

IEEE 802.11 Distributed Coordination Function(DCF): Analysis and Enhancement *

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Abstract- Being a part of IEEE project 802, the 802.11 Medium Access Control(MAC) is used to support asynchronous and time bounded delivery of radio data packets. It is proposed that a Distributed Coordination Function(DCF), which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and binary slotted exponential backoff, be the basis of the IEEE 802.11 WLAN MAC protocols. This paper proposes a throughput enhancement mechanism for DCF by adjusting the Contention Window(CW) resetting scheme. Moreover, an analytical model based on Markov chain is introduced to compute the enhanced throughput of 802.11 DCF. The accuracy of the model and the enhancement of the proposed scheme are verified by elaborate simulations.

Key Words: IEEE 802.11, CSMA/CA, DCF, analysis

I. INTRODUCTION

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

Wireless Local Area Networks(WLANs)[1-4], which provides higher flexibility and convenience than their wired counter part, are being developed to provide high bandwidth access for users in a limited geographical area. IEEE Project 802 recommends an international standard 802.11[1-2] for WLANs. The standards includes detailed specifications both for Medium Access Control(MAC) and Physical Layer(PHY). In WLANs, the physical media, which is shared by all stations and has limited connection range, has significant differences when compared to wired media. The IEEE 802.11 standards include Distributed Coordination Function(DCF) and 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 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.

There are two techniques used for packet transmitting in DCF. The default one is a two-way handshaking mechanism, also known as basic access method. A positive MAC 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 terminal. However, the drawback of RTS/CTS mechanism is increased overhead for short data frames.

In DCF, a binary slotted exponential backoff is used with CSMA/CA. Whenever a backoff occurs, the backoff time is set from a uniform distribution over the interval $[0, CW]$, while the Contention Window(CW) will be doubled for a retry and reset for a new packet. This paper proposes a little bit conservative way by resetting the CW to improve the throughput performance of DCF.

To analyze resetting CW, the modeling of 802.11 has been examined. Paper [5] gives the theoretical throughput limit of 802.11 based on a p -persistent variant. However, it doesn't take the effect of the Contention Window(CW) and binary slotted exponential back-off procedure used by DCF into consideration. Unlike those ones, Paper [6,7] use Markov process to analyze the saturated throughput of 802.11. The Markov model in paper[7] can be regarded as an extension of the model in paper[6] and it takes the retransmission limit of MAC frames into account. This paper analyzes the effect of proposed CW resetting scheme by a new Markov chain model, which is validated by elaborate simulations.

The paper is organized as following. Section II briefly describes the DCF of IEEE 802.11 MAC protocols. In section III, the new CW resetting scheme is introduced and an analytical model is proposed. Section IV validates the accuracy of this model by simulations, and the model is used for throughput performance analysis. Finally, section V concludes the paper.

II. DISTRIBUTED COORDINATION FUNCTION IN 802.11

The basic service set(BSS) is the fundamental building block of IEEE 802.11 architecture. The geographical area covered by the BSS is known as the basic service area(BSA), which is similar to a cell in a cellular network. 802.11

*This work is supported by Nokia-BUPT project

supports both the ad hoc network and infrastructure network architecture. This paper only gives a brief introduction of 802.11 DCF, the readers are referred to [1,2] for detailed information about 802.11. It consists of both a basic access method and an optional RTS/CTS access method.

A. The 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 transmission 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 until after a DIFS is detected and then generate a random back-off period 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 value $2^m W$, where W equals to $(CW_{min}+1)$ and $2^m W$ equals to $(CW_{max}+1)$.

Upon received a packet correctly, the destination station waits for a SIFS interval immediately following the reception of the data frame and transmits a MAC ACK back to the source station, indicating that the data frame 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 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.

B. The RTS/CTS access method

In 802.11[1], DCF also provides an optional way of transmitting data frames that involve transmission of special short RTS and CTS frames prior to the transmission of actual data frame. When the destination receives the RTS frame, it will transmit a CTS frame after SIFS interval immediately following the reception of the RTS frame. The source station is allowed to transmit its packet only if it receives the CTS correctly. If a collision occurs with RTS frames, less bandwidth is wasted when compared with the situation where larger data frames are in collision.

III. DCF PERFORMANCE ENHANCEMENT AND ANALYSIS

In this paper, we focus on the *saturated throughput*, which is also examined in paper [6,7]. It is a fundamental

performance figure defined as the throughput limit reached by the system as the offered load increases, and it represents the load that the system can carry in stable conditions.

A. New backoff scheme to reset the CW

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

Since a station use 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 802.11 breaks this progress, which will degrades the performance of DCF. Then the question is how to control the backoff counter, or CW optimally or near optimally.

This paper proposes a simple change for 802.11 in order to make the backoff counter oscillate around the optimal value without complex calculation and run-time estimation as in paper [5]. The way is conservative than that used in 802.11. It can be described as following:

1)Whenever the retry counter reaches the limit, the CW is kept and not reset; 2)After a successful transmission, w is set to the value $\max[w/2, CW_{min}+1]$; 3)Whenever a transmission for fails, w is set to the value $\min[2w, CW_{max}+1]$. It will be referred as new backoff scheme through out this paper.

Another contribution of this paper is the analytical evaluation of the saturated throughput of the new backoff scheme, in the assumption of ideal channel conditions. This paper does not choose the way in paper [5], 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 τ that the station transmit a packet; 2)The throughput of both basic and RTS/CTS access methods is examined.

B. Markov Chain Model

We use the same assumption in paper [6,7] for the analysis. The contending stations is supposed to a fixed number, 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 σ and the variable time interval between two consecutive backoff time counter decrements[6]. As in paper [6,7], the key approximation in

$$b_{0,0} = \begin{cases} \frac{2(1-2x)(1-x)}{W(1-(2x)^{m+1})(1-x) + (1-2x)(1-x^{m+1})} & m \leq m' \\ \frac{2(1-2x)(1-x)}{W(1-(2x)^{m+1})(1-x) + (1-2x)(1-x^{m+1}) + W2^m x^{m+1}(1-2x)(1-x^{m-m'})} & m > m' \end{cases} \quad (9)$$

this model is that the probability p that a transmitted packet collides is independent on 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.

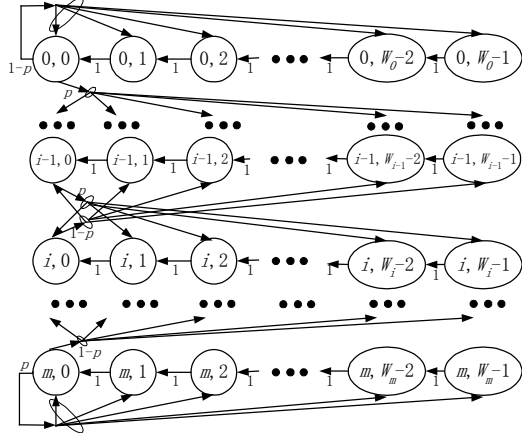


Fig.1 Markov chain model of new back-off window scheme

This paper use all the parameters assigned for 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} equal to 31 and 1023. Therefore, we have

$$\begin{cases} W_i = 2^i W & i \leq m' \\ W_i = 2^{m'} W & i > m' \end{cases} \quad (1)$$

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 the CW will be hold after that, which is shown in equation (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. In this paper, the backoff scheme to reset the CW is different from that in 802.11 DCF, so the Markov chain in this paper and that in paper [7] are different.

In this Markov chain, the only non-null one-step transition probabilities are¹

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

These transition probabilities account, respectively, for: 1)the decrements of the backoff timer; 2)after a successful

transmission at backoff stage i , the backoff timer of the new packet starts with a backoff stage $(i-1)$; 3)an unsuccessful transmission makes the backoff stages increase; 4)at the the maximum backoff stage, the CW will keep the same value if transmission is unsuccessful; 5)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

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

$$\text{we have } b_{i,0} = x^i b_{0,0} \quad 0 \leq i \leq m \quad (4)$$

$$\text{where } x = p/(1-p) \quad (5)$$

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

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

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

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad 0 \leq i \leq m \quad (7)$$

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

$$1 = \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^m b_{i,0} \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} = \sum_{i=0}^m b_{i,0} \frac{W_i + 1}{2} \quad (8)$$

Using equation (1)(4)(5)(8), we have equation (9), which is shown at the top of this page.

Now the probability τ that a station transmits in a randomly chosen slot time can be expressed as,

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

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

In the stationary state, a station transmits a packet with probability τ , so we have

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

Therefore, equations (5)(9)(10) and (11) represent a nonlinear system in the two unknowns τ and p , which can be solved by numerical results. 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 paper [7], the results obtained for $b_{0,0}$ is different from that in paper [7], so do τ and p . In fact, for the same other parameters, the value of τ and p are smaller than those in paper [7] because of the new backoff scheme used.

C. 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

¹ We adopt the same short notation used in paper [10]: $P\{i_1, k_1 | i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1 | s(t) = i_0, b(t) = k_0\}$

probability that a transmission is successful, given the probability P_{tr} . So we have

$$P_r = 1 - (1 - \tau)^n \quad (12)$$

$$P_s = \frac{n\tau(1 - \tau)^{n-1}}{P_r} = \frac{n\tau(1 - \tau)^{n-1}}{1 - (1 - \tau)^n} \quad (13)$$

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

$$S = \frac{E[\text{Payload Information in a slot time}]}{E[\text{Length of a slot time}]} \quad (14)$$

$$= \frac{P_s P_r E[P]}{(1 - P_r)\sigma + P_s P_r T_s + (1 - P_s)P_r T_c}$$

where we use the same symbols as those in paper [6]. Here, T_s and T_c are the average time the channel is sensed busy because of a successful transmission or a collision. The $E[P]$ is the average packet length and σ 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 δ . Then we must have the following expression.

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

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

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

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

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

IV. MODEL VALIDATION

This paper uses the well-known simulation tool *NS-2*^[8] from Lawrence Berkeley National Laboratory. To validate our model, we also compare the results of the new backoff scheme with those of 802.11 in paper [7].

Also, this paper assumes each station has enough data to send to obtain the saturated throughput performance of the new backoff scheme. All the parameters used in analytical model and our simulations follow the specifications in standard[1] for DSSS, and are the same as those in [7]. Note that we assume the application data payload is 1000bytes and IP header and UDP header are 20 and 8 bytes, so packet payload at MAC layer is 1028bytes.

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

A. Simulation results for basic access method

First we see the results of basic access method, which is shown in Fig.2. Here we use *802.11* to represent the model in paper [7] 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 seed. Each symbol “+” or “×” represents a simulation result, for 802.11 and new CW setting scheme respectively. 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 paper [7] also 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 follows our assumption that 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 simulations, there exists the transmission of routing packets, which are send 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 high.

Also we can see that the CW resetting scheme in this paper could enhance the performance of 802.11 DCF significant, 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 system especially when the number of stations is high.

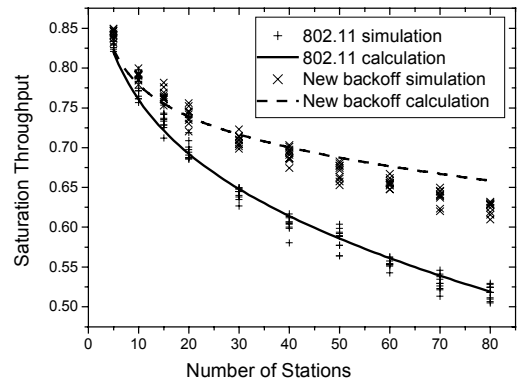


Fig.2 Analysis versus simulations: basic access method

B. Simulation results for RTS/CTS access method

The results comparison of RTS/CTS access method is similar to that of basic method. Note that in Fig.3, the vertical axis scale is different to that in Fig.2, so the reader may feel

that the analysis is much higher than simulations results. Another reason for the analysis overestimates 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 degraded.

From this figure, 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, 1028bytes, is large enough to compensate the overheads of RTS/CTS.

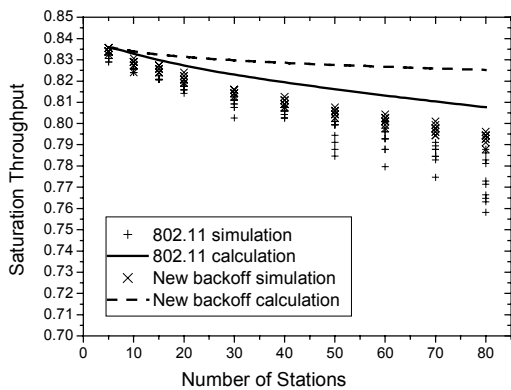


Fig.3 Analysis versus simulations: RTS/CTS access method

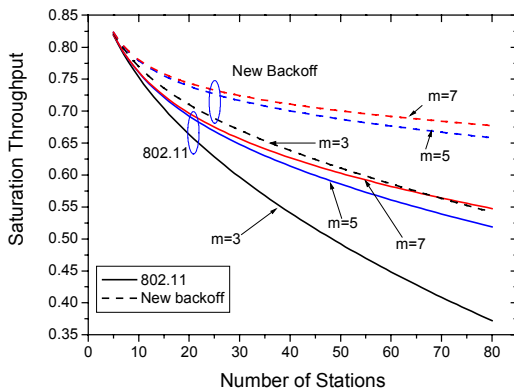


Fig.4 Effect of m for basic access method

C. Performance Analysis

This paper uses the proposed Markov model to analyze the throughput performance with different parameters. As we know from equation (9), the value of m , m' and W will affect the results we achieve. Since the value of m' and W has been assigned value 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 method respectively. From these figures, we can see the effectiveness of our new backoff scheme. Also,

we find that m can affect the performance greatly. Note in the paper [2], there is $m'=5$, which is for DSSS PHY. From the analysis we know that higher m brings higher stability and increased delay for retransmissions. From Fig.4 and Fig.5 we conclude that the m value of 5 and 7 for basic and RTS/CTS access method is a good tradeoff.

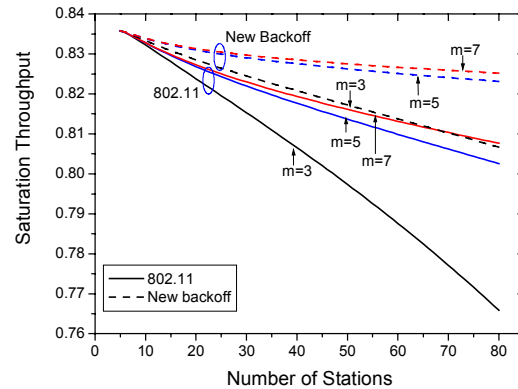


Fig.5 Effect of m for RTS/CTS access method

V. CONCLUSIONS

This paper proposes a simple and effective Contention Window(CW) resetting scheme to enhance the performance of IEEE 802.11 DCF. A new and simple analytical model based on Markov chain is introduced to compute the throughput of the proposed scheme. This model can be used in computation both for the basic access method and the RTS/CTS access method. Comparisons with simulation results as well as the model presented in paper [7] show that this model is accurate in predicting the performance and prove the effectiveness of the new backoff scheme.

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