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# IEEE 802.11 Distributed Coordination Function: Enhancement and Analysis

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**Abstract** IEEE 802.11 Medium Access Control (MAC) is proposed to support asynchronous and time bounded delivery of radio packets. Distributed Coordination Function (DCF), which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and binary slotted exponential backoff, is the basis of the 802.11 MAC. This paper proposes a throughput enhancement for DCF by adjusting the Contention Window (CW) setting scheme. Moreover, an analytical model based on Markov chain is introduced to compute the enhanced throughput. The accuracy of the model and the enhancement of the proposed scheme are verified by elaborate simulations.

**Keywords** IEEE 802.11, CSMA/CA, DCF

## 1 Introduction

Recently, there is an increasing need towards portable and mobile computers or workstations with the development wireless packet computing technology. Wireless networks should provide communications between mobile terminals, and high speed access to backbone networks needs to be provided too.

Wireless Local Area Networks[1–6] (WLANs), which provide more flexibility and convenience than their wired counterpart, are being developed to provide high bandwidth access for users in a limited geographical area. IEEE Project 802 recommends an international standard 802.11[1–3] for WLANs. The standard includes detailed specifications for both Medium Access Control (MAC) and Physical Layer (PHY). In WLANs, the physical medium, which is shared by all stations and has limited connection range, has significant differences from wired media. The IEEE 802.11 WLAN standard includes a basic Distributed Coordination Function (DCF) and an optional Point Coordination Function (PCF).

In 802.11, the DCF is the fundamental access method used to support asynchronous data transfer on a best effort basis. As specified in the standards, the DCF must be supported by all the stations in a basic service set (BSS). The DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CD is not used because a station is unable to listen to the channel for collision while transmitting. In 802.11 CS is performed both at physical layer, which is also referred to as physical carrier sensing, and at the MAC layer, which is known as virtual carrier sensing. The PCF in the 802.11 is a polling-based protocol, which is designed to support collision free and real time services. This paper focuses on the performance analysis and modeling of DCF in 802.11 WLAN.

There are two techniques used for packet transmitting in DCF. The default one is a two-way handshaking mechanism, also called basic access method. A positive acknowledgement (ACK) is transmitted by the destination station to signal the successful packet transmission. The other optional one is a four-way handshaking mechanism, which uses request-to-send/clear-to-send (RTS/CTS) technique to reserve the channel before data transmission. This technique has been introduced to reduce the performance degradation due to hidden terminals. However, the drawback of using the RTS/CTS mechanism is an increased overhead for short data frames.

In DCF, a binary slotted exponential backoff is

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*He is now in Microsoft Research Asia (MSRA) used with CSMA/CA. Whenever a backoff occurs, the backoff time is set with a uniform distribution over the interval [0, CW], where the Contention Window (CW) will double for a retry and reset for a new packet. This paper proposes a little bit conservative way to reset the CW to improve the throughput performance of DCF.

To analyze the way to reset CW, the modeling of 802.11 has been examined. [7] considers the effect of capture and hidden terminal and [8] gives the theoretical throughput limit of 802.11 based on a $p$-persistent variant. However, none of these models take the effect of the Contention Window (CW) and binary slotted exponential back-off procedure used by DCF into consideration. Unlike those researches, [9, 10] use Markov process to analyze the saturated throughput of 802.11. Unfortunately, due to some false transition in the Markov chain and some false hypotheses, the results of [9] overestimate the throughput in 802.11. A more accurate model is proposed in [10], which also uses Markov chain to analyze the throughput and correct the mistakes in [9]. This paper analyze the effect of proposed CW reset scheme by a new Markov chain model, which is validated by elaborate simulations.

The paper is organized as follows. Section 2 briefly describes the DCF of IEEE 802.11 MAC protocols, which includes both basic access and RTS/CTS mechanisms. In Section 3, the new CW reset scheme is introduced and an analytical model to compute the saturated throughput is proposed. Section 4 validates the accuracy of this model and the performance of CW reset scheme by comparing the results of modeling and simulations. In Section 5, the model is used to analyze throughput performance with variable parameters. Finally, Section 6 concludes the paper.

## 2 Distributed Coordination Function in 802.11

This paper only gives a brief introduction to 802.11, and the readers are referred to [1–3] for detailed information about 802.11. The DCF is based on CSMA/CA and it only provides asynchronous access for best effort data transmission.

### 2.1 Basic Access Method

In 802.11, priority access to the wireless medium is controlled by the use of inter-frame space (IFS) time between the transmissions of frames. Totally three IFS intervals have been specified by 802.11 standard: short IFS (SIFS), point coordination function IFS (PIFS), and DCF-IFS (DIFS). The SIFS is the smallest and the DIFS is the largest.

The station may proceed with its transmission if the medium is sensed to be idle for an interval larger than the Distributed Inter Frame Space (DIFS). If the medium is busy, the station defers action until a DIFS is detected and then a random back-off period is generated before transmitting. The back-off timer counter is decreased as long as the channel is sensed idle, frozen when the channel is sensed busy, and resumed when the channel is sensed idle again for more than a DIFS. A station can initiate a transmission when the back-off timer reaches zero. The back-off time is uniformly chosen in the range $(0, w-1)$. Also $(w-1)$ is known as Contention Window (CW), which is an integer with the range determined by the PHY characteristics $CW_{\min}$ and $CW_{\max}$. After each unsuccessful transmission, $w$ is doubled, up to a maximum value $2^{m'}W$, where $W$ equals $(CW_{\min}+1)$ and $2^{m'}W$ equals $(CW_{\max}+1)$.

Upon receiving a packet correctly, the destination station waits for an SIFS interval immediately following the reception of the data frame and transmits a positive ACK back to the source station, indicating that the data packet has been received correctly. In case the source station does not receive an ACK, the data frame is assumed to be lost and the source station schedules retransmission with the CW with back-off time doubled. When the data frame is transmitted, all the other stations hearing the data frame adjust their Network Allocation Vector (NAV), which is used for virtual CS at the MAC layer, based on the duration field value in the data frame, which includes the SIFS and the ACK following the data frame.

### 2.2 RTS/CTS Access Method

In 802.11, DCF also provides an optional way of transmitting data frames, which involves transmission of special short RTS and CTS frames prior to the transmission of actual data frame. An RTS frame is transmitted by a station, which needs to transmit a packet. When the destination receives the RTS frame, it will transmit a CTS frame after SIFS interval immediately following the reception of the data frame. The source station is allowed to transmit its packet only if it receives the CTS correctly. Note that all the other stations are capable of updating the NAVs based on the RTS from the source station and the CTS from the destination station, which helps to combat the *hidden terminal* problems. In fact, a station able to detect the transmission of at least one of the RTS or CTS frames can avoid collision even when it is unable to sense the channel busy. If a collision occurs with two RTS frames, far less bandwidth is wasted compared with a larger data frame in collision.

## 3 DCF Performance Enhancement and Analysis

In this paper, we focus on the *saturated throughput*, which is also examined in [9, 10]. This is a fundamental performance figure defined as the limit reached by the system throughput as the offered load increases, and represents the load that the system can carry in stable conditions.

### 3.1 New Backoff Scheme Preserving CW

In 802.11 DCF, a binary exponential backoff[11] is used with CSMA/CA. Whenever a backoff occurs, the backoff time is set with a uniform distribution over the interval $[0, w-1]$, and $(w-1)$ is also known as CW (Contention Window). After each unsuccessful transmission, $w$ is doubled, up to a maximum value $2^m W$, where $W$ equals $(CW_{\min}+1)$ and $2^{m'} W$ equals $(CW_{\max}+1)$. Once it reaches $CW_{\max}$, the CW will remain at the value of $CW_{\max}$ until it is reset. CW will be reset to $CW_{\min}$ after every successful transmission attempt of a data frame or an RTS frame, or where a retry counter reaches its limit, whose value is different for data frame and RTS frame in 802.11, i.e., 5 and 7 separately[2].

Therefore, in binary exponential backoff scheme used by 802.11, the CW value, which controls the range of the backoff slot number taken by a station, is determined by the retransmission number of the current frame. It is easily understood that this scheme is chosen to dynamically adapt to the number of stations trying to send. Since a station uses CW to control the backoff window of packet transmission, the optimal setting of CW will affect the performance of DCF. The backoff procedure of CW can be considered as a progress to probe the optimal value of CW, however, the resetting scheme in binary exponential backoff of 802.11 breaks this progress, which will degrade the performance of DCF. Then the question is how to control the backoff counter, or CW, optimally. As we know that the CW value adapts to the number of stations trying to send, so a CW value for the current data frame is also meaningful to the next data frame to be transmitted, because it represents the adaptation result of the current backoff time slot to the current contention situation in WLAN.

Therefore, this paper argues that the CW value should not be determined by the retransmission number of the current data frame to be transmitted as that in binary exponential backoff used by 802.11, because CW value is the adaptation result. All the adaptation procedures taken by the packet transmission, i.e., collisions or successful transmission, should affect the CW value and it is a value which is meaningful to all the transmitted and transmitting packets, not only for the currently sending packet. Thus the adaptation procedure of CW value to the current network contention is continuous for every station.

This paper proposes a simple but effective change to 802.11 to make the backoff counter oscillate to the optimal value without complex calculation and run-time estimation as in [8]. The way is conservative compared with that used in 802.11. It can be described as follows.

1) Whenever the retry counter reaches the limit, the CW is kept unchanged rather than reset. 2) After a successful transmission, $w$ is set to the value $\max[w/2,\ CW_{\min}+1]$. 3) Whenever a transmission fails, $w$ is set to the value $\min[2w,\ CW_{\max}+1]$. It will be referred to as new backoff scheme throughout this paper.

The difference of our backoff scheme and the binary exponential backoff scheme of 802.11 is as follows.

1) The backoff time slot of binary exponential backoff scheme of 802.11 is determined by the retransmission number of the current data frame waiting for transmission or its corresponding RTS frame. However, the CW value in our backoff scheme is kept unchanged and will be used as the initial CW value of the next data frame to keep the adaptation procedure continuous. 2) After every successful transmission, the CW value will be reset in binary exponential backoff scheme of 802.11, while it will be reduced by half in our scheme. 3) After retry counter reaches the limit, the CW is also reset in binary exponential backoff scheme of 802.11, while it will be kept unchanged and used as the initial CW value of the next data frame in our backoff scheme.

Another contribution of this paper is the analytical evaluation of the saturated throughput of the new backoff scheme, with the assumption of ideal channel conditions. This paper does not choose the way in [8], which uses a $p$-persistent variant that does not capture the effect of binary exponential setting of CW. This paper uses Markov chain to analyze the effect of new backoff scheme. A new Markov chain is proposed, which differentiates it from 802.11. The analysis includes two parts: 1) with a Markov chain, the behavior of a station is examined, which we use to get the stationary probability $\tau$ that the station transmits a packet; 2) the throughput of both basic and RTS/CTS access methods is examined.

### 3.2 Markov Chain Model

We use the same assumption as in [9, 10] for the analysis. The number of contending stations is supposed to be fixed as $n$. Let $b(t)$ be the stochastic process representing the back-off window size for a given station at slot time $t$. Note the slot time is referred to as the constant value $\sigma$ and the variable time interval between two consecutive backoff time counter decrements. As in [9], the key assumption in this model is that the probability $p$ that a transmitted packet collides is independent of the state $s(t)$ of the station. Thus, the bi-dimensional process $\{s(t), b(t)\}$ of our proposed scheme is a discrete-time Markov chain, which is shown in Fig.1.

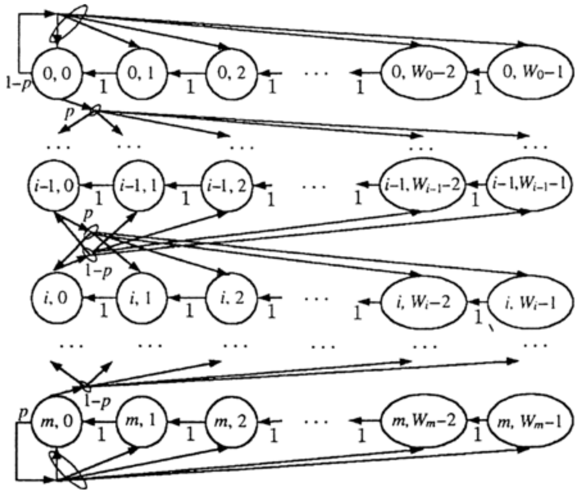

Fig.1. Markov chain model of the new back-off window scheme.

This paper uses all the parameters assigned for the Direct Sequence Spread Spectrum (DSSS) PHY in 802.11; for other PHY layers, the analysis process is similar. In DSSS, $CW_{\min}$ and $CW_{\max}$ are equal to 31 and 1,023 separately. Therefore, we have

$$\begin{cases} W_i = 2^i W, & i \leqslant m' \\ W_i = 2^{m'} W, & i > m' \end{cases} \tag{1}$$

where $W = (CW_{\min} + 1)$ and $2^{m'}W = (CW_{\max} + 1)$, so for DSSS, we have $m' = 5$.

Here we use $m$ to represent *maximum backoff stage*. As specified in 802.11[1] this value could be larger than $m'$, while CW will be held unchanged after that, which is shown in (1). In fact, here $m$ also means the maximum retransmission count, which is different for data frame and RTS frame, i.e., 5 and 7 separately. In this paper, the backoff scheme to reset CW is different from that in 802.11 DCF, so the Markov chain in this paper and that in [10] are different.

In this Markov chain, the only non-null one-step transition probabilities are ①

$$\begin{cases} P\{i,k|i,k+1\} = 1, k \in [0, W_i - 2], \ i \in [0, m] \\ P\{i-1,k|i,0\} = (1-p)/W_0, \\ \qquad\qquad k \in [0, W_{i-1} - 1], \ i \in [1, m] \\ P\{i,k|i-1,0\} = p/W_i, \\ \qquad\qquad k \in [0, W_i - 1], \ i \in [1, m] \\ P\{m,k|m,0\} = p/W_m, \qquad k \in [0, W_m - 1] \\ P\{0,k|0,0\} = (1-p)/W_0, \qquad k \in [0, W_0 - 1] \end{cases} \tag{2}$$

These transition probabilities account, respectively, for: 1) the decrements of the backoff timer; 2) that after a successful transmission at backoff stage $i$, the backoff timer of the new packet starts with a backoff stage $(i-1)$; 3) that an unsuccessful transmission makes the backoff stages increase; 4) that at the maximum backoff stage, CW will keep the same value if the transmission is unsuccessful; 5) that at backoff stage 0, it will stay on the same stage if the transmission is successful.

Let $b_{i,k}$ be the stationary distribution of the Markov chain. First note that

$$pb_{i-1,0} = (1-p)b_{i,0}, \quad 0 < i \leqslant m \tag{3}$$

and we have

$$b_{i,0} = x^i b_{0,0}, \quad 0 \leqslant i \leqslant m \tag{4}$$

where

$$x = p/(1-p) \tag{5}$$

①We adopt the same short notation used in [11]: $P\{i_1, k_1|i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1|s(t) = i_0, b(t) = k_0\}$.

Since the chain is regular, so for each $k \in (0, W_i - 1)$, we have

$$b_{i,k} = \frac{W_i - k}{W_i} \begin{cases} (1-p)(b_{1,0} + b_{0,0}), & i = 0 \\ pb_{i-1,0} + (1-p)b_{i+1,0}, & 0 < i < m \\ p(b_{m,0} + b_{m-1,0}), & i = m \end{cases} \tag{6}$$

With (4), (5) and transitions in the chain, (6) can be simplified to

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0}, \quad 0 \leqslant i \leqslant m \tag{7}$$

Therefore, by using the normalization condition for stationary distribution, we have

$$\begin{aligned} 1 &= \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} \\ &= \sum_{i=0}^{m} b_{i,0} \frac{W_i + 1}{2} \end{aligned} \tag{8}$$

Using (1), (4), (5), (8), we have

$$b_{0,0} = \begin{cases} [2(1-2x)(1-x)] \cdot \left[W(1-(2x)^{m-1})(1-x) \right. \\ \quad \left. +(1-2x)(1-x^{m+1})\right]^{-1}, \quad m \leqslant m' \\ [2(1-2x)(1-x)] \cdot \left[W(1-(2x)^{m'+1})(1-x) \right. \\ \quad +(1-2x)(1-x^{m+1}) + W2^{m'}x^{m'+1} \\ \quad \left. \cdot(1-2x)(1-x^{m-m'})\right]^{-1}, \quad m > m' \end{cases} \tag{9}$$

Now the probability $\tau$ that a station transmits in a randomly chosen slot time can be expressed,

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1 - x^{m+1}}{1 - x} b_{0,0} \tag{10}$$

where $b_{0,0}$ can be obtained from (9) and $x$ from (5).

In the stationary state, a station transmits a packet with probability $\tau$, so we have

$$p = 1 - (1-\tau)^{n-1} \tag{11}$$

Therefore, (5), (9), (10) and (11) represent a nonlinear system with two unknowns $\tau$ and $p$, which can be solved by numerical approach. Note that we must have $p \in (0,1)$ and $\tau \in (0,1)$.

Since the Markov chain transitions in Fig.1 are different from those in [10], the results obtained for $b_{0,0}$ are different from those in [10], the same for $\tau$ and $p$. In fact, under the same parameters, the values of $\tau$ and $p$ are smaller than those in [10] because of the new backoff scheme.

### 3.3 Throughput Analysis

Let $P_{tr}$ be the probability that there is at least one transmission in the considered slot time. And let $P_s$ be the probability that a transmission is successful with the given probability $P_{tr}$. So we have

$$P_{tr} = 1 - (1-\tau)^n \tag{12}$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{13}$$

Now we are able to express the normalized system throughput $S$ as the ratio,

$$\begin{aligned} S &= \frac{E[\text{Payload information in a slot time}]}{E[\text{Length of a slot time}]} \\ &= \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_s P_{tr} T_s + (1-P_s) P_{tr} T_c} \end{aligned} \tag{14}$$

where we use the same symbols as those in [10]. Here, $T_s$ and $T_c$ are the average times the channel is sensed busy because of a successful transmission or a collision, respectively. The $E[P]$ is the average packet length and $\sigma$ is the duration of an empty slot time.

Let packet header be $H = \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}}$ and let propagation be $\delta$. Then we must have the following expression.

$$\begin{cases} T_s^{\text{bas}} = H + E[P] + \text{SIFS} + \delta + \text{ACK} \\ \qquad +\text{DIFS} + \delta \\ T_c^{\text{bas}} = H + E[P^*] + \text{SIFS} + \delta + \text{ACK} \\ \qquad +\text{DIFS} + \delta \end{cases} \tag{15}$$

where *bas* means basic access method and $E[P^*]$ is the average length of the longest packet payload involved in a collision. In our cases, all the packets have the same fixed size, i.e., $E[P] = E[P^*] = P$.

For the RTS/CTS access method, assume that all the stations use RTS/CTS for the data frame for simplicity, then we have

$$\begin{cases} T_s^{\text{rts}} = \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + H \\ \qquad +E[P] + \text{SIFS} + \delta + \text{ACK} + \text{DIFS} + \delta \\ T_c^{\text{rts}} = \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{DIFS} + \delta \end{cases} \tag{16}$$

where *rts* means RTS/CTS access method. Note that here we suppose collision only occurs between RTS frames.

## 4 Model Validation

This paper uses the well-known simulation tool NS2[12] from Lawrence Berkeley National Laboratory. To validate our model, we also compare the results with those obtained in [10].

All the simulation assumptions are kept the same as those in [10] to facilitate the results comparison. Each wireless station is supposed to have enough data packets to transmit to satisfy the environment for *saturated* throughput, which is used in [10] for performance evaluation. Note that in DSSS, $CW_{\min}$ and $CW_{\max}$ are equal to 31 and 1,023 separately, and $m' = 5$. In this section, $m$, the maximum retransmission count, is 5 and 7 for data frame and RTS frame separately[2]. We will vary the value of $m$ to see its effect on throughput performance in the next section.

All the other parameters used in analytical model and our simulations follow the specifications in the standard[1] for DSSS, and are summarized in the following table.

| | |
|---|---|
| Packet payload | 8,224bits |
| MAC header | 224bits |
| PHY header | 192bits |
| ACK | 112bits+PHY header |
| RTS | 160bits+PHY header |
| CTS | 112bits+PHY header |
| Channel bit rate | 1Mbps |
| Propagation delay | 1$\mu$s |
| Slot time | 20$\mu$s |
| SIFS | 10$\mu$s |
| DIFS | 50$\mu$s |

Note that the MAC model equations are independent of the parameters. Therefore, it does not matter when choosing parameters for different PHY layers.

### 4.1 Simulation Results for Basic Access Method

First we see the results of basic access method, which are shown in Fig.2. Here we use 802.11 to represent the model in [10] for 802.11 standards and *New backoff* to represent the model in this paper for new CW setting scheme. For a fixed number of stations, we run 10 simulations with different random seeds separately. Each symbol "+" or "×" represents a simulation result, for 802.11 or new CW setting scheme. Note for some simulation series, some symbols are superposed because those results are identical or very close to each other.

From the figure we are able to see that the analytical model of this paper is accurate and captures the trend exactly. The model in [10] also is accurate to trace the results of 802.11 because it follows the standards closely both in the Markov chain transitions and in the throughput analysis. Our analysis closely models 802.11 and new backoff scheme especially when the number of stations is over dozens, which shows our assumption when the Markov chain is formed, i.e., that the probability $p$ that a transmitted packet collides is independent of the state $s(t)$ of the station is accurate when the number of stations is large. We also see that the analysis for the new CW setting a little bit overestimates the simulation results. This is because in simulation, the false transmission will trigger the transmission of routing packets, which are sent by broadcast and CW will be reset at the same time, therefore, it will break the CW resetting scheme proposed in this paper when the number of stations is very large.

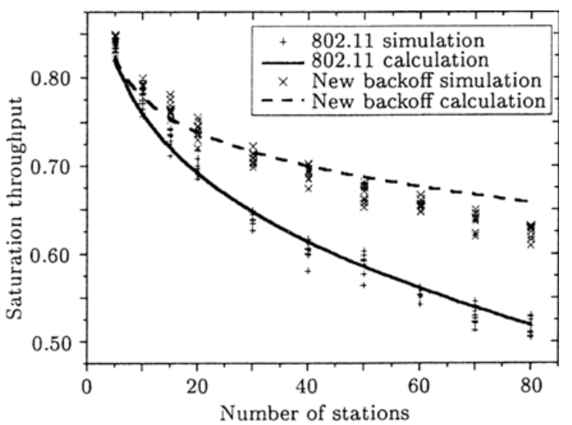


Fig.2. Basic access method.

Also we can see that the CW resetting scheme in this paper could enhance the performance of 802.11 DCF significantly, which is proved by both analysis and simulation results. Since the scheme is rather simple and effective, and can be regarded as an option for 802.11, it can improve the stability of the system especially when the number of stations is large.

### 4.2 Simulation Results for RTS/CTS Access Method

The result comparison for RTS/CTS access method is similar to that of basic access method. Note that in Fig.3, the vertical axis scale is different from that in Fig.2, so readers may feel that it is much higher than simulation results. Another reason for the analysis to overestimate the simulation results is that in our simulations, the routing packets in broadcast may cause collision with other routing packets or RTS frame, therefore, the simulation performance is a little bit degraded.

From Fig.3, we are able to conclude that RTS/CTS access method is useful to compensate the performance degradation due to collision, whose probability increases with the number of stations. Note that we can get these results because in this paper the packet payload length, 1,028 bytes, is large enough to compensate the overheads introduced by RTS/CTS.

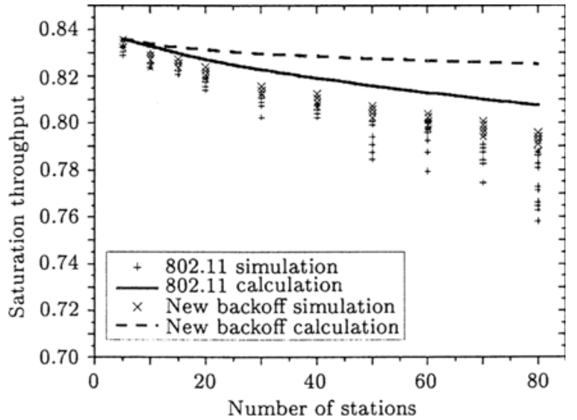


Fig.3. RTS/CTS access method.

## 5 Performance Analysis

Since the accuracy of our model has been validated by simulations, this paper uses the model to analyze the throughput performance with different parameters. As we know from (9), the values of $m$, $m'$ and $W$ will affect the results we achieve. Since $m'$ and $W$ have been assigned values related to PHY in the standards, we will examine the effect of $m$ in this paper.

The effect of $m$ is shown in Fig.4 and Fig.5, for basic and RTS/CTS access methods separately, which is obtained from our analysis model in Section 3. From these figures, we could see the effectiveness of our new backoff scheme. Note that the analysis with $m$ values of 5 and 7 for basic and RTS access methods has been verified by simulations in Section 4. Also, we find that $m$ can affect the performance greatly. Note in the standard, there is $m' = 5$ for DSSS PHY. We find that the $m$ values of 5 and 7 for basic and RTS/CTS access method is a good tradeoff.

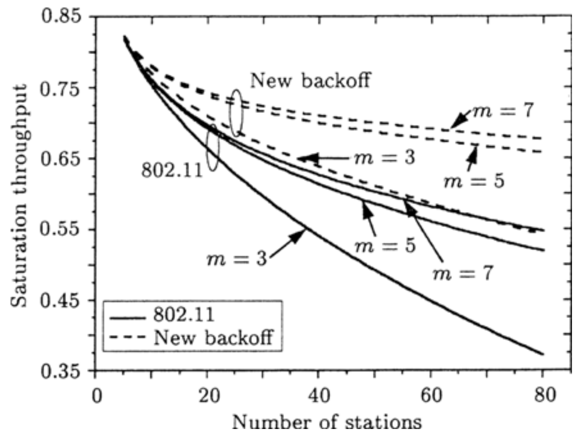


Fig.4. Effect of $m$: basic access method.

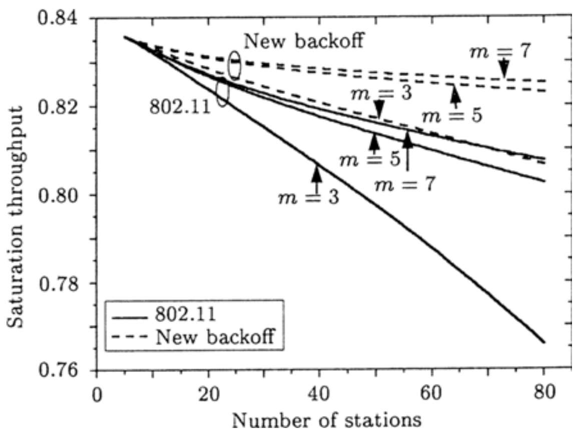


Fig.5. Effect of $m$: RTS/CTS access method.

## 6 Conclusions

This paper proposes a simple and effective Contention Window (CW) setting scheme to enhance the performance of IEEE 802.11 DCF. This paper also proposes a new and simple analytical model based on Markov chain to compute the throughput performance of the new proposed scheme in this paper. This model can be used for computation both for the basic access method and the RTS/CTS access method. Comparisons with simulations as well as the model presented in [10] show that this model is accurate in predicting the performance of new backoff scheme and the effectiveness of the new scheme is verified by both modeling and simulations.

## References

[1] IEEE standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. ISO/IEC 8802-11:1999 (E), Aug. 1999.

[2] Crow B P, Kim J G. IEEE 802.11 wireless local area networks. *IEEE Comm. Magazine*, Sept. 1997, 35(9): 116–126.
[3] Nee R, Awater G. New high-rate wireless LAN standards. *IEEE Comm. Magazine*, Dec. 1999, 37(12): 82–88.
[4] Anastasi G, Lenzini L. QoS provided by IEEE 802.11 wireless LAN to advanced data applications: A simulation analysis. *Wireless Networks*, 2000, 6(2): 99–108.
[5] Ho T, Chen K. Performance analysis of IEEE 802.11 CSMA/CA medium access control protocol. In *Proc. PIMRC*, Taipei, Oct. 1996, pp.407–411.
[6] Bianchi G. Fratta L, Oliveri M. Performance evaluation and enhancement of the CSMA/CA MAC protocol for 802.11 wireless LANs. In *Proc. PIMRC*, Taipei, Oct. 1996, pp.392–396.
[7] Chhaya H S, Gupta S. Performance modeling of asynchronous data transfer methods of IEEE 802.11 MAC protocol. *Wireless Networks*, 1997, 3: 217–234.
[8] Cali F, Conti M, Gregori E. Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit. *IEEE/ACM Trans. Networking*, Dec. 2000, 8(6): 785–799.
[9] Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE Journal on Selected Area in Comm.*, March 2000, 18(3): 535–547.
[10] Wu Haitao, Peng Yong, Long Keping *et al.* A simple model of IEEE 802.11 Wireless LAN. In *Proc. IEEE ICII'2001*, Oct. 2001, pp.514–519.
[11] Computer Networks (3rd Edition). Andrews Tanenbaum (eds.), Tsinghua University Publishing House, pp.282–283.
[12] NS2. http://www-mash.cs.berkeley.edu/ns/

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