Analysis of New Distributed Media Access Control Protocols Proposed for IEEE 802.11 Wireless Local Area Networks

Meerja Khalim Amjad, *Student Member, IEEE,* and Abdallah Shami, *Member, IEEE*
Department of Electrical and Computer Engineering
University of Western Ontario
London, Ontario, N6A 5B9, Canada.
Email: kmeerja2@uwo.ca, ashami@eng.uwo.ca

***Abstract*— Since distributed coordination function (DCF) is the basis protocol for IEEE 802.11 standard wireless local area networks, many modifications have been proposed in the literature to improve its throughput performance particularly under congested environments. These improvements are achieved by modifying the contention window reset mechanism in which a DCF station immediately reduces the window size to the minimum value (ω_0) after a successful transmission, irrespective of the congestion level observed on the channel. Recently, we have proposed a new media access control protocol N-DCF to improve the throughput performance of DCF by reducing the average backoff overhead that is required for the packet transmission. In this paper we present the analysis of N-DCF protocol by proposing a throughput model applicable for any arbitrary load conditions. The throughput model is verified by simulating N-DCF using NS-2 network simulator. We then compare the performance of N-DCF with the other recently proposed DCF enhancements in the literature. Comparisons have revealed that only N-DCF provides improvement in throughput performance under RTS/CTS access mechanism. Based on the reasoning, we propose two more media access control schemes to further improve the performance of DCF protocol in both basic and RTS/CTS access mechanisms. Finally, we analyze the performance of the proposed modifications to N-DCF protocol.**

***Index Terms*— Wireless local area networks (WLAN), Adhoc networks, IEEE 802.11, DCF, CSMA/CA.**

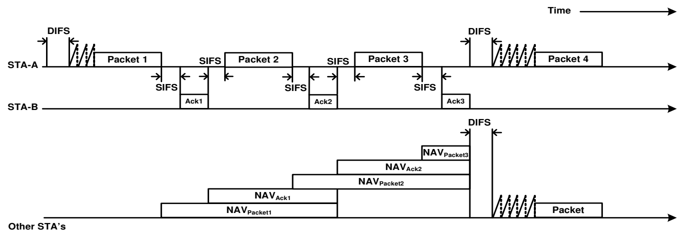
I. Introduction

Wireless local area networks (WLANs) are known since 1970 when IBM first published its results on an indoor WLAN experiment [2]. However, it was only during the late 80's that this WLAN technology started gaining popularity. With the increase in the demand for ubiquitous computing, IEEE 802.11 committee was formed in 1990 to provide inter-operability between the wireless devices made by different manufacturers. The IEEE 802.11 working group announced its first standard in 1997 that was able to provide upto 2 Mbps data rate which is now known as the legacy standard [1]. Since then IEEE 802.11 has announced many new standards capable of providing higher bandwidth [3] and quality of service features [4].

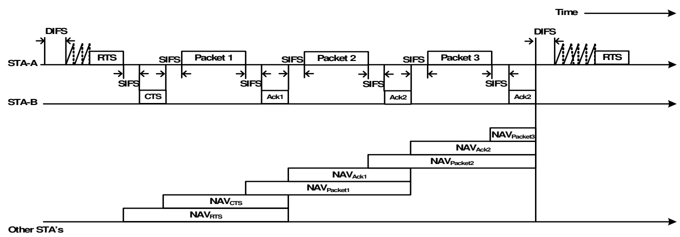
Distributed coordination function (DCF) is the basis protocol in all the IEEE 802.11 WLAN standards and is based on CSMA/CA protocol. DCF has two access mechanisms namely basic and request-to-send/clear-to-send (RTS/CTS) access mechanisms. A DCF station sends packets to destination through backoff process. If a collision occurs, the station increases the contention window (CW) size to retransmit the packet. However, once the data packet is transmitted successfully or discarded after reaching maximum retry attempts, the size of the CW is reset to the minimum value (ω_0) for the next packet transmission. For complete description of backoff process we refer readers to [3]. One of the drawbacks in DCF protocol is the CW reset mechanism used for the backoff process. DCF increases its CW size to adapt to the congestion level on the channel when it loses packet due to collision. However the CW reset mechanism completely ignores the channel conditions and reduces the CW value to ω_0 immediately after a packet is either successfully transmitted or dropped (after reaching maximum retransmission attempts). To minimize the probability of collision, the size of the CW must be adjusted according to the congestion level on the channel.

Many proposals are made in the literature to improve the throughput performance of DCF protocol particularly for the congested environments. A dynamic tuning mechanism for DCF protocol is introduced in [5] where each station estimates the number of competing stations on the channel to adjust its CW size. In another proposal [6], a fast collision resolution (FCR) algorithm is introduced to improve the throughput performance of DCF protocol. In FCR, a station increases its CW size whenever it finds the channel busy due to transmission(s). In addition, the station also increases its CW size when it makes a retransmission attempt. The station backs off exponentially if successive idle slots are observed on the channel. After transmitting few packets, FCR station sets it CW size to a maximum value (ω_{max}) to allow other stations to transmit on the channel.

Two other recent DCF enhancements proposed in [7] and [8] suggest a gentle/slow decrease in the CW size to take channel congestion into account. In [9], before every backoff process the size of the CW is calculated as a function of previous window size and estimated optimal window size. All these protocols are designed for congested environments where the size of the CW is decreased slowly compared to the DCF's CW reset mechanism. However their main drawback is that they have very high backoff time as an overhead. This overhead is supplemented by reducing the probability of collision during packet transmission. As will be shown later, these protocols are very effective in improving the throughput in basic access mechanism because the time spent by the data packets in collision is very significant. However in RTS/CTS access mechanism, they fail to improve throughput as backoff overhead overweighs the time spent by RTS packets in collisions. In [10], we have proposed a new distributed coordination function for 802.11 WLANs that reduces the average backoff overhead for the transmitted packets. This proposed protocol will be referred as N-DCF throughout this paper. It will be shown later that N-DCF is very effective in improving the



(a) Basic access.



(b) RTS/CTS access.

Fig. 1. Timing diagram for N-DCF protocol (N=3).

throughput performance not only in basic access mechanism but also in RTS/CTS access mechanism.

The rest of this paper is organized follows. First we present the details of N-DCF protocol in Section II. Then in Section III, we present our analytical model based on markov chains applicable to arbitrary load conditions. This is based on the model proposed in [11] for saturated conditions where each station always has packets to send and the unsaturated markov model proposed in [12]. We have observed that the model in [12] does not consider increasing the CW size when a collision occurs after the post-backoff process as in DCF. Further, it did not consider the transition probability, the probability of returning to the state *notx* from *notx* (refer to Figure 2 in [12]). We take these points into account in our proposed model. We validate our analytical model by implementing N-DCF protocol in NS-2 network simulator [13]. Then in Section IV we compare N-DCF protocol with other recently proposed DCF enhancements. Modifications to N-DCF are proposed in Section V. Finally, Section VI concludes the paper.

II. New Distributed Media Access Control Protocol

In this section, we briefly describe our proposed protocol, "a new distributed media access protocol (N-DCF) for 802.11 WLANs", to improve the throughput performance of DCF. Detailed description of this protocol is given in [10]. The following subsections provide the functionality of N-DCF protocol under basic access and RTS/CTS access mechanisms.

A. N-DCF: Basic Access Mechanism

In this access mechanism, a station in order to send a data packet contends for channel access through backoff process. If it could successfully send a packet in its first attempt, it assumes that the channel is lightly loaded and sends another packet to the destination after SIFS time following the reception of the acknowledgement of the previous packet. This process is repeated until a maximum of N packets present in the MAC buffer are sent. After sending N^{th} packet, it resumes the normal contention process through entering backoff. The timing diagram drawn for N-DCF protocol under basic access mechanism is given in Figure 1(a). If a packet was not delivered in the first attempt, it assumes that the channel is congested and the station starts successive retransmission attempts exactly as original DCF protocol would do.

B. N-DCF: RTS/CTS Access Mechanism

In RTS/CTS access mechanism, instead of sending a data packet, a corresponding RTS packet is sent to the destination. If the transmitting station received CTS response from the receiver in its first transmission attempt, it sends upto N data packets to the receiver, each packet sent waiting SIFS time after it receives a positive ACK from the receiver. If the queue does not contain N packets, a normal backoff process is initiated. The timing diagram for the N-DCF protocol under RTS/CTS access mechanism is shown in Figure 1(b).

III. Markov Chain Model for DCF and N-DCF for Arbitrary Load Conditions

In this section we present the details of our proposed throughput model for DCF and N-DCF protocols, which applicable for any arbitrary load conditions. We have used the same assumptions made in [11], [12] in our model. We assume that we have κ identical stations that transmit at the same rate. Packets arrive at the MAC buffer (i.e. queue) according to poisson distribution at a rate of λ packets/sec. Mobility is not considered and each station is in the transmission range of the other $(\kappa - 1)$ neighboring stations. Both packet collision probability (ξ) and the probability of finding an empty queue (ρ) for a station are considered bernoulli processes. A maximum of m retransmission attempts are made by the station to successfully deliver a packet and dropped subsequently. At any instant of time, variable r indicates the retransmission number and β represents the value of backoff timer.The range for these variables are given by the following expressions.

$$r \in [0', 0, 1, 2, 3, ..., m', m'+1, ..., m] \tag{1}$$

$$\beta \in [0, \omega_r - 1] \tag{2}$$

where $0'$ represents the post-backoff process when the queue is empty and ω_r is the size of the CW at any backoff stage. The expression for ω_r is given by the following equation.

$$\omega_r = \begin{cases} \min(2^r \omega_0, \omega_{max}) & r < m' \\ \min(2^{m'} \omega_0, \omega_{max}) & r \in [m', m] \end{cases} \tag{3}$$

The entire time frame can be divided into a sequence of time slots representing the activity on the channel. The channel can be idle, transmitting upto N data packets, or experiencing a collision due to simultaneous transmissions from more than one station. A random process is defined as a tuple (r, β) to represent the state of a station at any given slot time. It can be observed that the tuple (r, β) exhibits markov property and forms a markov chain as shown in Figure 2. The figure provides a schematic diagram for both N-DCF $(N = 2)$ and DCF protocols for throughput analysis.

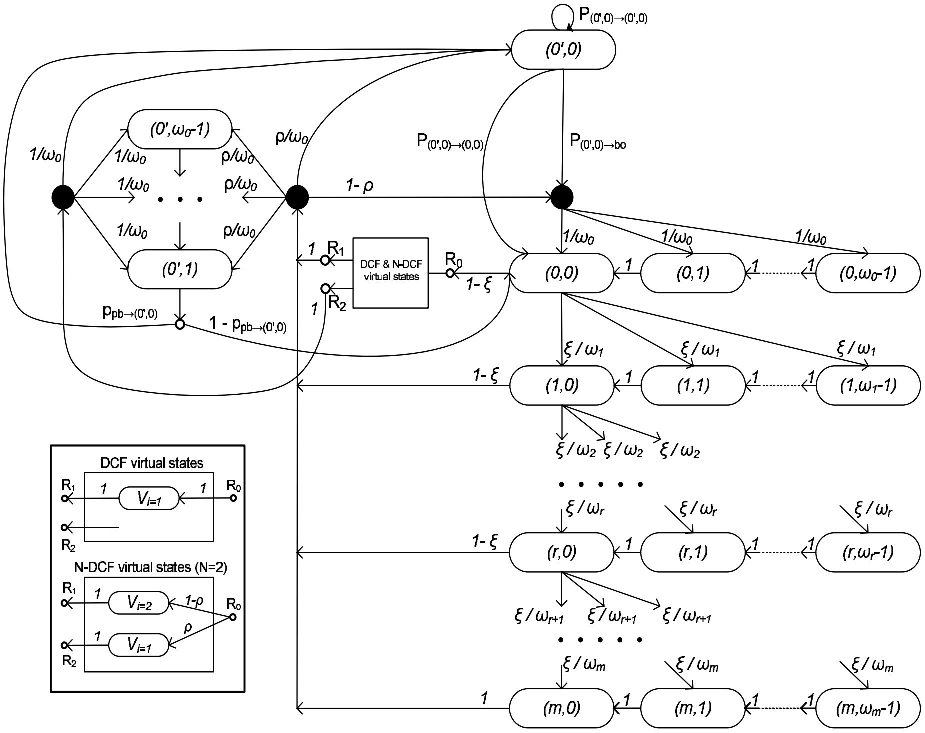


Fig. 2. Markov chain model for DCF and N-DCF protocols.

In Figure 2 a block "*DCF and N-DCF virtual states*" is introduced to consolidate both DCF and N-DCF protocols into one diagram. The virtual states (V_i) shown in the figure are not physical states. They are shown only to convey the number of packets sent from the state $(0, 0)$, as upto N packets can be sent in N-DCF. The connectors $(R_0,\ R_1$ and $R_2)$ shown in Figure 2 are reference points to insert appropriate block from the box into the markov chain to complete the model for a particular protocol. Finally, the probability of being in any state (r, β) is represented by $\upsilon_{(r,\beta)}$.

A. DCF Protocol

In this subsection we present the analysis of DCF protocol. At any instance of time, a station will be found in one of the states (r, β) as shown in Figure 2. The probability of being in any state (r, β) can be expressed in terms of the probability of being in state $(0, 0)$ as given by the following equations.

$$\upsilon_{(r,\beta)} = \begin{cases} \frac{\omega_0-\beta}{\omega_0}\ \rho A_0 & r = 0', \beta \in [1, \omega_0 - 1] \\ \frac{\omega_0-\beta}{\omega_0} A_1 & r = 0,\ \beta \in [1, \omega_0 - 1] \\ \frac{\omega_r-\beta}{\omega_r} \xi^r \upsilon_{(0,0)} & r \in [1, m],\ \beta \in [0, \omega_r - 1] \end{cases} \quad (4)$$

The probability of being in state $(0', 0)$ and the expressions for A_0 and A_1 are given by

$$\upsilon_{(0',0)} = \frac{\rho A_0 \left[1+(\omega_0-1)P_{pb\to(0',0)}\right]}{\omega_0\left(1-P_{(0',0)\to(0',0)}\right)} \quad (5)$$

$$A_0 = \upsilon_{(0,0)} \quad (6)$$

$$A_1 = \upsilon_{(0,0)}(1 - \rho)+P_{(0',0)\to bo}\ \upsilon_{(0',0)} \quad (7)$$

The transition probability $P_{(0',0)\to(0',0)}$, the probability of returning back to the same state $(0', 0)$ after an observed time slot was not considered in [12] for the analysis. A station transmits from one of the states $(r, 0)$ when its backoff timer β reaches 0. Therefore the transmission probability (ζ) for a station is given by the following equation.

$$\zeta = \textstyle\sum_{r=0}^{m} \upsilon_{(r,0)} = \sum_{r=0}^{m} \xi^r \upsilon_{(0,0)} \quad (8)$$

Since all the stations are identical, the expression for the collision probability (ξ) can be expressed by the following equation.

$$\xi = 1 - (1 - \zeta)^{\kappa-1} \quad (9)$$

As the sum of all state probabilities is equal to 1, $\upsilon_{(0,0)}$ can be calculated from the following equation.

$$\textstyle\sum_{r=0}^{m}\ \sum_{\beta=0}^{\omega_r-1}\ \upsilon_{(r,\beta)} + \sum_{\beta=0}^{\omega_0-1}\ \upsilon_{(0',\beta)} = 1 \quad (10)$$

The entire time frame is divided into a sequence of time slots. The length of a time slot depends on the transmission activity on the channel. We denote a variable τ to represent the length of a time slot. It takes three different values for idle, transmission, or collision states of the channel. The length of an idle slot τ_0 is constant and depends on the type of physical media. The slot lengths for successful transmission (τ_s) and collision (τ_c) are based on the type of access mechanism.

$$\tau_s^{[basic]} = PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \quad (11)$$

$$\tau_c^{[basic]} = PHY_{hdr} + MAC_{hdr} + E[P^*] + DIFS \quad (12)$$

$$\tau_s^{[rts]} = RTS + SIFS + CTS + SIFS + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \quad (13)$$

$$\tau_c^{[rts]} = RTS + DIFS \quad (14)$$

Where PHY_{hdr}, MAC_{hdr} represent the lengths of physical layer and media access control sub-layer headers respectively. $E[P]$ represents the average length of packets that are transmitted. Similarly $E[P^*]$ represents the average length of packets that are involved in collision (as defined in [11]).

When a station is listening to the channel without transmitting, the probability that atleast one of the other $(\kappa - 1)$ neighboring stations transmit at the beginning of a slot time (ζ_{tx}) is given by the following equation.

$$\zeta_{tx} \;=\; 1 - (1-\zeta)^{\kappa-1} \tag{15}$$

A successful transmission can be observed when only one of the $(\kappa - 1)$ neighboring stations transmit at the beginning of a slot time. The probability that a station observes successful transmission (ζ_s) during any time slot is given the following expression.

$$\zeta_s \;=\; \frac{(\kappa-1)\zeta(1-\zeta)^{\kappa-2}}{1-(1-\zeta)^{\kappa-1}} \tag{16}$$

Then the probability distribution of the slot lengths observed the listening station is given by the following equations.

$$P\{\tau = \tau_0\} \;=\; 1 - \zeta_{tx} \tag{17}$$

$$P\{\tau = \tau_s\} \;=\; \zeta_{tx}\zeta_s \tag{18}$$

$$P\{\tau = \tau_c\} \;=\; \zeta_{tx}(1 - \zeta_s) \tag{19}$$

Throughput: We define a variable ζ_{TX} to denote the probability that atleast one of the κ stations transmit during a particular time slot. The expression for ζ_{TX} is given as:

$$\zeta_{TX} \;=\; 1 - (1-\zeta)^{\kappa} \tag{20}$$

The probability of observing a successful transmission due to any one of the κ stations by the channel (ζ_S) is given by the following equation.

$$\zeta_S \;=\; \frac{\kappa\zeta(1-\zeta)^{\kappa-1}}{1-(1-\zeta)^{\kappa}} \tag{21}$$

Denoting $E[\tau_{CH}]$ as the average length of time slots observed by the channel and $(E[data])$ as the average data transmitted on the channel in a slot time, we can express $(E[data])$ and $E[\tau_{CH}]$ by the following equations.

$$E[data] = \;\kappa\zeta\,(1-\zeta_{tx})\,E[P] \tag{22}$$

$$E[\tau_{CH}] \;=\; (1-\zeta_{TX})\tau_0 + \zeta_{TX}\zeta_S\tau_s + \zeta_{TX}(1-\zeta_S)\tau_c \tag{23}$$

Then the total throughput (Γ) observed on the channel due to all κ stations transmitting on the channel is given by the following equation.

$$\Gamma = \;\frac{\kappa\zeta(1-\zeta_{tx})E[P]}{(1-\zeta_{TX})\tau_0+\zeta_{TX}\zeta_S\tau_s+\zeta_{TX}(1-\zeta_S)\tau_c} \tag{24}$$

Transition probability - $P_{pb\to(0',0)}$: This represents the probability of receiving zero packets during the time the station spends in the post backoff. To calculate this probability, we represent Q to denote the backoff timer for post backoff process. Then Q is a random variable uniformly distributed over the range $[0, \omega_0 - 1]$. A vector $\overline{\tau} = \{\tau_1, \tau_2, \ldots, \tau_Q\}$ of length Q is used to represent the sequence of time slots observed by the station on the channel during its post backoff process. Therefore the total time t the station spends in the post backoff is equal to $\sum_{i=1}^{Q}\tau_i$. Since the packet arrival is assumed to be poisson distributed with rate λ packets/sec, the probability density function for the packet arrival process is given by

$$P(\eta) = \;\frac{e^{-\lambda T}(\lambda T)^{\eta}}{\eta!} \qquad\qquad \eta = 0, 1, 2, \ldots \tag{25}$$

which denotes the probability of η packet arrivals in the duration of T time units. Therefore the probability of zero packet arrivals in the duration t $(= \sum_{i=1}^{Q}\tau_i)$ time units is given by the following equation.

$$P_{pb\to(0',0)}|_{Q,\overline{\tau}} = \;e^{-\lambda\sum_{i=1}^{Q}\tau_i} \tag{26}$$

Since Q is uniformly distributed over the rage $[0, \omega_0 - 1]$, for a known $\overline{\tau}$, we can write

$$P_{pb\to(0',0)}|_{\overline{\tau}} = \;\frac{1}{\omega_0}\sum_{q=0}^{\omega_0-1} e^{-\lambda\sum_{i=1}^{q}\tau_i} \tag{27}$$

$$= \;\frac{1}{\omega_0}\sum_{q=0}^{\omega_0-1}\prod_{i=1}^{q} e^{-\lambda\tau_i} \tag{28}$$

Since τ_i are independent and identically distributed, the probability of receiving zero packets during post backoff process is given by the following equation.

$$P_{pb\to(0',0)} = \;\frac{1}{\omega_0}\sum_{q=0}^{\omega_0-1}\left[E[e^{-\lambda\tau}]\right]^{q} \tag{29}$$

Transition probability - $P_{(0',0)\to(0,0)}$: The probability that atleast one packet arrives in the queue during an idle slot is equal $1 - e^{-\lambda\tau_0}$. Therefore the transition probability from $(0', 0)$ to $(0, 0)$ is given by the following equation.

$$P_{(0',0)\to(0,0)} = P\{\tau = \tau_0\}(1 - e^{-\lambda\tau_0}) \tag{30}$$

Transition probability - $P_{(0',0)\to bo}$: If a station receives packets in its buffer when the channel is busy, it starts the backoff process. Therefore the transition probability from $(0', 0)$ to $(0, \beta)$, $\beta \in [0, \omega_0 - 1]$ through backoff process is given by the following equation.

$$P_{(0',0)\to bo} = E[1 - e^{-\lambda\tau}] - P_{(0',0)\to(0,0)} \tag{31}$$

Transition probability - $P_{(0',0)\to(0',0)}$: If a station in state $(0', 0)$ does not receive any packet during an observed time slot, it remains in the same state $(0', 0)$ for the next time slot. Therefore, the expression for the transition probability from $(0', 0)$ to $(0', 0)$ is given by

$$P_{(0',0)\to(0',0)} = 1 - P_{(0',0)\to(0,0)} - P_{(0',0)\to bo} \tag{32}$$

Probability of empty queue (ρ): To calculate the probability of empty queue (ρ), the service time for a packet scheduled for transmission is calculated. It is defined as the time taken to successfully deliver or drop (after reaching maximum retry attempts) a packet . If $E[T_{serv}]$ is the average service time, the probability of finding an empty queue is given by the following expression.

$$\rho = \max(0, 1 - \lambda E[T_{serv}]) \tag{33}$$

As mentioned in [12], a packet may have different service times depending on the state of the queue upon its arrival. We denote $E[T_{empty}]$ to indicate the average service time of the packets that find the queue empty upon their arrival, and $E[T_{nonempty}]$ for the average service time of the packets that find nonempty queue upon their arrival. Therefore $E[T_{serv}]$ can be written in terms of $E[T_{empty}]$ and $E[T_{nonempty}]$ as shown below.

$$E[T_{serv}] = (1-\rho)E[T_{nonempty}] + \rho E[T_{empty}] \tag{34}$$

Combining Equations (33), (34), we can express ρ in terms of $E[T_{empty}]$ and $E[T_{nonempty}]$ as given below.

$$\rho = 1 - \min\left\{1, \frac{\lambda E[T_{empty}]}{1-\lambda(E[T_{nonempty}]-E[T_{empty}])}\right\} \tag{35}$$

$E[T_{nonempty}]$ has three components namely the average time spent in the backoff process, the average time spent in collisions, and the average time needed for packet transmission. Therefore $E[T_{nonempty}]$ can be obtained from the following equation.

$$\begin{aligned} E[T_{nonempty}] = {} & \textstyle\sum_{r=0}^{m} \xi^r \left[\frac{\omega_r - 1}{2}\right] E[\tau] + (1-\xi^{m+1})\tau_s + \\ & \left[\textstyle\sum_{r=1}^{m} \xi^r (1-\xi) r + \xi^{m+1}(m+1)\right]\tau_c \end{aligned} \tag{36}$$

As mentioned earlier $E[T_{empty}]$ is the average service time of the packets that arrive when the queue is empty. A packet may arrive when the station is in the post backoff period or when it is in the state $(0',0)$. We denote a variable α to represent a bernoulli process such that if $\alpha = 1$, station goes to the state $(0',0)$ after post backoff process. On the otherhand if $\alpha = 0$, station enters enters the transmission state $(0,0)$ from post backoff process. Therefore $\alpha = 0$ indicates that atleast one packet has arrived during post backoff process. The expression for $E[T_{empty}]$ is given by

$$\begin{aligned} E[T_{empty}] = {} & \big(1 - P_{pb\to(0',0)}\big)\big(E[T_{inpb}] + E[T_{\alpha=0}]\big) \\ & + P_{pb\to(0',0)} E[T_{\alpha=1}] \end{aligned} \tag{37}$$

Where $E[T_{inpb}]$ is the average time a packet spends in post backoff and $E[T_{\alpha=0}]$ is the average time needed to successfully send the packet starting from state $(0,0)$ or dropping (after reaching maximum retries). $E[T_{\alpha=1}]$ is the average service time of a packet that arrives when the station is in state $(0',0)$. The time a packet spends in post backoff process is defined as the residual time. The average residual time $R(t)$ for a packet that arrives at any time t_0 during post backoff interval $[0,t]$ is given by the following expression.

$$R(t) = \begin{cases} t - t_0 & t_0 < t \\ 0 & t_0 > t \end{cases} \tag{38}$$

During the post backoff process $[0,t]$, the queue is empty at time instant 0. The arrival time (t_0) of a packet is exponentially distributed according to the following PDF function.

$$p(t_0) = \lambda e^{-\lambda t_0} \tag{39}$$

Therefore the residual time $R(t = \sum_{i=1}^{Q} \tau_i)$ for known values of Q and $\overline{\tau}$ is given by the following equation.

$$R\big(\textstyle\sum_{i=1}^{Q} \tau_i\big)|_{Q,\overline{\tau}} = \sum_{i=1}^{Q} \tau_i + \frac{1}{\lambda} e^{-\lambda \sum_{i=1}^{Q} \tau_i} - \frac{1}{\lambda} \tag{40}$$

The average residual time $E[R(\sum_{i=1}^{Q} \tau_i)]$ and $E[T_{inpb}]$ are given by the following equations.

$$E\big[R(\textstyle\sum_{i=1}^{Q} \tau_i)\big] = \frac{1}{\omega_0} \sum_{q=1}^{\omega_0 - 1} \left[qE[\tau] + \frac{1}{\lambda} E[e^{-\lambda\tau}]^q\right] - \frac{1}{\lambda} \tag{41}$$

$$E[T_{inpb}] = \frac{\frac{1}{\omega_0} \sum_{q=1}^{\omega_0 - 1} \left[qE[\tau] + \frac{1}{\lambda} E[e^{-\lambda\tau}]^q\right] - \frac{1}{\lambda}}{1 - P_{pb\to(0',0)}} \tag{42}$$

The expressions for $E[T_{\alpha=0}]$ are given by

$$E[T_{\alpha=0}] = (1-\xi)\tau_s + \xi\big(\tau_c + E[T_{retrans}]\big) \tag{43}$$

$$\begin{aligned} E[T_{retrans}] = {} & \textstyle\sum_{r=1}^{m} \xi^{r-1} \left[\frac{\omega_r - 1}{2}\right] E[\tau] + (1-\xi^m)\tau_s + \\ & \left[\textstyle\sum_{r=1}^{m-1} \xi^r (1-\xi) r + \xi^m m\right]\tau_c \end{aligned} \tag{44}$$

To calculate the average service time of the packets that arrive when the station is in state $(0',0)$, we have to consider two possible cases. The first case is considered when a packet arrives during an empty time slot. In this case the packet is transmitted at the beginning of the next time slot from state $(0,0)$. The packet will have an average service time equal to $E[T_{tx}]$. On the otherhand, the second case is considered if a packet arrives when the channel is busy due to transmission(s). The station will schedule the transmission of the packet through backoff process. This packet will have $E[T_{bo}]$ as the average service time. Therefore the expression for $E[T_{\alpha=1}]$ is given as

$$E[T_{\alpha=1}] = P\{\tau = \tau_0\} E[T_{tx}] + \big(1 - P\{\tau = \tau_0\}\big) E[T_{bo}] \tag{45}$$

The expressions for both $E[T_{tx}]$ and $E[T_{bo}]$ contain residual time spent by the packet after it arrives during a particular time slot.

$$E[T_{tx}] = \frac{P\{\tau = \tau_0\} R(\tau_0)}{P_{(0',0)\to(0,0)}} + (1-\xi)\tau_s + \xi\big(\tau_c + E[T_{retrans}]\big) \tag{46}$$

$$E[T_{bo}] = \frac{E\big[R(\tau)\big] - P\{\tau = \tau_0\} R(\tau_0)}{P_{(0',0)\to bo}} + E[T_{nonempty}] \tag{47}$$

Equations (36) through (47) are used in Equation (35) to calculate the probability that a station has an empty queue.

B. N-DCF Protocol

In this section we present our proposed throughput model for N-DCF which applicable to any arbitrary load conditions. For simplicity of exposition, we first present the analysis of N-DCF protocol with $N = 2$. Later we present expressions that are valid for any value of N. From the markov chain diagram shown in Figure 2, the transition probabilities between the states represented by tuple (r,β) are given by

$$\begin{array}{ll} P\{r,\beta|r,\beta+1\} = 1 & r \in [0,m], \beta \in [0,\omega_r - 2] \\ P\{0,\beta|r,0\} = (1-\xi)(1-\rho)/\omega_0 & r \in [1,m-1], \beta \in [0,\omega_0 - 1] \\ P\{0,\beta|m,0\} = (1-\rho)/\omega_0 & \beta \in [0,\omega_0 - 1] \\ P\{V_{i=1}|0,0\} = (1-\xi)\rho & \\ P\{V_{i=2}|0,0\} = (1-\xi)(1-\rho) & \\ P\{0,\beta|V_{i=2}\} = (1-\rho)/\omega_0 & \beta \in [0,\omega_0 - 1] \\ P\{0',\beta|r,0\} = (1-\xi)\rho/\omega_0 & r \in [1,m-1], \beta \in [0,\omega_0 - 1] \\ P\{0',\beta|m,0\} = \rho/\omega_0 & \beta \in [0,\omega_0 - 1] \\ P\{0',\beta|V_{i=1}\} = 1/\omega_0 & \beta \in [0,\omega_0 - 1] \\ P\{0',\beta|V_{i=2}\} = \rho/\omega_0 & \beta \in [0,\omega_0 - 1] \\ P\{0,\beta|0',0\} = P_{(0',0)\to bo}/\omega_0 & \beta \in [0,\omega_0 - 1] \\ P\{0',0|0',1\} = P_{pb\to(0',0)} & \\ P\{0,0|0',1\} = 1 - P_{pb\to(0',0)} & \\ P\{0,0|0',0\} = P_{(0',0)\to(0,0)} & \\ P\{0',0|0',0\} = P_{(0',0)\to(0',0)} & \end{array} \tag{48}$$

We can relate the probability of being in any state (r,β) to the probability of being in state $(0,0)$ through the use of non-zero stationary transition probabilities listed in Equation (48). Since $\upsilon_{(r,\beta)}$ represents the probability of being in state (r,β), we obtain the following relations between the states assumed by the tuple (r,β) under steady state conditions.

$$\upsilon_{(r,0)} = \xi\upsilon_{r-1,0} = \xi^r\upsilon_{(0,0)} \quad r\in[1,m] \tag{49}$$

$$\upsilon_{(0',0)} = \frac{\rho A_0\left[1+(\omega_0-1)P_{pb\to(0',0)}\right]}{\omega_0\left(1-P_{(0',0)\to(0',0)}\right)} \tag{50}$$

$$\upsilon_{i=1} = \rho(1-\xi)\upsilon_{(0,0)} \tag{51}$$

$$\upsilon_{i=2} = (1-\rho)(1-\xi)\upsilon_{(0,0)} \tag{52}$$

$$\upsilon_{(r,\beta)} = \begin{cases} \frac{\omega_0-\beta}{\omega_0}\rho A_0 & r=0', \beta\in[1,\omega_0-1] \\ \frac{\omega_0-\beta}{\omega_0}A_1 & r=0,\ \beta\in[1,\omega_0-1] \\ \frac{\omega_r-\beta}{\omega_r}\xi^r\upsilon_{(0,0)} & r\in[1,m],\ \beta\in[0,\omega_r-1] \end{cases} \tag{53}$$

Where $\upsilon_{i=1}$ and $\upsilon_{i=2}$ are the probabilities that a station transmits packet(s) from virtual states $V_{i=1}$ and $V_{i=2}$ respectively. The expressions for A_0 and A_1 are given by the following equations.

$$A_0 = \upsilon_{(0,0)}[1+(1-\xi)(1-\rho)] \tag{54}$$

$$A_1 = \upsilon_{(0,0)}[\xi(1-\rho)+(1-\xi)(1-\rho)^2] + P_{(0',0)\to bo}\ \upsilon_{(0',0)} \tag{55}$$

The expressions presented in previous subsection for the four transition probabilities $P_{pb\to(0',0)}$, $P_{(0',0)\to(0,0)}$, $P_{(0',0)\to bo}$ and $P_{(0',0)\to(0',0)}$ are still valid for N-DCF analysis. Also the expression for ρ is valid for N-DCF. Finally $\upsilon_{0,0}$ can be obtained from the following equation.

$$\sum_{r=0}^{m}\sum_{\beta=0}^{\omega_r-1}\upsilon_{(r,\beta)} + \sum_{\beta=0}^{\omega_0-1}\upsilon_{(0',\beta)} + \upsilon_{i=1} + \upsilon_{i=2} = 1 \tag{56}$$

The station transmission probability is given by Equation (8). The transmission and collision slot lengths are given by the following expressions.

$$\tau_s^{2,[basic]} = PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + SIFS + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \tag{57}$$

$$\tau_s^{1,[basic]} = PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \tag{58}$$

$$\tau_c^{[basic]} = PHY_{hdr} + MAC_{hdr} + E[P^*] + DIFS \tag{59}$$

$$\tau_s^{2,[rts]} = RTS + SIFS + CTS + SIFS + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + SIFS + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \tag{60}$$

$$\tau_s^{1,[rts]} = RTS + SIFS + CTS + SIFS + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \tag{61}$$

$$\tau_c^{[rts]} = RTS + DIFS \tag{62}$$

A station transmits from state $(0,0)$ with probability μ_0. It transmits from any other transmission states $(r,0)$ with probability μ_r. Therefore μ_0 and μ_r are given by

$$\mu_0 = \frac{\upsilon_{(0,0)}}{\sum_{r=0}^{m}\upsilon_{(r,0)}} \tag{40}$$

$$\mu_r = 1-\mu_0 \tag{41}$$

The probability distribution of slot lengths observed by a station listening to the channel (without transmitting) is given by the following equations.

$$P\{\tau=\tau_0\} = 1-\zeta_{tx} \tag{63}$$

$$P\{\tau=\tau_s^1\} = \zeta_{tx}\zeta_s\left[\mu_0\rho+\mu_r\right] \tag{64}$$

$$P\{\tau=\tau_s^2\} = \zeta_{tx}\zeta_s\mu_0(1-\rho) \tag{65}$$

$$P\{\tau=\tau_c\} = \zeta_{tx}(1-\zeta_s) \tag{66}$$

The average length of the slots observed by the channel is

$$E[\tau_{CH}] = (1-\zeta_{TX})\tau_0 + \zeta_{TX}(1-\zeta_S)\tau_c + \zeta_{TX}\zeta_S\left[(\mu_0\rho+\mu_r)\tau_s^1 + \mu_0(1-\rho)\tau_s^2\right] \tag{67}$$

And expression for the total throughput is given by

$$\Gamma = \frac{\kappa\zeta(1-\zeta_{tx})\{\mu_0\rho+2\mu_0(1-\rho)+\mu_r\}E[P]}{E[\tau_{CH}]} \tag{68}$$

N-DCF Expressions for any N: In this section we present the expressions for N-DCF which are valid for any N.

$$\upsilon_{(r,0)} = \xi\upsilon_{r-1,0} = \xi^r\upsilon_{(0,0)} \quad r\in[1,m] \tag{69}$$

$$\upsilon_{(0',0)} = \frac{\rho A_0\left[1+(\omega_0-1)P_{pb\to(0',0)}\right]}{\omega_0\left(1-P_{(0',0)\to(0',0)}\right)} \tag{70}$$

$$\upsilon_{i=1} = \rho(1-\xi)\upsilon_{(0,0)} \tag{71}$$

$$\upsilon_i = (1-\rho)^{i-1}(1-\xi)\upsilon_{(0,0)} \quad i=2,3,\ldots,N \tag{72}$$

$$\upsilon_{(r,\beta)} = \begin{cases} \frac{\omega_0-\beta}{\omega_0}\rho A_0 & r=0', \beta\in[1,\omega_0-1] \\ \frac{\omega_0-\beta}{\omega_0}A_1 & r=0,\ \beta\in[1,\omega_0-1] \\ \frac{\omega_r-\beta}{\omega_r}\xi^r\upsilon_{(0,0)} & r\in[1,m],\ \beta\in[0,\omega_r-1] \end{cases} \tag{73}$$

Where the expressions for A_0 and A_1 are given by the following equations.

$$A_0 = \upsilon_{(0,0)}[1+(1-\xi)\sum_{i=1}^{N-1}(1-\rho)^i] \tag{74}$$

$$A_1 = \upsilon_{(0,0)}[\xi(1-\rho)+(1-\xi)(1-\rho)^N] + P_{(0',0)\to bo}\ \upsilon_{(0',0)} \tag{75}$$

Expressions for $P_{pb\to(0',0)}$, $P_{(0',0)\to(0,0)}$, $P_{(0',0)\to bo}$ and $P_{(0',0)\to(0',0)}$ are given by Equations (29) through (32). The expression for ρ is given by the Equation (35). The state probability $\upsilon_{0,0}$ can be obtained from the following equation.

$$\left.\begin{array}{l} \sum_{r=0}^{m}\sum_{\beta=0}^{\omega_r-1}\upsilon_{(r,\beta)} + \sum_{\beta=0}^{\omega_0-1}\upsilon_{(0',\beta)} + \\ \upsilon_{i=1}+\upsilon_{i=2}+\cdots+\upsilon_{i=N} \end{array}\right\} = 1 \tag{76}$$

The station transmission probability is given by Equation (8). The slot lengths for N-DCF under basic and RTS/CTS access mechanisms are given by the following equations.

$$\tau_s^{i,[basic]} = \begin{cases} (i-1)(PHY_{hdr}+MAC_{hdr}+E[P]+SIFS+ACK+SIFS) \\ +PHY_{hdr}+MAC_{hdr}+E[P]+SIFS+ACK+DIFS, \\ i\in[1,N] \end{cases}$$

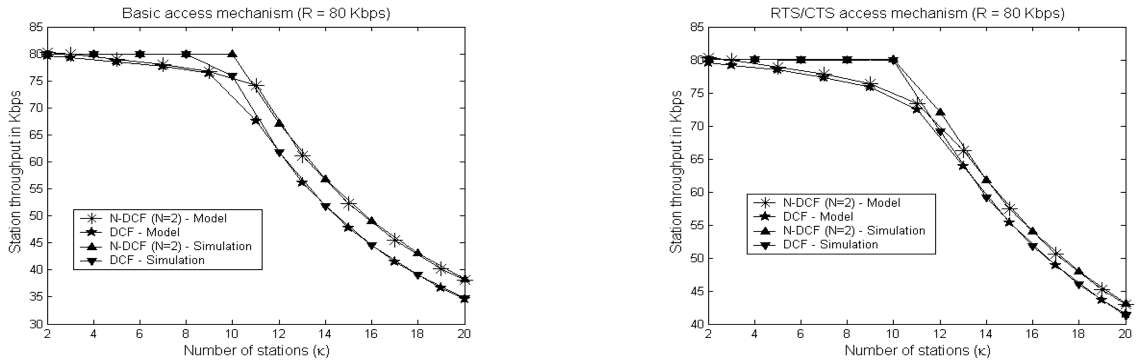
$$\tau_c^{[basic]} = PHY_{hdr}+MAC_{hdr}+E[P^*]+DIFS$$

$$\tau_s^{i,[rts]} = \begin{cases} RTS+SIFS+CTS+SIFS+ \\ (i-1)(PHY_{hdr}+MAC_{hdr}+E[P]+SIFS+ACK+SIFS) \\ +PHY_{hdr}+MAC_{hdr}+E[P]+SIFS+ACK+DIFS, \\ i\in[1,N] \end{cases}$$

$$\tau_c^{[rts]} = RTS+DIFS$$

The slot length distribution observed by a station is

$$P\{\tau=\tau_0\} = 1-\zeta_{tx} \tag{77}$$



(a) Basic access.

(b) RTS/CTS access.

Fig. 3. Station throughput as a function of network size.

$$P\{\tau = \tau_s^1\} = \zeta_{tx}\zeta_s\left[\mu_0\rho + \mu_r\right] \tag{78}$$

$$P\{\tau = \tau_s^i\} = \zeta_{tx}\zeta_s\mu_0\rho(1-\rho)^{i-1} \quad i \in [2, N-1] \tag{79}$$

$$P\{\tau = \tau_s^N\} = \zeta_{tx}\zeta_s\mu_0(1-\rho)^{N-1} \tag{80}$$

$$P\{\tau = \tau_c\} = \zeta_{tx}(1-\zeta_s) \tag{81}$$

The expression for $E[\tau_{CH}]$ is given by

$$\begin{aligned} E[\tau_{CH}] &= (1-\zeta_{TX})\tau_0 + \zeta_{TX}(1-\zeta_S)\tau_c \\ &+ \zeta_{TX}\zeta_S\left[(\mu_0\rho + \mu_r)\tau_s^1 + \textstyle\sum_{i=2}^{N-1}\mu_0\rho(1-\rho)^{i-1}\tau_s^i\right] \\ &+ \zeta_{TX}\zeta_S\mu_0(1-\rho)^{N-1}\tau_s^N \end{aligned} \tag{82}$$

Finally, the generalized expression for N-DCF throughput (any N) is given by the following equation.

$$\Gamma = \frac{\kappa\zeta(1-\zeta_{tx})\left\{\mu_0\rho + \sum_{i=2}^{N-1} i\mu_0\rho(1-\rho)^{i-1} + N\mu_0(1-\rho)^{N-1} + \mu_r\right\}E[P]}{E[\tau_{CH}]} \tag{83}$$

C. Validation of the Throughput Model

In this section we validate our proposed throughput model through comparing the numerical results with the simulations performed using NS-2 network simulator. We compare numerical and simulation results under both basic and RTS/CTS access mechanism. For this we consider an adhoc network with κ stations. The data rate is considered R bits per second (bps). In our throughput model the parameter λ is adjusted according to the data rate R. In NS-2 simulations, packets arrive in the queue from UDP sources at constant bit rate equal to R bps. The NS-2 simulated stations have a buffer size of 50 packets. The size of data packets in both analysis and simulation is considered as P bytes. Further, all the parameters that are used for performance evaluation are summarized in Table I.

In Figure 3, we present the performance of N-DCF $(N = 2)$ and DCF protocols under unsaturated conditions. In unsaturated conditions, the stations are not overloaded. Therefore a station may not always have packets to transmit in its buffer. To study the performance of these two protocols, we add stations to increase the load on the channel. Under both basic and RTS/CTS access mechanisms, the channel is not overloaded when the number of stations on the channel is below 10. Both DCF and N-DCF stations are able to maintain throughput at 80 Kbps which is equal to the data arrival rate at their MAC queue. When the channel becomes overloaded, N-DCF station maintains higher throughput under both access mechanisms.

TABLE I

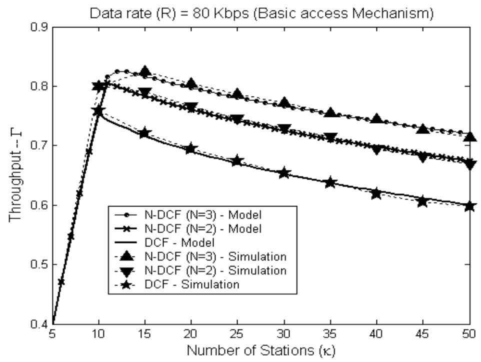
PARAMETERS USED IN ANALYTICAL AND SIMULATION RESULTS

Parameter	***Value***
Packet Size (P)	1023 Bytes
$PHY_{hdr} + MAC_{hdr}$	44 Bytes
RTS	36 Bytes
CTS	30 Bytes
ACK	30 Bytes
Channel Bandwidth	1 Mbits/sec
Idle Slot Time (τ_0)	50 μs
SIFS	28 μs
DIFS	128 μs
Initial window size (ω_0)	32
Maximum window size (ω_{max})	1024
Max retransmissions (m)	7

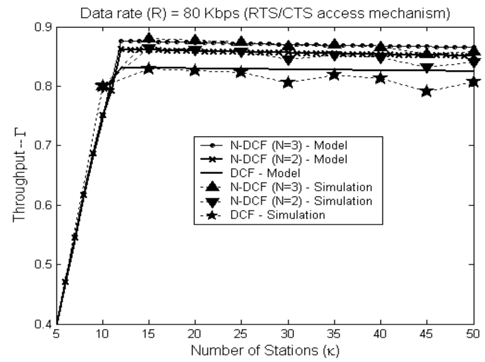
In Figure 4, we present the throughput performance due to transmissions from all the stations on the channel. The total throughput on the channel under basic access mechanism for N-DCF $(N = 3)$, N-DCF $(N = 2)$ and DCF protocols is shown in Figure 4(a). The total throughput under RTS/CTS access mechanism is shown in Figure 4(b). It can be observed that the channel efficiency (defined as the maximum achievable throughput due to transmissions from all the stations on the channel) can be improved by increasing the value of N in N-DCF protocol.

We now study the performance of the DCF and N-DCF protocols by varying the data arrival rate R. For this we consider a network size with 10 stations. Each station has data arrival rate R at its MAC buffer. Now the load on the channel is increase by increasing the data rate R. Figure 5(a) shows that N-DCF stations perform better when the data rate is increased beyond 80 Kbps. Similarly for RTS/CTS access mechanism shown in Figure 5(b), N-DCF stations perform better at high loads.

Form performance evaluations conducted using numerical analysis and simulations, we find that N-DCF protocol performs better than DCF protocol. The performance of N-DCF and DCF protocols under saturated conditions will be presented in the next section where we describe other recent DCF

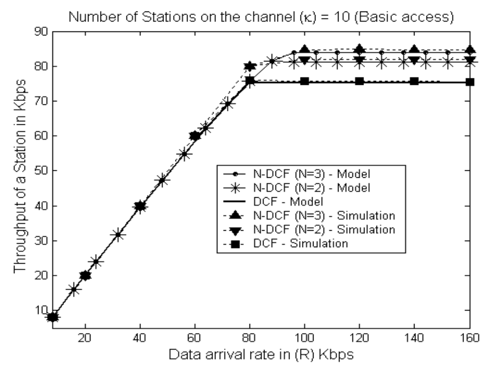


(a) Basic access.

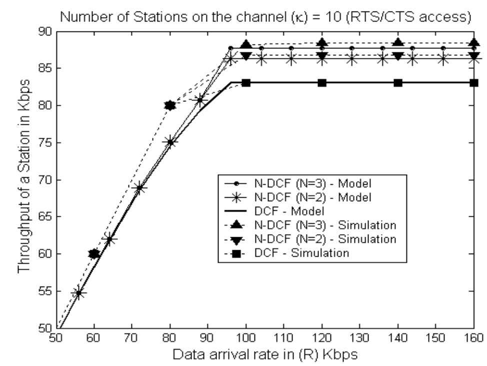


(b) RTS/CTS access.

Fig. 4. Channel efficiency under basic and RTS/CTS access mechanisms.



(a) Basic access.



(b) RTS/CTS access.

Fig. 5. Station throughput as a function of data arrival rate R.

enhancements proposed in the literature. As all these protocols have similar goals, i.e. improving the throughput performance of DCF protocol, we compare them both analytically and through NS-2 simulations.

IV. Comparison of N-DCF with Other Proposals on DCF Improvement

In this section we describe two recent DCF enhancements proposed in the literature namely *"gentle decrease DCF (GDCF)"* and *"slow decrease DCF (SD-DCF)"*. We compare the throughput performance of GDCF and SD-DCF protocols with N-DCF protocol under saturated conditions. In saturated conditions, stations always have packets to transmit as they are overloaded. Therefore saturated conditions present the worst case scenario to test the performance of a protocol [11].

A. GDCF protocol

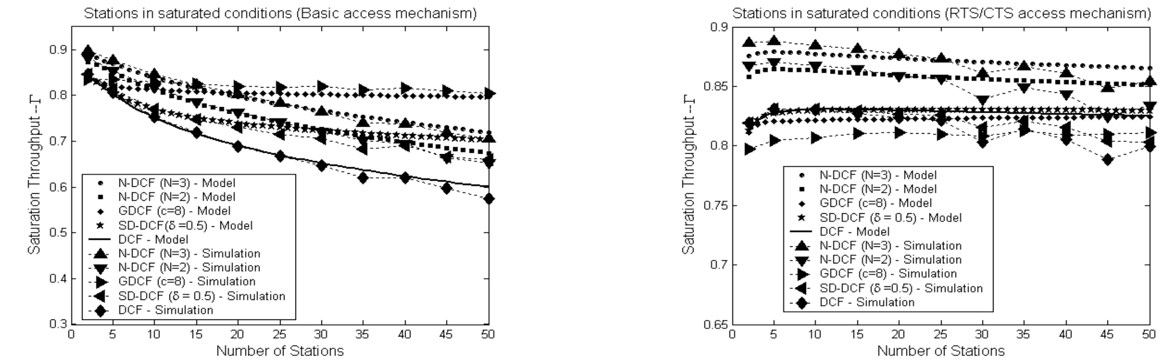
The GDCF protocol proposed in [7] modifies the CW reset mechanism. The CW reset mechanism is changed to improve the throughput on the channel when it is heavily loaded. A GDCF station halves the CW size for the next packet transmission only if c successive packet transmissions are made with the current CW size. The rest of the protocol is similar to DCF, i.e. a GDCF station uses backoff process exactly as DCF station and doubles its CW size if a packet is lost due to collision. The markov chain model for GDCF protocol is shown in Figure 9 with $N = 1$. We have proposed NG-DCF protocol later in this paper. The analytical model presented for NG-DCF is also applicable for GDCF. Therefore the analysis for GDCF can be understood from the NG-DCF throughput model presented in Section V. Alternatively, reader may also refer to [7] for analytical model of GDCF protocol.

B. SD-DCF protocol

Similar to GDCF, SD-DCF protocol proposed in [8] modifies the CW reset mechanism to improve the throughput performance of DCF under congested environments. A SD-DCF station decreases the size of CW by a decreasing factor δ if a packet is transmitted successfully. The decreasing factor δ is chosen as equal to 2^{-d} where d is an integer greater than 0. If d is selected as 1, then the decreasing factor δ will be equal to 0.5. Therefore in SD-DCF ($\delta = 0.5$), a station halves its CW size after every successful transmission of the packet. We have presented our proposed NS-DCF and its throughput model (which is also applicable for SD-DCF) in Section V. The markov chain diagram shown in Figure 10 is applicable for SD-DCF protocol provided $N = 1$.

C. Comparison of N-DCF, GDCF and SD-DCF protocols

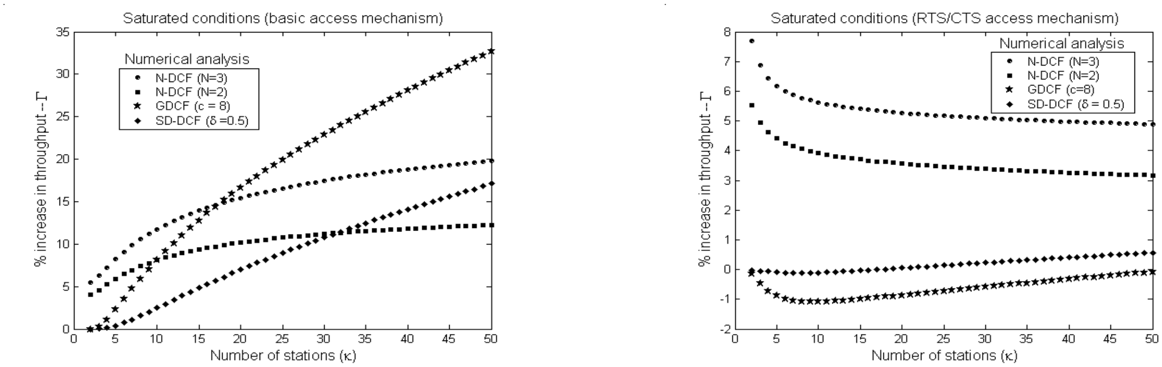
In this section we compare the performance of N-DCF protocol with GDCF and SD-DCF protocols under saturated



(a) Basic access.

(b) RTS/CTS access.

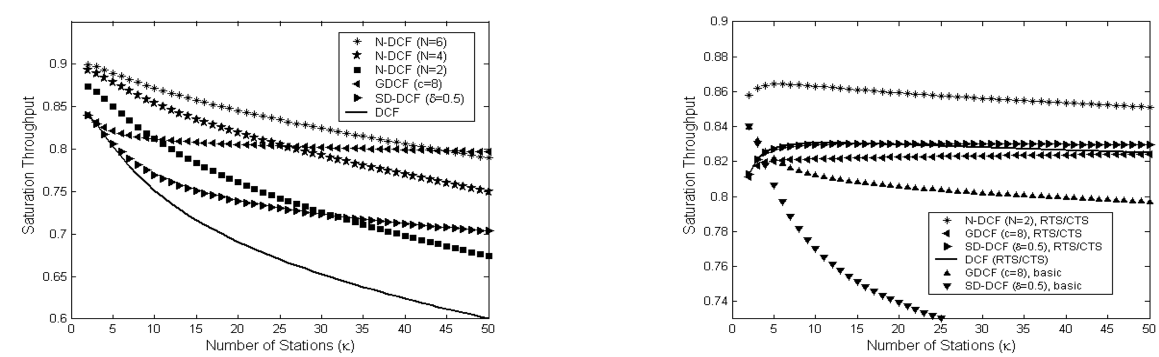
Fig. 6. Throughput performance of N-DCF, GDCF, SD-DCF and DCF protocols.



(a) Basic access.

(b) RTS/CTS access.

Fig. 7. Percentage improvement shown by N-DCF, GDCF and SD-DCF protocols over DCF.



(a) Basic access.

(b) Basic and RTS/CTS access.

Fig. 8. Comparison of N-DCF with GDCF, SD-DCF and DCF protocols.

conditions. In our proposed throughput model for N-DCF, we set data arrival rate R equal to 1000 Kbps to ensure stations are saturated. Figure 6 presents the saturation throughput of the protocols obtained numerically and through NS-2 simulations. Figure 6(a) shows that all the proposed enhancements namely N-DCF, GDCF and SD-DCF protocols improve throughput performance under basic access mechanism. However, it can be seen from Figure 6(b) that only N-DCF protocol provides throughput improvement under RTS/CTS access mechanism. To elaborate on this further, we present in Figure 7 the percentage improvement provided by these protocols over DCF. In basic access mechanism (see Figure 7), when the network has less than 10 stations, N-DCF provides more improvement in throughput than GDCF. When the network size grows beyond 15 stations, GDCF performs better than N-DCF $(N = 3)$ protocol. Also SD-DCF protocol shows better improvement compared to N-DCF $(N = 2)$ when the network has more than 30 stations but falls short when compared with N-DCF $(N = 3)$ performance. Though GDCF and SD-DCF protocols show good improvement in the throughput performance under

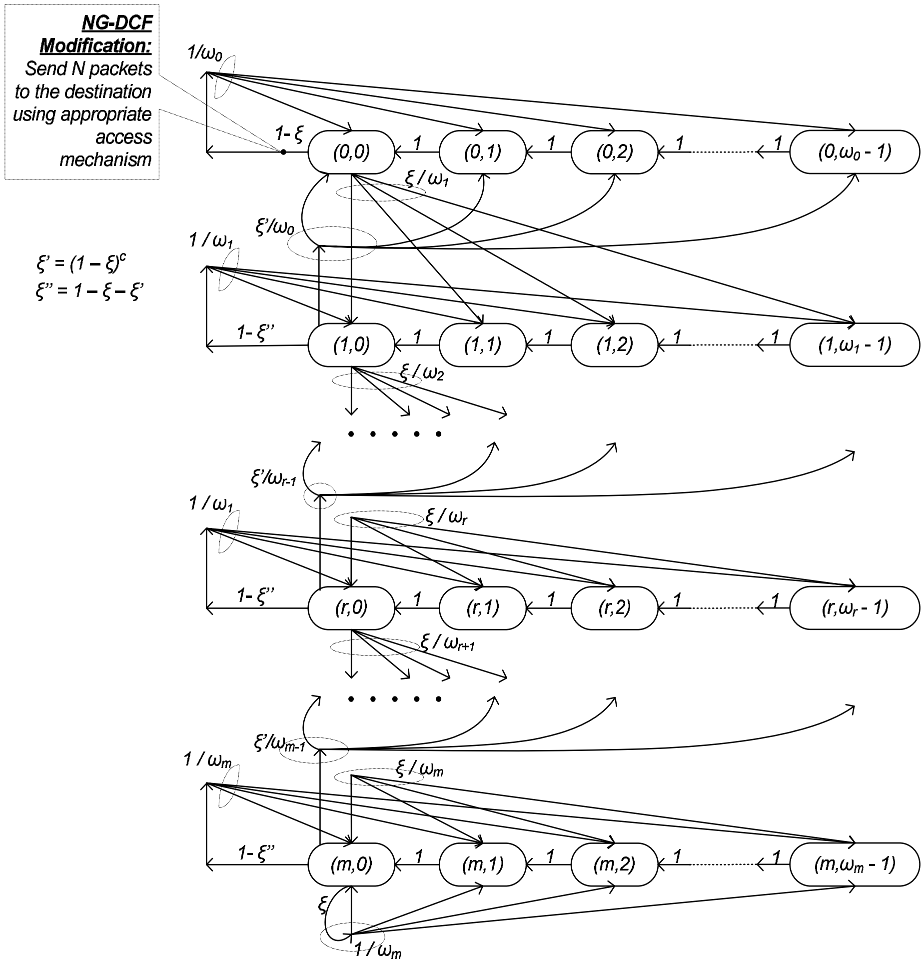


Fig. 9. Markov chain model for GDCF and NG-DCF protocols.

basic access mechanism, they show negative improvement when used with RTS/CTS access mechanism. Therefore, as shown in Figure 7(b), GDCF reduces the throughput by more than 1% in RTS/CTS access mechanism. SD-DCF also shows no improvement in throughput performance. On the other hand N-DCF provides improvement even in RTS/CTS access mechanism.

GDCF performs better than SD-DCF in basic access mechanism because it decreases the CW size much slower than SD-DCF. Since the overhead due to collision of a large data packet is significant, lowering the collision probability through gentle or slow decrease provides profound improvement in throughput for a moderately congested network. N-DCF on the other hand uses CW reset mechanism similar to DCF but relies on sending more than one packet when the channel is less congested. Therefore the throughput for N-DCF falls when the network size gets bigger. As shown in Figure 8(a), N-DCF has to send between 4 and 6 packets to maintain the throughput comparable to GDCF.

However, as mentioned earlier, both GDCF and SD-DCF fail to improve throughput in RTS/CTS access mechanism. This is because, in RTS/CTS access mechanism, the overhead due to RTS packet collision is less significant compared to the overhead of high backoff process time. Since N-DCF reduces the average backoff time of the packets, it shows immediate improvement in throughput performance by just sending a maximum of two data packets from state $(0, 0)$ under RTS/CTS access mechanism. As shown in Figure 8(b), when the network consists of 5 or more stations, the throughput improvement provided by GDCF and SD-DCF protocols under basic access mechanism is less than the obtained throughput by DCF with RTS/CTS access mechanism.

Though GDCF and SD-DCF provide better improvements in basic access mechanism, they are of little use when DCF uses RTS/CTS mechanism for transmitting data packets. Given the importance of RTS and CTS packets in resolving the hidden node problems, N-DCF is highly suitable because of the improvement shown in the throughput performance in RTS/CTS mechanism. In the next section, we propose modifications to N-DCF protocol to improve its performance under basic access mechanism in large network environments.

V. Proposed Modifications to N-DCF Protocol

Based on the observations made in previous section, we propose two modifications to N-DCF. These modifications are proposed for basic access mechanism to reduce decline in N-DCF throughput when network size becomes large.

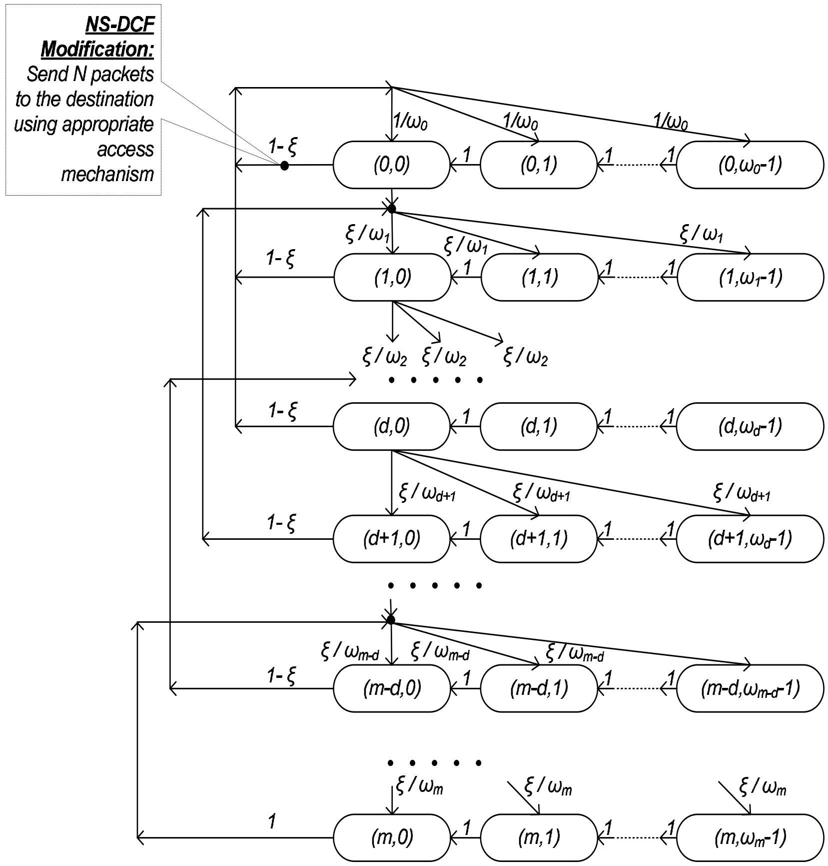


Fig. 10. Markov chain model for SD-DCF and NS-DCF protocols.

A. NG-DCF Protocol

NG-DCF protocol is a modified version of N-DCF protocol. The CW reset mechanism used in N-DCF is replaced by the gentle decrease CW reset mechanism used in GDCF. Therefore in NG-DCF, with gentle decrease in CW, we can reduce the decline in the throughput performance as network size grows. Simultaneously reducing the average backoff process overhead by sending more than one packet from state $(0, 0)$, we can effectively improve the DCF throughput performance in both basic and RTS/CTS access mechanisms.

For analysis we assume κ stations on the channel. All the stations are assumed to be in saturated conditions. The stations have identical MAC characteristics and transmit at the same physical rate. The transmission probability of a station is ζ. The collision probability is ξ irrespective of the retransmission attempt. The markov chain diagram for NG-DCF throughput model is shown in Figure 9. The probability of being in state (r, β), represented by $\upsilon_{(r,\beta)}$ is given by the following equation.

$$\upsilon_{(r,\beta)} = \begin{cases} \frac{\omega_0-\beta}{\omega_0}\ \left[(1-\xi)\upsilon_{(0,0)} + \xi'\upsilon_{(1,0)}\right], & \text{for } r=0,\ \beta\in[0,\omega_0-1] \\ \frac{\omega_r-\beta}{\omega_r}\left[\xi\upsilon_{(r-1,0)} + (1-\xi-\xi')\upsilon_{(r,0)} + \xi'\upsilon_{(r+1,0)}\right], & \text{for } 0<r<m,\ \beta\in[0,\omega_r-1] \\ \frac{\omega_m-\beta}{\omega_m}\left[\xi\upsilon_{(r-1,0)} + (1-\xi')\upsilon_{m,0}\right], & \text{for } r=m,\ \beta\in[0,\omega_m-1] \end{cases} \tag{84}$$

Where $\xi' = (1-\xi)^c$ and c is the number of successive successful transmissions made from a transmission state $(r, 0)$, $r \in [0, m]$. All the transmission states can be expressed in terms of $\upsilon_{(0,0)}$ as given by the following equation.

$$\upsilon_{(r,0)} = \gamma^r\upsilon_{(0,0)} \qquad r\in[0,m] \tag{85}$$
$$\text{where } \gamma = \xi/\xi'$$

Since the sum of all the state probabilities of the random process (r, β) is equal to 1, the probability of being in the state $(0, 0)$ can be obtained from the following equation.

$$\sum_{r=0}^{m}\ \sum_{\beta=0}^{\omega_r-1}\ \upsilon_{(r,\beta)} = 1 \tag{86}$$

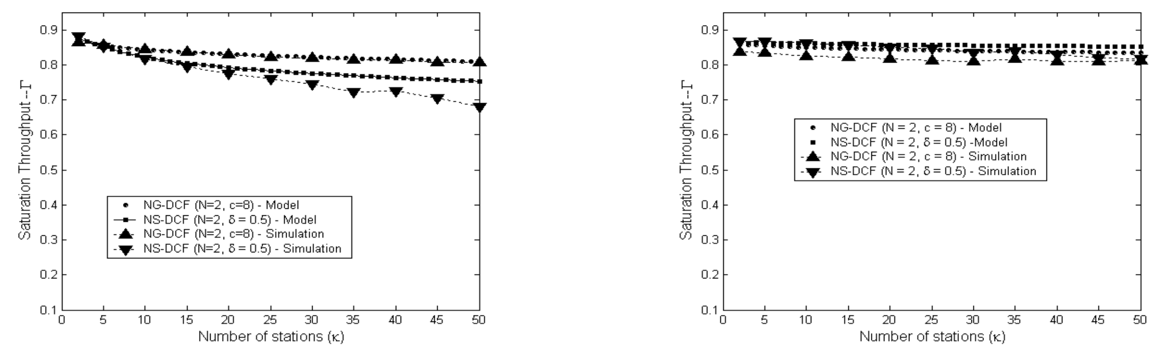
The expression for $\upsilon_{(0,0)}$ can be obtained as

$$\upsilon_{(0,0)} = \frac{2}{\sum_{r=0}^{m}\gamma^r(\omega_r+1)} \tag{87}$$

From the markov chain diagram shown in Figure 9, the transmission probability of a NG-DCF station can be written as

$$\zeta = \sum_{r=0}^{m}\upsilon_{(r,0)} = \sum_{r=0}^{m}\gamma^r\upsilon_{(0,0)} \tag{88}$$

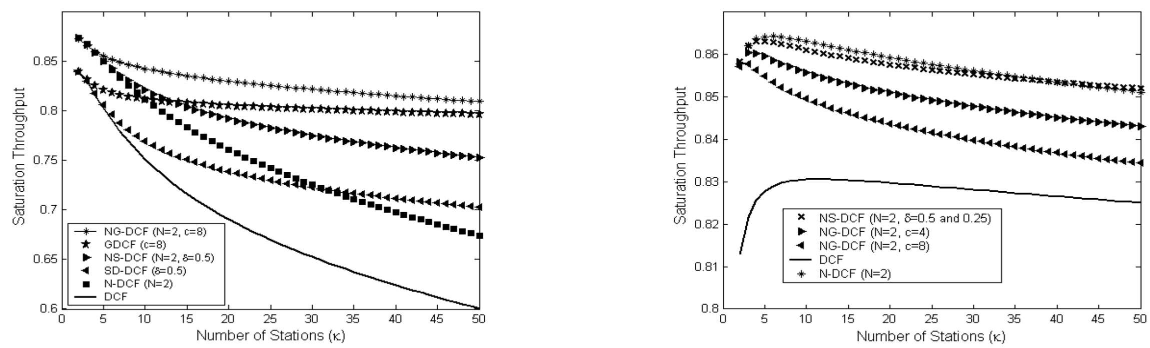
Since κ stations are transmitting on the channel, ζ can also be expressed in terms of ξ using Equation (9). We can obtain the two unknowns ζ and ξ by solving the Equations (88) and (9). After obtaining ζ, we can calculate the throughput under saturated conditions as shown in Section V-C.



(a) Basic access.

(b) Basic and RTS/CTS access.

Fig. 11. Comparison of analysis and simulation results for NG-DCF and NS-DCF protocols.



(a) Basic access.

(b) RTS/CTS access.

Fig. 12. Comparison of NG-DCF and NS-DCF protocols with GDCF, SD-DCF, N-DCF and DCF protocols.

B. NS-DCF Protocol

NS-DCF is based on the modification of N-DCF protocol. In NS-DCF the CW reset mechanism is replaced by the slow decrease CW reset mechanism used in SD-DCF protocol. The slow decrease in CW reduces the decline in the throughput when the network size becomes large. Therefore in NS-DCF, a maximum of N data packets are transmitted by a station if it is in state $(0, 0)$. From other transmission states $(r, 0)$ where $r \in [1, m]$, only a single data packet is transmitted. After the successful transmission of data packet(s), the CW is decremented by a factor δ. However when a collision is encountered, the CW size is doubled for the retransmission attempt. The value of the decrementing factor δ is chosen equal to 2^{-d} where d is an integer value greater than 0.

Each of the κ saturated and identical stations transmit on the channel with probability ζ. Therefore the collision probability can be expressed using Equation (9). The random process for NS-DCF is defined by the tuple (r, β) to represent the state of a NS-DCF station under steady state. The random process forms a markov chain as shown in Figure 10. In NS-DCF, the initial window size packet $k+1$ depends on the window size when packet k was successfully transmitted or dropped (after reaching maximum retransmission attempts). If packet k was successfully transmitted in r^{th} retransmission attempt then the size of the current CW size represented by ω_k is equal to ω_r. Therefore the initial CW size ω_{k+1} for packet $k+1$ is given by the following equation.

$$\omega_{k+1} = \max(\omega_0, \delta\omega_k) = \max(\omega_0, \omega_{r-d}) \tag{89}$$

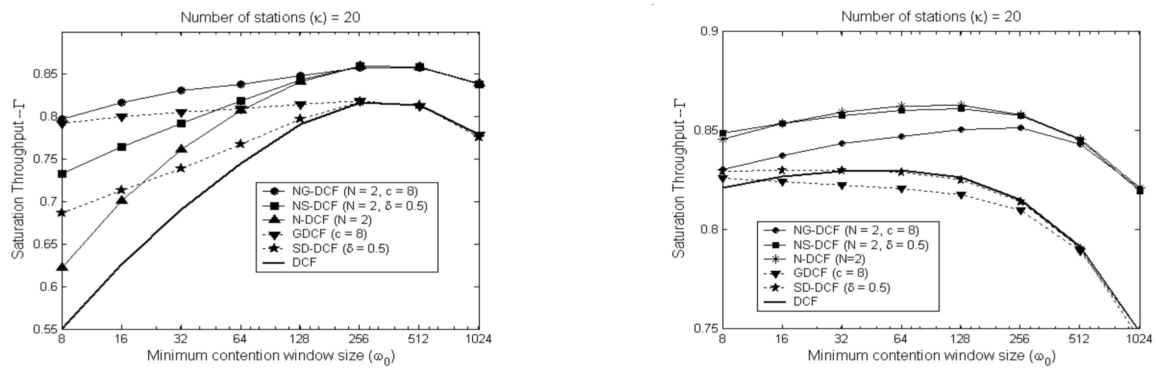
The probability of being in state (r, β) is given by the following equations.

$$\upsilon_{(r,\beta)} = \begin{cases} \frac{\omega_0-\beta}{\omega_0}\left[(1-\xi)\sum_{r'=0}^{d}\upsilon_{(r',0)}\right], \\ \qquad \text{for } r=0,\ \beta\in[0,\omega_0-1] \\ \frac{\omega_r-\beta}{\omega_r}\left[\xi\upsilon_{(r-1,0)}+(1-\xi)\upsilon_{(r+d,0)}\right], \\ \qquad \text{for } r\in[1,m-d-1],\ \beta\in[0,\omega_r-1] \\ \frac{\omega_{m-d}-\beta}{\omega_{m-d}}\left[\xi\upsilon_{(r-1,0)}+\upsilon_{(r+d,0)}\right], \\ \qquad \text{for } r=m-d,\ \beta\in[0,\omega_{m-d}-1] \\ \frac{\omega_r-\beta}{\omega_r}\left[\xi\upsilon_{(r-1,0)}\right], \\ \qquad \text{for } r\in[m-d+1,m],\ \beta\in[0,\omega_r-1] \end{cases} \tag{90}$$

The state probability $\upsilon_{(0,0)}$ can be found from Equation (86). The transmission probability ζ for NS-DCF station is the sum of the transmission state probabilities given by the following equation.

$$\zeta = \sum_{r=0}^{m}\upsilon_{(r,0)} \tag{91}$$

As mentioned in Section V-A, the unknown ζ can be obtained by solving Equations (91) and (9). In the following Section V-C we present expressions to calculate the total throughput under saturated conditions.



(a) Basic access.

(b) RTS/CTS access.

Fig. 13. Saturation Throughput versus minimum CW size (ω_0).

C. Throughput Calculation for NG-DCF and NS-DCF

In this section we present throughput expressions for that are valid for NG-DCF and NS-DCF protocols. The slot lengths for successful transmission (τ_s) and collision (τ_c) for basic and RTS/CTS access mechanisms are given by

$$\tau_s^{1,[basic]} = PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS$$

$$\tau_s^{N,[basic]} = \begin{cases} (N-1)(PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + SIFS) \\ + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \end{cases}$$

$$\tau_c^{[basic]} = PHY_{hdr} + MAC_{hdr} + E[P^*] + DIFS$$

$$\tau_s^{1,[rts]} = \begin{cases} RTS + SIFS + CTS + SIFS + \\ + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \end{cases}$$

$$\tau_s^{N,[rts]} = \begin{cases} RTS + SIFS + CTS + SIFS + \\ (N-1)(PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + SIFS) \\ + PHY_{hdr} + MAC_{hdr} + E[P] + SIFS + ACK + DIFS \end{cases}$$

$$\tau_c^{[rts]} = RTS + DIFS$$

If a station is listening to the channel without transmitting, it observes an idle slot length with probability equal to

$$P\{\tau = \tau_0\} = 1 - \zeta_{tx} \tag{92}$$

Therefore the average data transmitted in a slot length on the channel by any of the κ stations is given by

$$E[data] = \kappa\zeta\,(1-\zeta_{tx})\left[N\mu_0 + \mu_r\right]E[P] \tag{93}$$

And the average slot length observed by the channel ($E[\tau_{CH}]$) due to transmission for all the κ stations is given by the following equation.

$$E[\tau_{CH}] = (1-\zeta_{TX})\tau_0 + \zeta_{TX}\zeta_S\left[\mu_0\tau_s^N + \mu_r\tau_s^1\right] + \zeta_{TX}(1-\zeta_S)\tau_c \tag{94}$$

Therefore the expression for total throughput for any N (under saturated conditions) is given by the following equation.

$$\Gamma = \frac{\kappa\zeta(1-\zeta_{tx})\left[N\mu_0+\mu_r\right]E[P]}{E[\tau_{CH}]} \tag{95}$$

D. Performance Analysis of NG-DCF and NS-DCF

For both numerical analysis and simulation, we have used parameters from Table In Figure 11 we compare the analytical results with the simulations conducted in NS-2 network simulator. Figure 11(a) compares the performance of NG-DCF and NS-DCF protocols under basic access mechanism. Previously we have observed that GDCF was superior to SD-DCF because of the slower decrease in contention window size. Since NG-DCF adopts the CW decrease mechanism that is used in GDCF, its performance in basic access mechanism is better than NS-DCF. However from Figure 11(b) it is clear that NG-DCF performance in RTS/CTS mechanism is below NS-DCF performance. This because the overhead due to backoff process is considerable compared to the overhead due to RTS or CTS packet collision.

We now compare the performance of NG-DCF and NS-DCF protocols with N-DCF, GDCF, SD-DCF and DCF protocols under both basic and RTS/CTS access mechanisms. From Figure 12(a), it is evident that NG-DCF performs better than any other protocols under basic access mechanism. This is because it draws the advantages from both N-DCF and GDCF protocols. The throughput of NS-DCF protocol falls below GDCF when there are more than 15 saturated stations on the channel. However in both NG-DCF and NS-DCF the decline in throughput with increase in network size is reduced compared to N-DCF protocol. The comparison of the throughput performance under RTS/CTS access mechanism is shown in Figure 12(b). Since the performance of GDCF deteriorates in RTS/CTS mechanism, NG-DCF performance also falls below N-DCF protocol. However, NS-DCF protocol performance is very similar to the performance of N-DCF.

In previous scenarios, we found that NG-DCF performs better than other protocols in basic access mechanism. However, in RTS/CTS access mechanism, N-DCF is still the better protocol as can be seen from Figure 12(b). We now keep the number of stations (κ) on the channel fixed and vary the minimum contention window size (ω_0) and compare the performance of these protocols under saturated conditions. Figure 13 presents the performance of the protocols as ω_0 is varied from 8 to 1024. We first discuss the performance of basic access mechanism. From Figure 13(a), it is interesting to see that when ω_0 is equal to 64, N-DCF ($N = 2$) protocol performance is comparable to GDCF. Further its performance increases with increase in in the value of ω_0 while the performance of GDCF decreases. GDCF provides no improvement to DCF when ω_0 value is 256 and beyond. On the other hand N-DCF reaches the performance of NG-DCF when ω_0 is equal to 128. Now coming to RTS/CTS access mechanism, GDCF performance is below DCF when ω_0 is increased beyond 16. It is very clear from Figure 13(b) that both N-DCF and NS-DCF provide similar throughput performance in RTS/CTS access mechanism (actually N-DCF is slightly better compared to NS-DCF). NG-DCF performance fall short of N-DCF performance for any value of ω_0.

From comparisons, we find that there is no real advantage in modifying N-DCF for RTS/CTS access scheme. Therefore for 802.11 wireless stations, it is apt to use NG-DCF for basic access mechanism when the data packet size is smaller than a threshold value (RTS-threshold) and N-DCF for sending larger packets through RTS/CTS access mechanism or when there is hidden station problem.

VI. Conclusion

In this paper we have proposed an analytical model for our new N-DCF protocol which is valid for any arbitrary load conditions. We have verified our N-DCF model by simulating the protocol in NS-2 network simulator. N-DCF was proposed to improve the throughput performance of DCF protocol. Therefore, we have compared the performance of N-DCF with other DCF enhancements proposed recently in literature. It was found that only N-DCF provides improvement over DCF when RTS/CTS access mechanism is used to transmit data packets. To further improve the performance of N-DCF in basic access mechanism, we have proposed NG-DCF and NS-DCF. Results show that NG-DCF performs better in basic access mechanism while N-DCF is still the best in RTS/CTS access mechanism. Since both NG-DCF and N-DCF are based on modifications to DCF protocol, the stations implementing NG-DCF/N-DCF protocols are backward compatible and can coexist with other DCF stations on the channel. More importantly the proposed protocols are very simple for implementation and they do not require any modification to packet headers.

References

[1] M. Guizani and J. Asghar, "Status of IEEE 802.11 wireless lans: A survey," *Special Issue in Journal of Internet Technology on Design of Wireless LANs*, vol. 4, no. 3, pp. 135–146, July 2003.

[2] K. Pahlavan, T. H. Probert, and M. E. Chase, "Trends in local wireless networks," *IEEE Communications Magazine*, vol. 33, no. 3, pp. 88–95, March 1995.

[3] *International Standard [for] Information Technology - Telecommunications and information exchange between systems-Local and metropolitan area networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*, 1999th ed., IEEE 802.11 WG, Reference number ISO/IEC 8802-11: 1999 (E) IEEE STD 802.11, 1999.

[4] *IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, 1999. Amendment: Medium Access Control (MAC) Quality of Service (QoS) Enhancements*, 2003rd ed., IEEE P802.11e/D13.0, Draft Supplement to IEEE STD 802.11 - 1999, 2005.

[5] F. Cal, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Transactions on Networking*, vol. 8, no. 6, pp. 785–799, December 2000.

[6] Y. Kwon, Y. Fang, and H. Latchman, "Design of mac protocols with fast collision resolution for wireless local area networks," *IEEE Transactions on Wireless Communications*, vol. 3, no. 3, pp. 793–807, May 2004.

[7] C. Wang, B. Li, and L. Li, "A new collision resolution mechanism to enhance the performance of IEEE 802.11 DCF," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 4, pp. 1235–1246, July 2004.

[8] I. Aad, Q. Ni, C. Barakat, and T. Turletti, "Enhancing IEEE 802.11 MAC in congested environments," *Elsevier Computer Communications Journal*, vol. 28, no. 14, pp. 1605–1617, September 2005.

[9] D.-J. Deng and H.-C. Yen, "Quality-of-service provisioning system for multimedia transmission in IEEE 802.11 wireless LANs," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 6, pp. 1240–1252, June 2005.

[10] K. A. Meerja and A. Shami, "Improving the throughput performance of ieee 802.11 distributed coordination function," in *to appear in 23rd Queen's Biennial Symposium on Communications*.

[11] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, March 2000.

[12] G. R. Cantieni, Q. Ni, C. Barakat, and T. Turletti, "Performance analysis under finite load and improvements for multirate 802.11," *Elsevier Computer Communications Journal*, vol. 28, no. 10, pp. 1095–1109, June 2005.

[13] "http//www.isi.edu/nsnam/ns/," NS-2 Simulator.

[14] B. McFarland and M. Wong, "The family dynamics of 802.11," *ACM Queue*, vol. 1, no. 3, May 2003.

[15] R. O. LaMarie and A. Krishna, "Analysis of a wireless MAC protocol with client-server traffic and capture," *IEEE Journal on Selected Areas in Communications*, vol. 12, no. 8, pp. 1299–1313, October 1994.