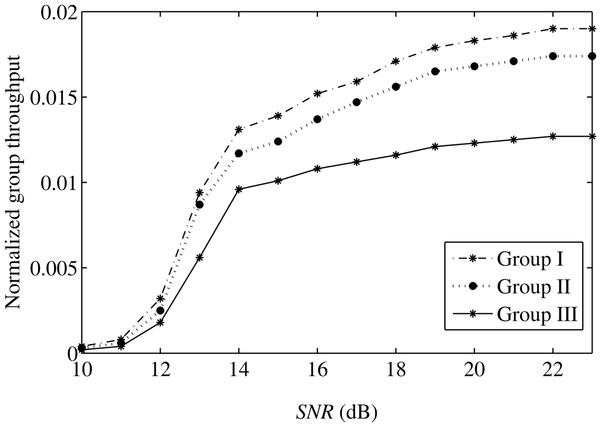

Fig. 11 Normalized group throughput versus SNR for class 1 groups

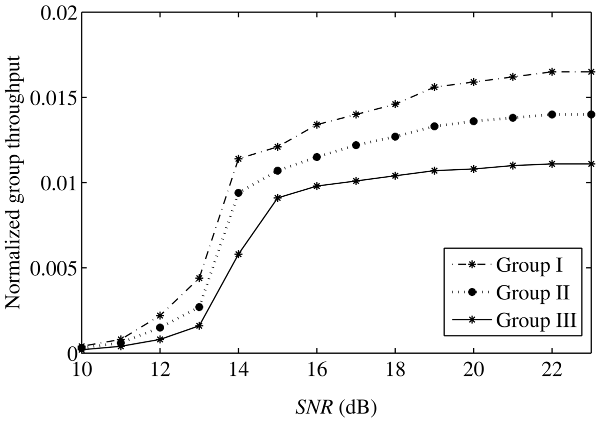

Fig. 12 Normalized group throughput versus SNR for class 2 groups

5 Throughput efficiency

The packet length plays an important role in the performance of the IEEE 802.11 MAC. In nonsaturated networks, a too large packet length results in more transmission errors and thus reduces throughput efficiency. Conversely, if packet length is too small, then a larger number of control packets for handshaking leads to a reduction in throughput efficiency. Figs. 13 and 14 show the predicted per-station throughput against the number of stations for IEEE 802.11 DCF and modified IEEE 802.11 DCF. Fig. 13 shows that the throughput is significantly degraded when the packet length is increased. The throughput performance is very close for MB-DCF, even though the packet length is increased. This is expected because the probability of error depends on the packet length. We observe that the performance of the MB-DCF is same for two different packet lengths when there is a smaller number of stations.

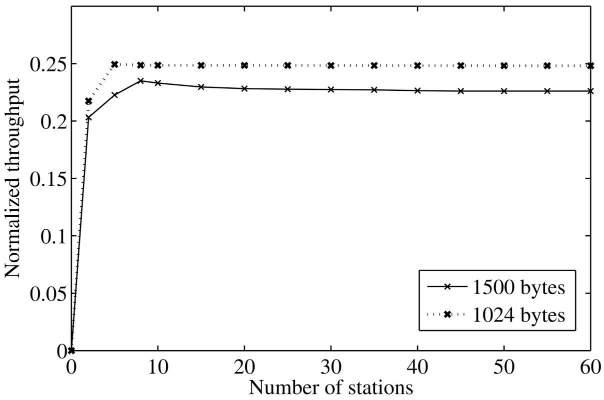

Fig. 13 Number of stations versus normalized throughput for IEEE 802.11 DCF

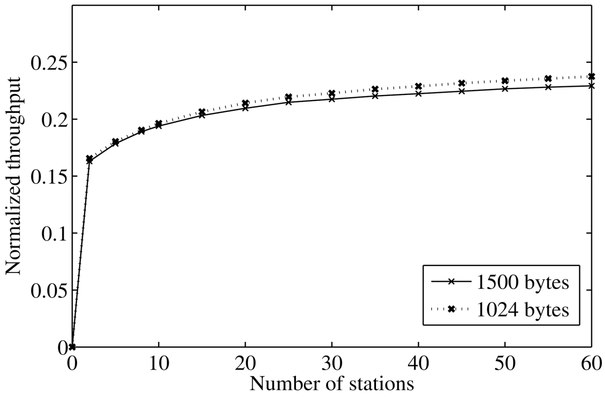

Fig. 14 Number of stations versus normalized throughput for modified IEEE 802.11 DCF

6 Conclusions

In this paper, the predicted results show that the performance of the MB-DCF is considerably improved over the performance of the IEEE 802.11 DCF. We have presented an accurate analytical model to evaluate the performance of MB-DCF under nonsaturated and heterogeneous conditions. Simulation and analysis results show that our analytical model can accurately predict the throughput performance of MB-DCF under heterogeneous conditions in the presence of transmission errors. We have presented the analysis of the modified IEEE 802.11 station in different radio conditions. With this analytical approach, the impact of physical layer techniques on the performance of the MAC protocol can be efficiently studied. The increase in packet length does not degrade the performance of the MAC very much in the MB-DCF under the noisy channel. We conclude that when the probability of error is high, under the circumstances of a smaller number of stations and low traffic, the proposed modified method will lead to a more efficient channel allocation and will give a better throughput performance than the presently existing IEEE 802.11 DCF.

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