Contention Window Optimization for IEEE 802.11 DCF Access Control

Der-Jiunn Deng, Chih-Heng Ke, Hsiao-Hwa Chen, and Yueh-Min Huang

***Abstract*—According to the latest version of the IEEE 802.11 standard, the backoff parameters of its collision avoidance mechanism are far from optimal, especially in a heavy load or error-prone WLAN environment. This strategy has a high collision probability and channel utilization is degraded in bursty arrivals or congested scenarios. Besides, the standard backoff mechanism may treat noise corruption as packet collisions. In this paper, we identify the relationship between backoff parameters, contention level, and channel BER in order to propose a simple, but yet well-performing distributed algorithm that allows a station to dynamically adjust its contention window size based on turn-around-time measurement of channel status. In addition to theoretical analysis, simulations are conducted to evaluate its performance. The proposed scheme works very well in providing a substantial performance improvement in heavy loaded and error-prone WLAN environments.**

***Index Terms*—IEEE 802.11, wireless network, distributed coordination function, backoff, bit error rate.**

I. Introduction

THE collision avoidance operation of IEEE 802.11 standard [1] is performed by a variable to control users access times. The stations start to transmit their frames in random to reduce the probability of collisions. However, collisions may still occur if two or more stations select the same backoff slot. When this happens, the stations involved have to reenter the competition cycle with an exponentially increasing backoff parameter value, and the increase of backoff parameter value after collisions is the mechanism provided by CSMA/CA to make the access control adaptive to channel conditions. This strategy avoids long access delays when the load is relatively light because it selects a small initial parameter value of contention window (CW) by assuming a low level of congestion in the system. However, it incurs a high collision probability and channel utilization is degraded in bursty arrival or congested scenarios. Furthermore, after a successful transmission, the size of CW is reset again to the minimum value without any memory of the current channel status.

In addition, the performance of the CSMA/CA access scheme will be severely degraded not only in congested scenarios but also in a situation where bit error rate (BER) increases in the wireless channel. The fundamental problem again comes from the backoff algorithm. In the CSMA/CA access scheme, immediate positive acknowledgement informs the sender of successful reception of each data frame. This is accomplished by a receiver initiating the transmission of an acknowledgement frame after a small time interval, SIFS, immediately following the reception of the data frame. In case that an acknowledgement is not received, as we mentioned earlier, the sender should automatically presume the data frame that was lost due to collision. Consequently, when a timer goes off, it exponentially increases backoff parameter value and retransmits the data frame less intensively. The idea behind this approach is to alleviate the probability of collisions. Unfortunately, wireless transmission links are noisy and highly unreliable. Path loss, channel noise, fading, and interference may cause significant bit errors. What this means is that an unacknowledged frame could result from not only collisions but also frame loss. A proper approach dealing with lost but non-collided frames is to send them again, as quickly as possible. Extending the backoff time has no benefit in this situation.

Although in the literatures there have been adequate excellent discussions on the issues on DCF and its performance analysis [2]-[8], none of the above studies proposed a mechanism to force the network stations to adopt an adaptive contention window size that maximizes the channel capacity for current channel status.

In [9]-[10], feedback-based mechanisms have been proposed for adapting the station backoff to the network congestion and maximizing channel capacity. In [11], the authors proposed and evaluated a distributed mechanism, named Asymptotically Optimal Backoff (AOB), for improving the efficiency of the IEEE 802.11 standard protocol. The AOB mechanism dynamically adapts the contention window size to the current network contention level and guarantees that a network asymptotically achieves its optimal channel capacity. Our work follows the same direction but in different approach as it is based on an estimation of number of active stations (i.e., stations that are actually in the process of transmitting packets), in the system and uses a very simple feedback signal: transmission failure rate. In fact, performance evaluation studies in [7] show that the performance of IEEE 802.11 protocol strongly depends on the number of active stations, especially when the basic access method is employed.

A new distributed contention-based MAC algorithm (namely, the fast collision resolution (FCR) algorithm), was proposed in [12]. The FCR algorithm attempts to resolve the

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collisions by increasing the contention window size for both colliding and deferring stations in the contention procedure. In [13]-[15], the authors proposed a mechanism to tune the contention window size based on the number of active stations, and the number being estimated by observing the channel status. In contrast to previous works, the mathematical models we present in this paper not only differs from the analytic models proposed in [9]-[12], it is also different from the other techniques in the literatures [13]-[15]. Whereas these studies use stochastic analysis (e.g., Markov chains), our model uses the average value for a variable wherever possible. This technique is more simple and easy to understand, yet effective.

Besides, although all the mechanisms cited above are based on analytic models of an IEEE 802.11 WLANs, and provide an optimal setting of the backoff parameters for achieving the channel capacity, there were few papers that considered the situation, in which transmission failures are due to data frame lost, rather than collisions, in a noisy or interference-prone environment. Unfortunately, as disclosed by the studies conducted in the literature [16]-[23], the performance of DCF will be significantly degraded by channel BER in wireless channels. In an environment where noise and interference are present, the size of CW should not increase with the times that frames are sent all over again. In such case, the network efficiency will be satisfactory only if CW is set to a considerably large value. The authors in [21] proposed a modified backoff rule for IEEE 802.11 protocol to improve the throughput. This modification relies on the optional 802.11 tools to recognize a reason of a transmission failure and does not increase the mean backoff interval if a failure happens due to distortion by noise. However, this approach is not satisfactory since it did not take into account the number of active stations.

Based on the above observations, we propose that a proper choice of the CW parameter values based on channel status has a great influence on overall network performance. In this paper, we develop an analytical model to study the theoretical throughput limit of a p-persistent CSMA/CA protocol under a congested and noisy operation condition. We use this analytical model to search for an optimal value of p (i.e., optimal contention window size) that maximizes the capacity of the IEEE 802.11 protocol based on the current channel status. The proposed scheme is called "distributed adaptive contention window scheme", which can not only dynamically adjust the contention window size according to the current network contention level and channel BER, but also provide an optimal performance which is close to the theoretical throughput upper bound of the IEEE 802.11 DCF access scheme in a congested and noisy environment. The proposed scheme works at each station in a distributed manner, and it can be implemented in the present IEEE 802.11 standard with only relatively minor modifications. Furthermore, with slight changes, it will be able to provide many levels of priorities, and can be compatible with EDCA access method provided by IEEE 802.11e standard.

In addition to the theoretical analysis, we have also carried out comprehensive simulations implemented by network simulator NS2 [24] to evaluate the performance of the proposed scheme. The results show that the proposed scheme provides a remarkable performance improvement in heavy load and error-prone WLAN environments.

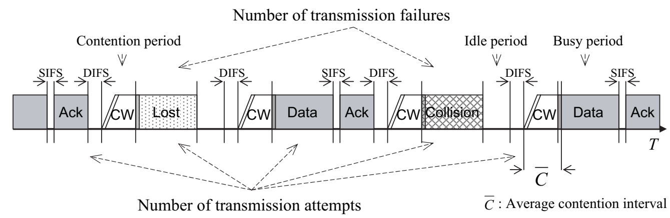


Fig. 1. The channel status of 802.11 DCF access method.

TABLE I
NOTATIONS AND VARIABLES USED IN ANALYSIS.

Notations and variables	Meaning and explanation
p_f	Probability of a transmission failure
M	Number of active stations
p	Transmission probability
$\overline{W}$	Average backoff window size
$\overline{C}$	Average contention interval
W	Initial backoff window size
m	Maximum number of backoff stages
BER	Channel bit error rate
L_{DATA}	Mean payload size
p_{opt}	Optimal value of p parameter
$\overline{W}_{opt}$	Optimal backoff window size
L_{ACK}	Ack frame size
L_{RTS}	Request-to-send frame size
L_{CTS}	Clear-to-send frame size
T_p	Duration of a Physical Layer Convergence Protocol (PLCP) preamble
T_H	Duration of a PLCP header
τ	Propagation delay
T_{DIFS}	Duration of DCF interframe space (DIFS)
T_{SIFS}	Duration of short interframe space (SIFS)
R_{DATA}	Maximum data rate in Wireless LANs
T_{slot}	Time needed for each time slot

The remainder of this paper is outlined as follows. Section II introduces the proposed scheme. In Section III, we present the analytical model that estimates the theoretical throughput upper bound of IEEE 802.11 DCF access scheme. Simulation and experimental results are given in Section IV, followed by Section V which concludes this paper.

II. DISTRIBUTED ADAPTIVE CONTENTION WINDOW SCHEME

Before we start to discuss the issues of interest, important notations and variables are defined in Table I, and they will be used throughout this paper.

A. Run-Time Estimation of Channel Status

In order to exploit the information about the actual channel status, we define the probability of transmission failure, P_f, to be the probability that a frame transmitted by the station of interest fails. Recall that the channel status can be generally divided as three states: busy, idle, and contention period as shown in Fig. 1. Therefore, the probability of transmission failure can be defined as follows:

$$p_f = \frac{Number\ of\ transmission\ failures}{Number\ of\ transmission\ attempts} \quad (1)$$

As the channel status are ever-changing, in practice, the value of P_f has to be updated at the end of each transmission to reflect the actual state of the channel. However, such a common heuristic would make the value of P_f fluctuate rapidly. To avoid this undesirable behavior, each station estimates P_f based on run-time measurement, and uses the following formula to update its value:

$$p_f = \alpha \times p_f + (1-\alpha) \times p_{f(Estimated)} \tag{2}$$

where the new value of P_f is a weighted combination of the previous value of P_f and the new value for estimated P_f, and $\alpha \in [0, 1]$ is a smoothing factor.

B. Number of Active Stations Estimation

To simplify the analysis, we assume a geometric distributed backoff time in CSMA/CA protocol, which differs from the standard protocol only in the selection of the backoff interval. Based on geometric densities, the probability that there are x failures of Bernoulli trials before the first success is

$$P(X = x) = (1-p)^{x-1}p \;, 1 \le x \le \infty \tag{3}$$

Hence, the average contention window size is determined by the expected value of random variable X, and thus we have

$$\begin{aligned} \tfrac{\overline{W}+1}{2} &= \sum_{x=1}^{\infty} xp\;(1-p)^{x-1} \\ &= \tfrac{p}{1-p} \sum_{x=1}^{\infty} x(1-p)^{x-1} = \tfrac{1}{p} \end{aligned} \tag{4}$$

Now let us try to estimate the average contention window size at a saturation condition. Since the backoff time is uniformly distributed over $\{0, W\}$ for the first attempt, the average contention window size is

$$\begin{aligned} \overline{W} &= \tfrac{(1-p_f)W + p_f(1-p_f)2W + \ldots + p_f^m(1-p_f)2^m W}{1-p_f^{m+1}} \\ &= \tfrac{W(1-p_f)[\frac{1-(2p_f)^{m+1}}{1-2p_f}]}{1-p_f^{m+1}} = \tfrac{W(1-p_f)[1-(2p_f)^{m+1}]}{(1-2p_f)(1-p_f^{m+1})} \end{aligned} \tag{5}$$

Substituting $\overline{W}$ expressed in equation (4) into equation (5), we obtain:

$$p = \tfrac{2(1-2p_f)(1-p_f^{m+1})}{W(1-p_f)[1-(2p_f)^{m+1}] + (1-2p_f)(1-p_f^{m+1})} \tag{6}$$

Since the probability of a transmission failure is defined as the probability that a transmitted frame encounters a collision or is received in error, this yields

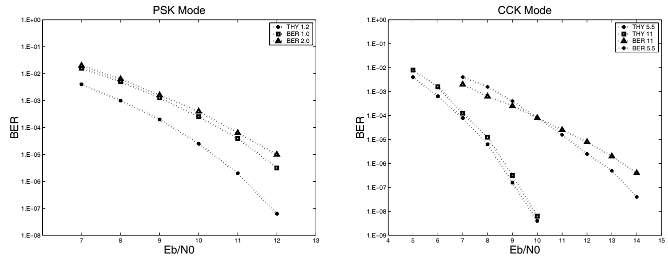
$$p_f = 1 - (1-p)^{M-1} \times (1-BER)^{L_{DATA}} \tag{7}$$

¿From equation (7), we obtain

$$M = 1 + \frac{\log\left[\dfrac{1-p_f}{(1-BER)^{L_{DATA}}}\right]}{\log(1-p)} \tag{8}$$

Substituting p as expressed in equation (6) into equation (8), we obtain

$$M = 1 + \frac{\log\left[\frac{1-p_f}{(1-BER)^{L_{DATA}}}\right]}{\log\left[1 - \frac{2(1-2p_f)(1-p_f^{m+1})}{W(1-p_f)[1-(2p_f)^{m+1}] + (1-2p_f)(1-p_f^{m+1})}\right]} \tag{9}$$



(a) PSK Mode. (b) CCK Mode.

Fig. 2. BER versus SNR for Intersil HFA3861B chipset.

Finally, we still need to engineer the current channel BER to complete this scheme. Fig. 2 shows the BER curves vs. signal to noise ratio (SNR) for IEEE 802.11b PHY modes. These curves could be derived theoretically [25]. However, since typical off the shelf wireless chipsets [26]-[27] report SNR measurements in terms of received signal strength indication (RSSI) value once per packet, these empirical curves provided by the chipsets vendor have been used to estimate the channel BER in both analysis and simulation results shown in the following sections.

C. Contention Window Optimization

Suppose there are M stations making a transmission attempt in a slot, and $Mp_{opt} = i$ is the expected value in which exactly i stations transmit in a slot. It is an intuition that the maximum throughput is obtained by setting the transmission probability of each station equal to $\frac{1}{M}$. However, based on our analysis, the collision probability could be larger than 0.5 as the number of the stations reaches 20 if the contention window size is fixed to the number of stations in the network. Under such circumstances, the performance of the network will be severely degraded as significant packet loss occurs due to collisions caused by simultaneous transmission of packets.

Now let us define the average contention interval, $\overline{C}$, to be the average number of slots observed in the contention period as illustrated in Fig. 1. Since $Mp = 0$ indicated that a slot in the contention period remains empty, we have

$$Mp_{opt} = \sum_{i=1}^{M} i \cdot P\{M=i\} \ge \sum_{i=1}^{M} P\{M=i\} = 1 - p\{M=0\} = \tfrac{1}{\overline{C}} \tag{10}$$

It is noted that the collision probability will become relatively low if the stations utilize the optimal value of p parameter, meaning that

$$p\{M > 1 \mid M > 0\} < p\{M = 1 \mid M > 0\} \tag{11}$$

In paper [11] the authors pointed out that Mp_{opt} is a tight upper bound of $\frac{1}{\overline{C}}$ in a system operating with the optimal channel utilization level. Since the average size of contention window $\overline{W}$ is $\frac{1}{p}$ when a station transmits in a slot with probability p as we mentioned earlier. Substituting $\overline{W}$ and M as expressed in equations (5) and (9) respectively, we can obtain the approximated optimal contention window size $\overline{W}_{opt}$

which is defined as

$$2\overline{C}\left\{1+\frac{\log\left[\frac{1-p_f}{(1-BER)^{L_{DATA}}}\right]}{\log\left[1-\frac{2(1-2p_f)(1-p_f^{m+1})}{W(1-p_f)[1-(2p_f)^{m+1}]+(1-2p_f)(1-p_f^{m+1})}\right]}\right\}-1 \tag{12}$$

D. Using Block-Code for Error Correction

Due to attenuation, fading, scattering or interference from other active sources, wireless communication channels generally suffer higher loss rates than their wired counterparts. Packet losses in wireless networks are usually recovered through the use of Automatic Repeat reQuest (ARQ) or Forward Error Correction (FEC) techniques. The basic principle of FEC entails injecting redundant data into the original transmission data such that packet losses can be recovered without the need for retransmission. It generates a fixed number (h) of redundant packets to protect the k source packets in each block. In wireless networks protected by FEC schemes, provided that a minimum of k packets belonging to the same block are correctly received, the entire block can be successfully recovered, irrespective of whether the received packets are source packets (k) or FEC redundant packets (h).

Assuming that each transmission block comprises k packets. The probability of a block being successfully recovered is given by

$$\sum_{i=k}^{k+h}\binom{k+h}{i}\times(1-BER)^{i\times L_{DATA}}\times\left[1-(1-BER)^{L_{DATA}}\right]^{k+h-i} \tag{13}$$

where $\binom{k+h}{i}$ denotes all possible combinations of i packets successfully received in a whole block. Substituting the result expressed in equation (13) into equations (12), we can refine the approximated optimal contention window size as

$$2\overline{C}\left\{1+\frac{\log\left\{\frac{1-p_f}{\sum_{i=k}^{k+h}\binom{k+h}{i}\times(1-BER)^{i\times L_{DATA}}\times\left[1-(1-BER)^{L_{DATA}}\right]^{k+h-i}}\right\}}{\log\left\{1-\frac{2(1-2p_f)(1-p_f^{m+1})}{W(1-p_f)[1-(2p_f)^{m+1}]+(1-2p_f)(1-p_f^{m+1})}\right\}}\right\}-1 \tag{14}$$

It is noted that the value of P_f should be counted by each block instead of each packet in equation (14).

E. Priority Enforcement Mechanism

To expend support for applications with quality of service (QoS) requirements, the IEEE 802.11e amendment aims at providing QoS provisioning to support real-time traffic in WLANs [28]. The Enhanced Distributed Channel Access (EDCA) is a QoS extension of the DCF in legacy IEEE 802.11 protocol. In this section we propose a backward compatible priority enforcement mechanism, thereby making the proposed scheme compliant stations to coexist with IEEE 802.11e EDCA enabled stations.

The basic idea behind our method is that the prioritized access to the wireless medium is provided by allowing faster access to the channel to traffic classes with higher priority.

TABLE II
DEFAULT ATTRIBUTE VALUES USED IN THE SIMULATION.

Attribute	Value	Meaning & Explanation
R_{DATA}	54 Mb/s	Maximum data rate (64 QAM modulation)
T_{slot}	9 μs	Time needed for each time slot
T_{SIFS}	16 μs	Duration of short interframe space (SIFS)
T_{DIFS}	34 μs	Duration of DCF interframe space (DIFS)
L_{DATA}	1000 bytes	Mean payload size
L_{ACK}	112 bits	ACK frame size
L_{RTS}	160 bits	Request-to-send frame size
L_{CTS}	112 bits	Clear-to-send frame size
L_{MAC}	224 bits	MAC overhead
T_p	16 μs	Duration of a PLCP preamble
T_H	4 μs	Duration of a PLCP header
T_S	4 μs	Interval of an OFDM symbol
τ	1 μs	Propagation Delay
W	16 slots	Minimum contention window size
m	6	Maximum backoff stages
d	250 meters	Simulation topology 250m×250m

Assume that there are M_i stations with access category AC_i traffic, and AC_1 is assumed to be the higher priority traffic. To support multi levels of priorities, instead of using the one defined in equation (12), we refine the approximated optimal contention window as

$$\left\{2\overline{C}\left[1+\frac{\log\left[\frac{1-p_f}{(1-BER)^{L_{DATA}}}\right]}{\log\left[1-\frac{2(1-2p_f)(1-p_f^{m+1})}{W(1-p_f)[1-(2p_f)^{m+1}]+(1-2p_f)(1-p_f^{m+1})}\right]}\right]-1\right\}\times\frac{\sum_{j=1}^{i}M_j}{M} \tag{15}$$

for stations with access category AC_i traffic to complete our scheme.

III. Throughput Upper Bound Analysis

In this section, we present an analytical model that estimates the theoretical throughput upper bound of the IEEE 802.11 DCF access scheme.

A. Basic Access Method

A transmission cycle of DCF access method consists of DIFS deferral, backoff, data transmission, SIFS deferral and ACK transmission. Since the data transmission is the only useful transmission time in a transmission cycle, we can obtain the theoretical throughput upper bound of the basic access method given as

$$\frac{L_{DATA}(1-BER)^{(L_{DATA}+L_{ACK})}}{2T_p+2T_H+2\tau+T_{DIFS}+\frac{L_{DATA}+L_{ACK}}{R_{DATA}}+T_{SIFS}+\frac{W}{2}T_{slot}} \tag{16}$$

B. RTS/CTS Mechanism

In addition to the basic access method, an optional four-way handshaking technique, known as the RTS/CTS mechanism, has been used in IEEE 802.11 DCF. Before transmitting a packet, a station operating in RTS/CTS mode reserves the channel bandwidth by sending a special RTS short frame. The destination station acknowledges the receipt of an RTS by sending back a CTS frame, after which normal data frame

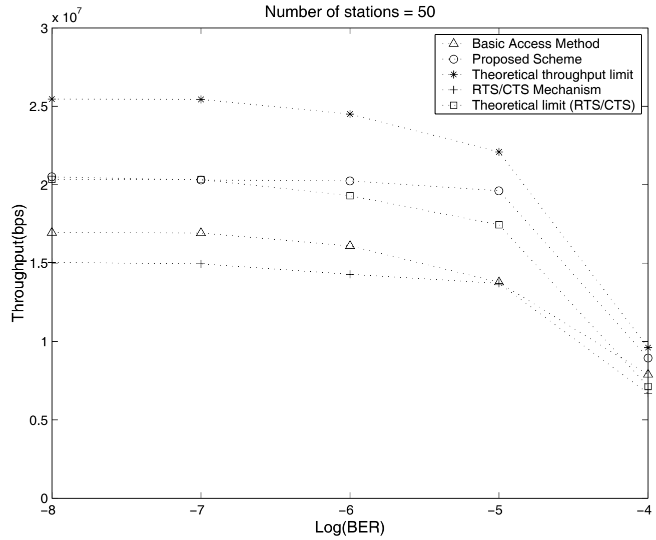


Fig. 3. Achievable throughput versus channel BER in congested environments.

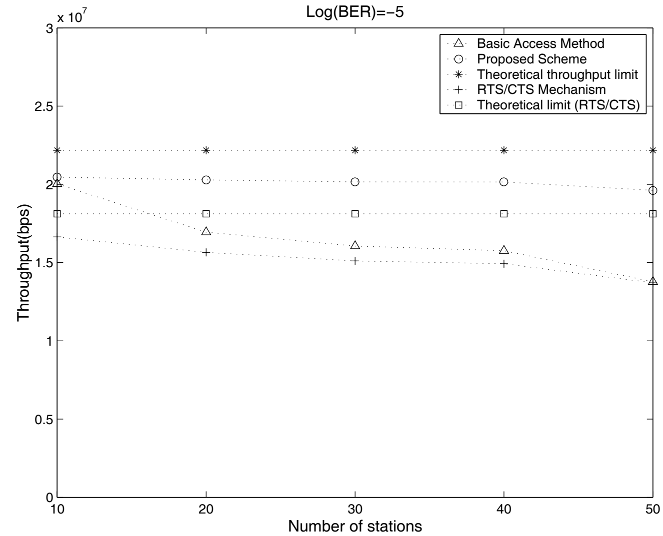


Fig. 5. Achievable throughput versus number of stations in noisy environments.

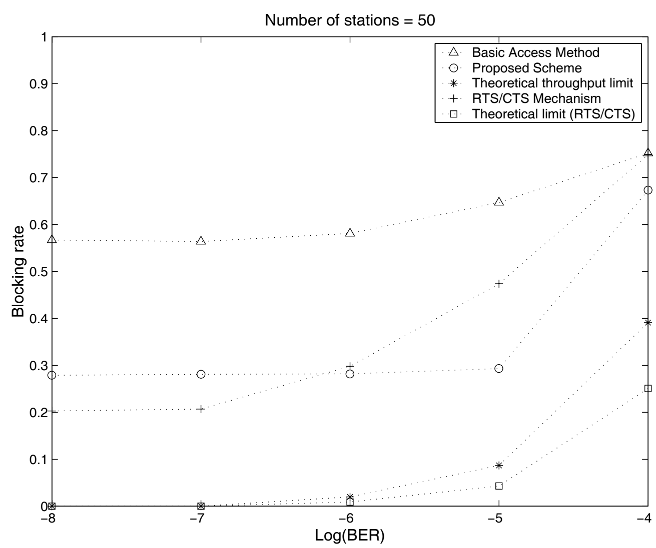


Fig. 4. Blocking rate versus channel BER in congested environments.

transmission and ACK response occur. Hence, the theoretical throughput upper bound for the RTS/CTS mechanism is

$$\frac{L_{DATA}(1-BER)^{(L_{RTS}+L_{CTS}+L_{DATA}+L_{ACK})}}{4T_p+4T_H+4\tau+T_{DIFS}+\frac{L_{RTS}+L_{CTS}+L_{DATA}+L_{ACK}}{R_{DATA}}+3T_{SIFS}+\frac{W}{2}T_{slot}} \tag{17}$$

IV. Simulations and Performance Evaluation

A. Simulation Environment

In this section, we will evaluate the performance of the proposed scheme. Our simulation model is built using the network simulator NS2 [24]. The NS2 802.11 wireless link is extended to generate an error probability by employs the Gilbert-Elliot (GE) error model [29] to characterize fading in the communication channel. The rate at which errors occur in the GE model is dependent on the channel condition. CBR applications are used as traffic generators. The default values used in the simulations are listed in Table II. All the simulations are conducted on Linux 2.4.20 on a Xeon 3.4 GHz Server with 2 GB memory. The version of NS2 is ns-2.28, and each simulation runs at least for 100 simulation seconds.

B. Simulation Results

In what follows, the performances of the proposed scheme, legacy IEEE 802.11 basic access method, the RTS/CTS mechanism, and theoretical bound are compared based on simulations. Fig. 3 depicts the achievable throughput as the channel BER increases when the number of stations is fixed at 50. As illustrated in Fig. 3, we can see that there is not much difference in the values of the performance measures when BER is low. However, the proposed scheme provides a better performance than the basic access method and RTS/CTS mechanism as the channel BER is increased, especially when the channel BER reaches approximately to 10^{-5}. Fig. 4 shows the effect of channel BER by plotting the (data) frame blocking rate under congested scenario. As shown in the figure, the frame blocking rate of the basic access method has been greatly increased when the channel BER increases, but the performance of the proposed scheme is satisfactory at all time until the channel BER approximates to 10^{-5}. Fig. 5 depicts the achievable throughput as the number of stations increases when the channel BER is 10^{-5}. As shown in the figure, the throughput improvement can be as much as 20% and is more pronounced than that when the RTS/CTS mechanism is employed. Fig. 6 depicts the (data) frame blocking rate as the number of stations increases. As we expected, the proposed scheme obviously outperforms the basic access method and RTS/CTS mechanism in most cases, except for the case that the channel BER is greater than 10^{-4}.

Figures 7, 8 and 9 show the BER performance and the number of stations versus the achievable throughput for the basic access method, RTS/CTS mechanism, and the proposed scheme, respectively. When comparing and contrasting these figures, it can be seen that the throughput of our scheme is not affected by channel BER between 10^{-7} to 10^{-5}. Besides, the throughput of our proposed scheme changes little as the

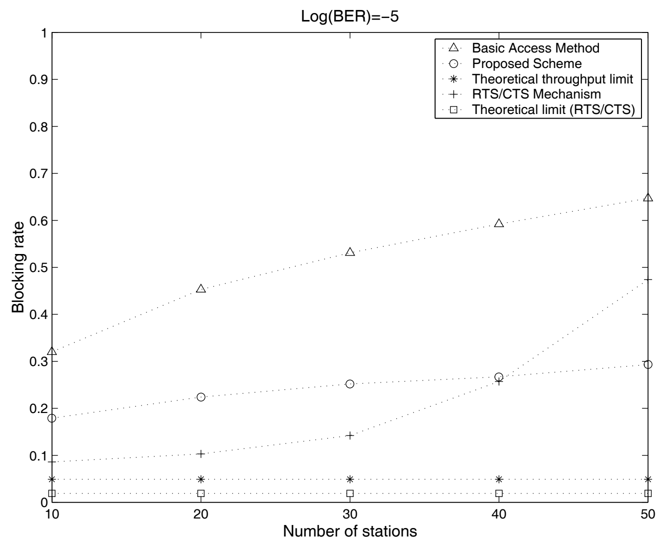


Fig. 6. Blocking rate versus number of stations in noisy environments.

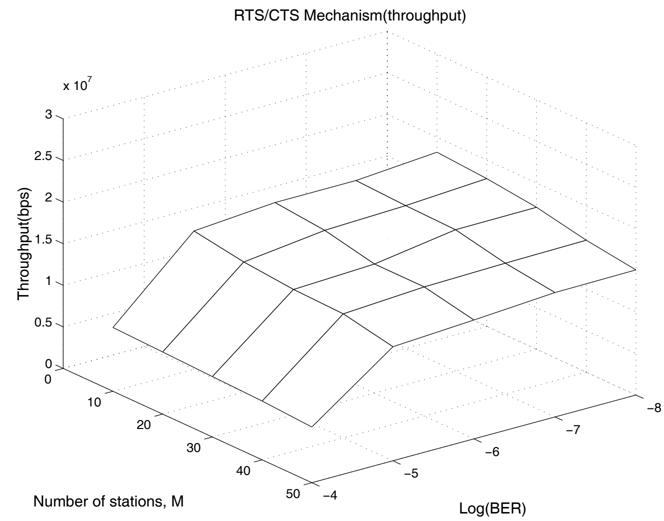


Fig. 8. Throughput versus channel BER and number of stations for RTS/CTS mechanism.

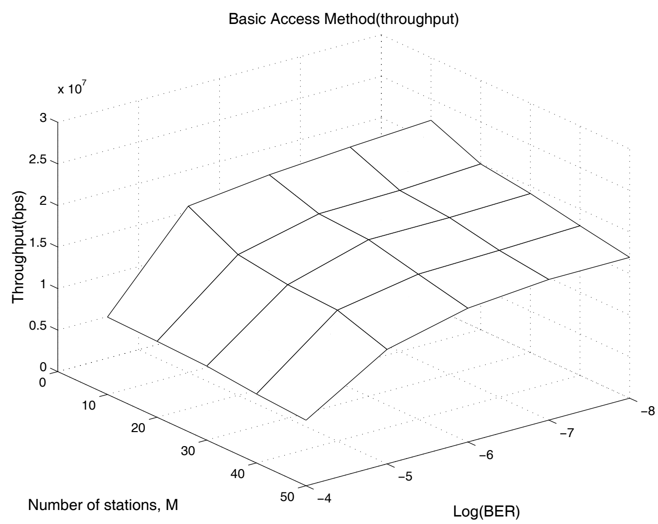


Fig. 7. Throughput versus channel BER and number of stations for basic access method.

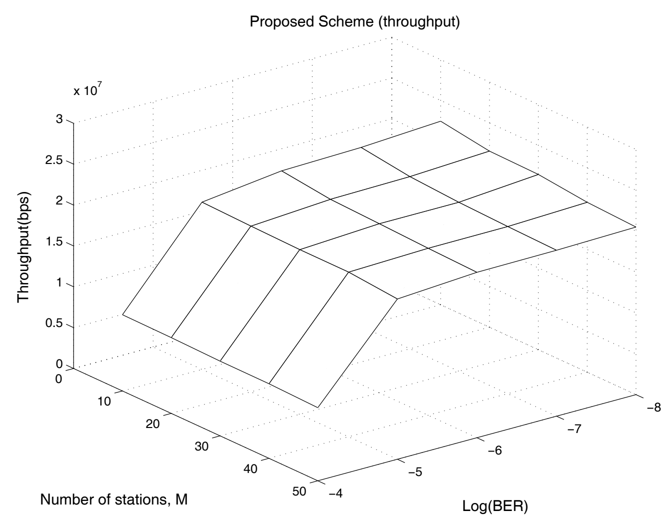


Fig. 9. Throughput versus channel BER and number of stations.

number of stations varies. This indicates that the proposed scheme is quite resistant towards influences form wireless environments, and it provides a remarkable improvement over both congested and noisy wireless environments.

V. Conclusion

The backoff parameters in the IEEE 802.11 DCF access method are far from being optimal in a heavy-loaded and error-prone WLAN environment. This yields a high collision probability and degraded channel utilization in bursty arrival or congested scenarios. Besides, in a noisy and highly unreliable wireless environment, an unacknowledged frame could result from not only collisions but also frame losses. When the sender is unable to distinguish the causes of the frame loss, it is difficult to make a correct decision. In this paper, we propose a pragmatic solution to solve the problem. The proposed scheme works at each station in a distributed way, and it can be implemented in IEEE 802.11 networks with relatively minor modifications. Through extensive simulations, we have demonstrated quantitatively the effectiveness of our proposed scheme. The given results show that the proposed scheme works satisfactorily in most cases, offering a remarkable performance improvement in a congested and noisy wireless environment.

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