Analysis of Enhanced Collision Avoidance Scheme Proposed for IEEE 802.11e-Enhanced Distributed Channel Access Protocol

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Abstract—In enhanced distributed channel access (EDCA) protocol, small contention window (CW) sizes are used for frequent channel access by high-priority traffic (such as voice). But these small CW sizes, which may be suboptimal for a given network scenario, can introduce more packet collisions, and thereby, reduce overall throughput. This paper proposes enhanced collision avoidance (ECA) scheme for AC_VO access category queues present in EDCA protocol. The proposed ECA scheme alleviates intensive collisions between AC_VO queues to improve voice throughput under the same suboptimal yet necessary (small size) CW restrictions. The proposed ECA scheme is studied in detail using Markov chain numerical analysis and simulations carried out in NS-2 network simulator. The performance of ECA scheme is compared with original (legacy) EDCA protocol in both voice and multimedia scenarios. Also mixed scenarios containing legacy EDCA and ECA stations are presented to study their coexistence. Comparisons reveal that ECA scheme improves voice throughput performance without seriously degrading the throughput of other traffic types.

Index Terms—Wireless LAN, IEEE 802.11e, QoS, EDCA, CSMA/CA, Markov chain, performance analysis.

1 Introduction

Wireless local area networks (WLANs) have now become a common means of access to the Internet for both multimedia and data services. Voice-over-Wi-Fi (Vo-Fi) or Voice-over-WLAN (VoWLAN), which is a direct extension of Voice-over-IP (VoIP), is an important and most appealing application for business environments.

Voice is scheduled through the highest priority AC_VO queue in 802.11e enhanced distributed channel access (EDCA) protocol. Many schemes are proposed in the past to improve throughput performance of AC_VO queue [1], [2], [3], [4], [5], [6]. Some of these schemes are energy inefficient as they send black bursts to gain channel access. Some schemes tend to further reduce the contention window (CW) size used for AC_VO queues to give priority to handover traffic. Moreover, these schemes do not realize that CW sizes for AC_VO queues are already small to provide any appreciable voice service. A brief overview of these schemes can be found in [7].

Most carrier sensing multiple access (CSMA) protocols have similar performance under low-load scenarios. Many variations (commonly referred as schemes) are proposed to improve a protocol's performance when contention level on the channel increases [9]. The efficiency of a protocol is expressed as the fraction of channel bandwidth used for actual data transmission (i.e., excluding media access control and physical layer headers), which is normally called "the channel utilization ratio" or "normalized throughput."

Both minimum and maximum CW sizes used in the backoff process have profound affect on throughput performance in IEEE 802.11 distributed media access control (MAC) protocol. Optimal CW sizes can deliver the "maximum" normalized throughput [10]. This maximum normalized throughput is also called the "(achievable) protocol capacity" [11].

Calì et al. [12] used p-persistent protocol for IEEE 802.11 WLAN in which a transmission generally spans several slot times.[1] The throughput performance of p-persistent protocol corresponds to the performance of standard 802.11 protocol, where both have the same average backoff time related by the expression "$E[CW] = 2/p - 1$." The value p_{min} that maximizes throughput is obtained by ensuring *the time wasted* in idle periods is equal to *the time spent* in collisions, a network operating condition which is previously identified by Gallager [13]. For this purpose, the number of stations in the network is estimated from channel observations. The resulting 802.11 protocol with average CW size "$E[CW]$" corresponding to "p_{min}" will be able to achieve throughput performance close to its protocol capacity.

Bononi et al. [11] proposed an alternative backoff scheme called asymptotically optimal backoff (AOB) scheme. In this scheme, a station upon completing its backoff time proceeds to transmit with a certain probability "P_T." Variable P_T is similar to p in p-persistent protocol. However, the main difference is that P_T is determined by the observation of slot utilization (SU) during the actual backoff process. For obtaining optimal performance, SU is bounded by an SU_{opt}

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1. In IEEE 802.11 standard, the idle channel time is slotted. A transmission may start only at the beginning of an *idle* slot time. Once a transmission is started, the duration of entire packet exchange sequence takes several *idle* slot times.

TABLE 1
Optimal Contention Window Values ($\mathrm{CW}^{\mathrm{opt}} = \bar{\kappa}\sqrt{2T}$), Where $\bar{\kappa}$ Is the Estimated Network Size

$\bar{\kappa} \rightarrow$	2	4	6	8	10	12	14	16	18	20
$\sqrt{2T} \downarrow$					$\leftarrow$	$\mathrm{CW}^{\mathrm{opt}}$	$\rightarrow$			
4	8	16	24	32	40	48	56	64	72	80
6	12	24	36	48	60	72	84	96	108	120
8	16	32	48	64	80	96	112	128	144	160
10	20	40	60	80	100	120	140	160	180	200

Packet transmission time "T" is measured in slot times.

value. The value for SU_{opt} is obtained based on the same network condition mentioned above for p-persistent protocol (i.e., average idle time and time wasted in collisions must be equal). AOB scheme throughput performance gets closer to protocol capacity as network size gets larger.

Bianchi et al. [14] proposed an adaptive contention window (ACW) mechanism. ACW mechanism uses a single CW size for backoff process. The CW size is varied adaptively based on the estimated number of stations in a WLAN to achieve protocol capacity. In particular, if $\bar{\kappa}$ is the estimated number of stations and all transmissions take T slot times, the optimal CW size is given by $\mathrm{CW}^{\mathrm{opt}} = \bar{\kappa}\sqrt{2T}$. The optimal CW sizes for which 802.11 protocol will be able to achieve its protocol capacity, for various estimated network sizes $\bar{\kappa}$ and transmission durations T in slot times, are given in Table 1.

It must be emphasized here that values used for T in Table 1 are very nominal. Still the CW sizes are very large. All mentioned protocols (schemes or mechanisms) namely ACW, p-persistent, and AOB must provide average backoff time corresponding to the optimal CW sizes ($\mathrm{CW}^{\mathrm{opt}}$) listed in Table 1 in order to achieve 802.11 protocol capacity.

Kwon et al. [15] proposed a fast collision resolution (FCR) scheme to improve 802.11 protocol capacity. To achieve this, FCR scheme suggests further increase in $\mathrm{CW}_{\max}$ to allow exponential backoff. In order to overcome fairness problem, FCR is combined with another fair scheduling algorithm. More importantly, due to large CW sizes in FCR, authors used regular 802.11 protocol (with small CW sizes) whenever there is voice traffic to transmit from AC_VO queue (see RT-FCR algorithm description in [15]).

Wang et al. [16] proposed a more gentle decrease in CW size upon successful transmissions. Particularly, in gentle decrease distributed coordination function (GDCF), a station halves its CW size only after experiencing "c" consecutive successful transmissions of its data packets. GDCF is a very simple scheme, which maintains high average CW size to improve (normalized) throughput performance.

All these schemes have high average backoff time. They are useful for data transmission (using basic access mechanism) in legacy 802.11 WLANs, where priority differentiation is not essential. To provide multimedia service, it is essential to have a priority-based MAC protocol. Using different CW ranges for different priority traffic is considered very effective for providing differentiated service. This is also adopted by IEEE 802.11e standard-based EDCA protocol. Higher priority queues "AC_VO" and "AC_VI" in EDCA use CW sizes, which are

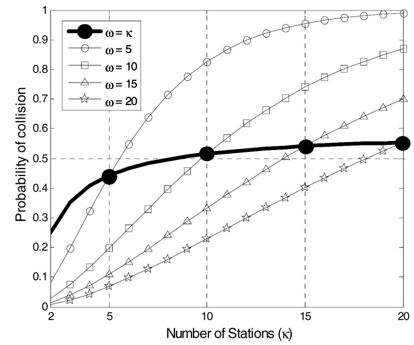


Fig. 1. Collision probability as a function of network size. Bianchi's model in [17] is used for the result.

much smaller compared to the optimal CW values summarized in Table 1.

When CW sizes are small, there will be loss in throughput as collisions increase significantly. The loss of throughput is higher in case of AC_VO access category due to its smaller CW sizes. To improve voice throughput and accommodate more stations to transmit voice, collision probability between AC_VO queues must be reduced. This can easily be achieved by just increasing the CW sizes used for AC_VO queue. But, to maintain priority and give voice transmissions frequent access to the channel, the CW sizes must be maintained small. Therefore, this work adheres to the CW sizes suggested in IEEE 802.11e draft. Instead, an enhanced collision avoidance (ECA) scheme is proposed for AC_VO queue to improve voice throughput. The main emphasis of ECA scheme is that, this scheme improves performance without altering the "CW based priority" differentiation used for AC_VO queue in EDCA protocol.

Precisely, ECA scheme for EDCA protocol (or ECA-EDCA scheme) modifies the contention process of AC_VO queue. It will be shown that ECA scheme is backward compatible, and ECA-enabled stations can coexist with legacy IEEE 802.11e standard QoS-enabled stations (QSTAs).

The rest of the paper is organized as follows: Section 2 gives detailed description of the proposed ECA scheme. Numerical analysis of ECA scheme is carried out in Section 3 under backlogged conditions. Results and discussions are presented in Section 4. Finally, conclusions are given in Section 5.

2 Enhanced Collision Avoidance Scheme for Voice Transmission

2.1 Motivation

The CW size should generally be large to reduce the number of collisions. For simple illustration, consider an ad hoc network scenario containing κ stations. Each station on the network maintains a single queue and has backlogged traffic to transmit. Assume that all stations are identical and draw values for their backoff counters from uniform distribution $[0, \omega]$. Initially, let the CW size ω be fixed equal to the network size (i.e., $\omega = \kappa$). The variation of collision probability as a function of network size is plotted as shown in Fig. 1 (by a thick solid line, displayed along with black dots to indicate line crossings). The

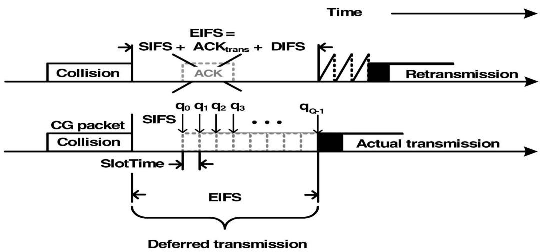


Fig. 2. Initiating transmission within EIFS deferral period.

collision probability is 0.2500 when $\kappa = 2$ and starts to increase with growing network size. As network size reaches 20 stations, the collision probability reaches 0.5541. It is also seen that collision probability is relatively low when $\kappa \leq 5$, even though the CW size is same as the number of competing stations.

Next, as shown in Fig. 1 (by a thin circled line), the CW is set to 5 for all the network sizes plotted. It can be seen that, as long as the network size is below 5, the collision probability drops below the previously obtained values. However, when the network size increases beyond 5, the collision probability raises sharply and reaches close to 1. Similar plots are obtained by setting CW size to 10, 15, and 20 (see Fig. 1).

Observations drawn from these results are: 1) the CW size should be at least equal to the number of competing stations on the network and 2) as long as the number of competing stations on the network is below 5, CW size equal to the number of competing stations (i.e., $\omega = \kappa$) is sufficient to maintain reasonably low collision probability.

Typical range of values used for CW size of AC_VO queue, $[\mathrm{CW}_{\min}, \mathrm{CW}_{\max}]$, in EDCA protocol are either [3,7] or [7,15]. The number of stations competing for channel access should be well below, for instance, "$\kappa_0 = 3$, or 7" ($<\mathrm{CW}_{\min}$) to have a low collision probability. Otherwise, there will be higher number of collisions as collision probability raises sharply. Assuming that the number of competing stations on channel are always maintained below κ_0, this number is very small.

When CW sizes are small, a better scheme is needed to resolve collisions among stations in WLAN. Assume that a small packet is sent initially to grab the channel for actual data transmission. The channel grab (CG) packet can be used to inform the duration of transmission to neighboring stations. Along with the complete duration of data packet transmission sequence, the CG packet can also reserve additional channel time equal to the extended interframe space (EIFS) duration. This EIFS duration will start immediately after the completion of CG packet transmission. A random slot time within this EIFS duration can be selected for data packet transmission. If CG packet collides, the neighboring stations will detect this collision and defer their channel access for EIFS time. Again, this EIFS time will be available for arbitration among the stations involved in collision.

The timing diagram illustrating this concept is shown in Fig. 2. In normal circumstances, when collisions occur, transmitting stations will not receive acknowledgments (ACKs). However, when neighboring stations detect a collision, they defer their transmission for EIFS time to allow a possible transmission of ACK packet on channel. This is done to protect transmissions from other neighboring

TABLE 2
E[κ]—Average Number of Stations Transmitting in a Randomly Chosen Slot

κ	E[κ]	κ	E[κ]	κ	E[κ]	κ	E[κ]	κ	E[κ]
1	1.0000	5	1.3615	9	1.6881	13	2.0382	17	2.4198
2	1.1050	6	1.4423	10	1.7728	14	2.1306	18	2.5200
3	1.1953	7	1.5233	11	1.8593	15	2.2251	19	2.6219
4	1.2797	8	1.6051	12	1.9477	16	2.3215	20	2.7256

The CW range is [7,15]. Backoff counter draws values from range $[0, \omega_r]$, where "ω_r" is CW size during rth of maximum "$m = 7$" retransmission attempts. Bianchi's model in [17] is used for the result.

stations that may wrongly conclude a successful data packet transmission as collision.

Stations with data packets for transmission will first grab the channel using their CG packets. When they send CG packet, they do not expect any acknowledgment. So whether or not a CG packet collision occurs, these stations will use EIFS time duration (available immediately after the end of CG packet transmission) for initiating transmission of their actual data packets. For this purpose, they use a collision avoidance counter q to arbitrate channel among stations that have sent CG packet. The deferred transmission during EIFS period is shown in Fig. 2, where stations select a slot corresponding to their generated value of q. If channel becomes busy before their selected slot, stations will initiate a defer process. During defer process, stations prepare for transmission of data packet by starting a new backoff process and reselecting a new value for their collision avoidance counter q. It is essential to note that the value of Q should always be such that the deferred transmission does not start after "EIFS."

For this, let ζ be the transmission probability of each station in the network of size κ. Probability that a transmission occurred in any slot is simply $p_t = 1 - (1 - \zeta)^\kappa$. Given that a transmission occurred in a randomly chosen slot, probability that n out of κ stations transmitted in that slot is given by $p(n) = \frac{1}{p_t}\binom{\kappa}{n}\zeta^n(1-\zeta)^{\kappa-n}$. Then the average number of stations transmitting in a randomly chosen slot is given by expression $\mathrm{E}[\kappa] = \sum_{n=1}^{\kappa} np(n)$. The average number E[$\kappa$] for various network sizes κ for CW range is [7,15] as given in Table 2. The summarized values in Table 2 suggest that a smaller collision avoidance window ($Q \leq 5$) is sufficient. A small value for Q also ensures that deferred transmission starts within in EIFS duration. For example, a collision avoidance window with range $[0, 2]$ is sufficient when collision between more than two stations is very rare. Then the effective collision probability will be 0.2500.

2.2 ECA Scheme

A QoS-enabled wireless station (QSTA) maintains four separate queues to serve different priority traffic as stipulated by IEEE 802.11e standard [18]. Each queue is known as an access category (AC) and uses different contention parameters summarized in Table 3. Voice transmission is scheduled through AC_VO queue, which receives the highest priority to transmit among all the four queues. For convenience, the AC_VO queue contention process of a QSTA is referred simply as voice station (VSTA) contention process and ECA as the proposed modification to voice stations contention process.

TABLE 3
EDCA Protocol Parameter Set

i	AC	AIFSN[AC]	CW $_{\text{min}} = \omega_{0,i}$	CW $_{\text{max}} = \omega_{max,i}$
0	AC_VO	2	$\left(\frac{\Omega_{min}+1}{4}\right)-1$	$\left(\frac{\Omega_{min}+1}{2}\right)-1$
1	AC_VI	2	$\left(\frac{\Omega_{min}+1}{2}\right)-1$	Ω_{min}
2	AC_BE	3	Ω_{min}	Ω_{max}
3	AC_BK	7	Ω_{min}	Ω_{max}

In ECA scheme, all VSTAs (i.e., AC_VO queues) send a CG packet on channel before transmitting their actual voice packet. The CG packet is used by VSTAs to reserve channel until the end of their transmission. The proposed frame format for CG packet is shown in Fig. 3. It is similar to any other control frame used in IEEE 802.11e standard protocol suite. The neighboring stations listening to the CG packet set their network allocation vector (NAV) according to the duration field in the CG packet. In the event of CG packet collision, stations set their NAV to extended interframe space (EIFS) duration similar to any packet collision.

After sending CG packet, a VSTA pauses for a very short and arbitrary duration to observe channel for any ongoing transmission. After making sure that channel is still idle during its short observation period, the VSTA then proceeds with transmission of its voice packet. In particular, each ECA capable VSTA maintains a collision avoidance counter q, which is an integer random variable uniformly distributed over the range $[0, Q-1]$. The value of q determines the observation period,[2] which is the interframe space "IFS" between CG packet and voice packet.

When a VSTA has voice packet to transmit, it performs a backoff process during which it also generates a value for its collision avoidance counter q. Upon completion of backoff process, it sends a CG packet on channel. After transmitting the CG packet, it observes channel for IFS time corresponding to the value of its counter q. If it observes a transmission during this observation period, it initiates a defer process. During defer process, it starts a new backoff process using CW size "ω_d," including generating a new value for its q. However, it will not change its CW variable as it will normally do upon a successful transmission or collision for its voice packet.

On the other hand, if there is no transmission during the observation interval, the VSTA will transmit its voice packet to the destination. The destination will acknowledge upon reception of the voice packet. Then the VSTA will reset its CW variable to the minimum CW size to schedule transmission of the next voice packet waiting in its queue. Whenever the transmitting VSTA does not receive positive ACK, it prepares retransmission of the voice packet by increasing the size of its CW variable to perform backoff process. Retransmission attempts are made until a maximum limit is reached after which the voice packet is dropped. Then, the next voice packet in the queue is scheduled for transmission. ECA scheme pseudocode is given in [7].

2. It is assumed that all ECA capable QSTAs are able to detect busy channel due to transmissions from (low-priority queues of) other neighboring QSTAs right after the end of their CG packet transmission. It is further assumed that these ECA capable QSTAs are able to transmit right after SIFS time following the end of their CG packet transmission (when $q = 0$) upon observing idle channel during the entire SIFS observation interval. In practice, a suitable minimum interframe space (MIFS) can be used instead of SIFS as "the minimum observation period" between CG and voice packets.

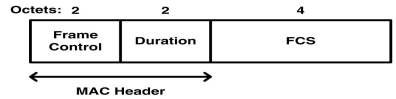


Fig. 3. CG packet format.

2.3 ECA-EDCA Scheme

Consider an ad hoc network with QSTAs that transmit from any of their four priority queues. Now assume that QSTA-A is sending voice and QSTA-B during that time is transmitting video packets as shown in Fig. 4. Suppose that at instant "t_0" given in Fig. 4, both QSTA-A and QSTA-B complete their backoff process and transmit CG and VIDEO packets, respectively. At the end of CG packet transmission, channel around QSTA-A will still be busy as VIDEO packet transmission continues. Channel will become idle at time "t_1" when VIDEO packet transmission is complete. EIFS duration starts after t_1, which may be used for deferred transmission, as shown through "Case 2" in Fig. 4.

On the other hand, QSTA-A can choose not to transmit during this particular EIFS duration (lying between t_1 and t_2 instants) and start defer process with CW size "ω_d." Backoff process of all QSTAs in network including QSTA-A and QSTA-B will resume at time instant "t_2." Assuming that at "t_3," QSTA-A finishes backoff (probably along with other QSTAs that are sending only voice, which are not shown in Fig. 4), it will send CG packet on channel. This is shown as "Case 1" in Fig. 4. As QSTA-A finds channel idle just after its transmission of CG packet (i.e., after "t_4" time instant), it will now initiate deferred transmission and schedule voice packet transmission depending on the value of its collision avoidance counter q. If only QSTA-A has transmitted CG packet at t_3, all the neighboring stations defer their channel access according to the duration information in CG packet. If more than one voice station transmits CG packet at t_3, neighboring stations defer their transmission for EIFS time starting after t_4. This time is used by voice stations to transmit their actual voice packets using collision avoidance counter q.

While "Case 2" is a more efficient way of scheduling voice packets, "Case 1" presents the worst limiting case with regard to the performance of ECA-EDCA scheme. So, "Case 1" is chosen for performance analysis of ECA-EDCA scheme.

3 Performance Analysis of ECA Scheme under Backlogged Conditions

A QoS-enabled wireless station (QSTA) has four queues or access categories (ACs). These ACs use their assigned set of CW ranges and arbitrary interframe spaces (AIFSs) to obtain their relative priority service. EDCA contention parameters are given in Table 3. To present improvement only due to ECA scheme, AIFS differentiation and transmission opportunity (TXOP) is not used in analysis. QSTAs are assumed to always have backlogged traffic.

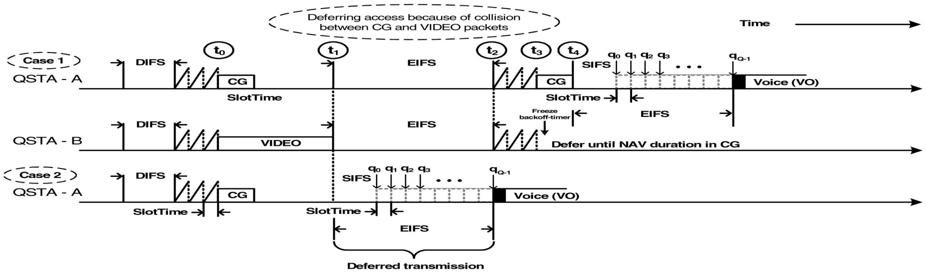


Fig. 4. Defer process in multimedia network scenario, where stations QSTA-A and QSTA-B transmit through all four queues.

Each queue of a QSTA is represented by a bidirectional Markov chain model. Evolution of Markov chain model for each queue uses similar approach proposed by Bianchi [17]. As AIFS priority differentiation is not used, all four queues observe the same sequence of slot times (namely idle slots, collisions, and successful transmissions) on the channel. More discussion on AIFS and the adopted time scales to address AIFS prioritization can be obtained from [19]. All nonzero transition probabilities in finite state Markov chain model for each queue in QSTA are independent. More description of queue-based Markov chain model is given in [20].

The main assumptions made in the analysis are:

1. all QSTAs are identical,
2. all QSTAs are able to listen to each other,
3. packets are lost only due to collisions,
4. constant and independent collision probability for each queue in QSTA irrespective of its retransmission attempt, and
5. in ECA scheme, each VSTA defers with a constant and independent defer probability after CG packet transmission.

A variable $i \in [0, 3]$ is used to represent the priority of all four queues. Let $i = 0$ denote the highest priority "AC_VO" queue and $i = 3$ denote the lowest priority "AC_BK" queue (see Table 3). The CW size during rth retransmission attempt by a priority i queue is given by the expression

$$\omega_{r,i} = \begin{cases} \min(2^r \omega_{0,i} \quad \omega_{max,i}) & r \in [0, m' - 1] \\ \min(2^{m'} \omega_{0,i} \quad \omega_{max,i}) & r \in [m', m], \end{cases} \tag{1}$$

where "$\omega_{0,i}$" and "$\omega_{max,i}$" are minimum and maximum CW sizes for priority i queue. Whereas $m' = 5$ and $m = 7$ are default parameter settings for limiting increment of CW size and retransmission attempts, respectively.

3.1 OV—Only Voice Scenario

Consider initially a single AC_VO queue transmitting voice. Other queues will be incorporated later to study ECA scheme performance under multimedia traffic scenarios.

Suppose that there are "κ_L" identical legacy EDCA stations, and similarly "κ_E" identical ECA-enabled stations. All stations are transmitting only voice. Then, the total number of VSTAs present in the network is "$\kappa = (\kappa_L + \kappa_E)$."

VSTA (i.e., single AC_VO queue) is described by a Markov chain model. A generalized Markov chain model can be used to represent both types of VSTAs present in the network. As mentioned, κ_E out of total κ VSTAs are ECA-enabled VSTAs (simply called E-VSTAs). E-VSTAs send CG packet when their backoff counters expire. They defer their voice packet transmission after sending their CG packet with a nonzero probability α_E. The remaining κ_L EDCA-based VSTAs (or legacy VSTAs, abbreviated as L-VSTAs) immediately transmit voice packet upon completion of their backoff process. In other words, L-VSTAs do not defer voice packet transmission when their backoff counters expire. Therefore, for L-VSTAs, defer probability α_L is always 0. Next, the probability of collision of a voice packet transmitted by an L-VSTA is denoted by ξ_L, and for E-VSTA, it is given by ξ_E.

Finite state Markov chain defined by tuple (r, β) completely describes a VSTA (i.e., L-VSTA or E-VSTA) under steady-state conditions. Retransmission variable "r" takes values in range $[0, 1, \ldots, m]$ and backoff counter "β" takes values from range $[0, \omega_r]$. The CW size ω_r is given by (1). Note that index i is dropped because of a single queue. Notation $r^{\{d\}}$ is used to indicate defer process initiated by a E-VSTA during its retransmission attempt r. When r is equal to $r^{\{d\}}, \beta$ takes values from range $[0, \omega_d]$. States reached by tuple (r, β) during defer process are called deferred states, denoted by $(r^{\{d\}}, \beta)$. This notation is useful to differentiate deferred states $(r^{\{d\}}, \beta)$ from normal states (r, β) that are reached by all VSTAs during their regular backoff process (i.e., when backoff is not initiated through defer process).

Let a variable "p" denote the protocol type, which is used to represent either ECA scheme (E) or legacy EDCA (L). Under steady-state network conditions, a VSTA remains in a normal state (r, β) with probability $\upsilon_p(r, \beta)$. The probability of being in a deferred state $(r^{\{d\}}, \beta)$ is given by $\upsilon_p(r^{\{d\}}, \beta)$. As defer probability α_L for L-VSTAs is always 0, deferred states are never reached in L-VSTAs.

Transition probabilities between different states of a VSTA, i.e., between any states (r, β) and $(r^{\{d\}}, \beta)$, can be expressed in terms of its collision probability (ξ_p), defer probability (α_p), retransmission CW size (ω_r), and defer CW size (ω_d). In a VSTA's Markov chain model, it is possible to express the probability of being in any state, whether a normal state (r, β) or a deferred state $(r^{\{d\}}, \beta)$, in terms of the probability of being in a particular state—say $\upsilon_p(0, 0)$:

$$\upsilon_p(r, \beta) = \left[\frac{\omega_r + 1 - \beta}{\omega_r + 1}\right] \left[\frac{\xi_p}{1 - \alpha_p}\right]^r \upsilon_p(0, 0), \tag{2}$$

$$\upsilon_p(r^{\{d\}}, \beta) = \left[\frac{\omega_d + 1 - \beta}{\omega_d + 1}\right] \left[\frac{\alpha_p}{1 - \alpha_p}\right] \left[\frac{\xi_p}{1 - \alpha_p}\right]^r \upsilon_p(0, 0), \tag{3}$$

where $p \in \{E, L\}$. The probability of being in state $(0,0)$ can be expressed entirely in terms of protocol parameters, collision probability (ξ_p), and defer probability (α_p):

$$\upsilon_p(0,0) = \frac{2}{(\omega_d + 2)\sum_{r=0}^{m}\left[\frac{\xi_p}{1-\alpha_p}\right]^r\left[\frac{\alpha_p}{1-\alpha_p} + \frac{\omega_r+2}{\omega_d+2}\right]}. \tag{4}$$

A VSTA transmits whenever its backoff counter β reaches 0. Then the probability that a VSTA transmits at the beginning of a generic slot time is equal to the sum of the probabilities of all states with $\beta = 0$. If "ζ_p" represents transmission probability of a VSTA, it can be evaluated as

$$\begin{aligned}\zeta_p &= \sum_{r=0}^{m}\left[\upsilon_p\left(r^{\{d\}}, 0\right) + \upsilon_p(r, 0)\right] \\ \Rightarrow \zeta_p &= \frac{1}{1-\alpha_p}\sum_{r=0}^{m}\left[\frac{\xi_p}{1-\alpha_p}\right]^r \upsilon_p(0,0).\end{aligned} \tag{5}$$

When there are only E-VSTAs (i.e., when $\kappa_L = 0$) present in the network, a successful transmission or collision is decided after an actual voice packet transmission. So, the probability of transmission $\zeta_E^{(onlyE)}$ is defined for this scenario. Given that a E-VSTA did not defer when its backoff expired, the probability of voice packet transmission $\zeta_E^{(onlyE)}$ is obtained as

$$\begin{aligned}\zeta_E^{(onlyE)}\big/_{1-\alpha_E} &= \sum_{r=0}^{m}\left[\upsilon_E\left(r^{\{d\}}, 0\right) + \upsilon_E(r, 0)\right] \\ \Rightarrow \zeta_E^{(onlyE)} &= \sum_{r=0}^{m}\left[\frac{\xi_E}{1-\alpha_E}\right]^r \upsilon_E(0,0).\end{aligned} \tag{6}$$

Equation (6) must be used instead of (5) in scenarios where there are only E-VSTAs in the network.

State and transmission probabilities for an L-VSTA can be obtained by substituting $\alpha_p = \alpha_L = 0$ in (2)-(5). There is another unknown $\xi_p = \xi_L$, which is needed before evaluating these probabilities. The probability of collision ξ_L for an L-VSTA in a randomly chosen slot time is nothing but the probability of a simultaneous transmission by at least one of the other $(\kappa - 1)$ neighboring VSTAs in that slot time:

$$\xi_L = 1 - (1-\zeta_L)^{\kappa_L - 1}(1-\zeta_E)^{\kappa_E}. \tag{7}$$

Similarly, to evaluate state and transmission probabilities of an E-VSTA, defer (α_E) and collision (ξ_E) probabilities are required. The defer probability for an E-VSTA is given by the expression (details in [20])

$$\begin{aligned}\alpha_E = 1 - (1-\zeta_L)^{\kappa_L}\Bigg\{&(1-\zeta_E)^{\kappa_E - 1} \\ &+ \frac{1}{Q}\sum_{z=0}^{Q-1}\sum_{n=1}^{\kappa_E - 1}\binom{\kappa_E - 1}{n}\left[\frac{Q-z}{Q}\right]^n \zeta_E^n (1-\zeta_E)^{\kappa_E - 1 - n}\Bigg\}.\end{aligned} \tag{8}$$

Defer probability in (8) is obtained by subtracting from "1" probability of all events under which E-VSTA will not defer. In limiting case, when $Q = 1$, defer probability α_E reduces to $1 - (1-\zeta_L)^{\kappa_L}$. This states that E-VSTA defers after sending CG packet if L-VSTAs transmit simultaneously. This is consistent with "Case 1" in Fig. 4, which describes the reaction of ECA scheme when CG packet collides with a non-CG packet on the channel.

Along with $Q = 1$, when there are no L-VSTAs, $\kappa_L = 0$ can be substituted in (8). Now E-VSTA will not defer as α_E is 0. It will transmit CG packet when its backoff counter expires. Following that, it will observe idle channel for short interframe space (SIFS) and then transmit voice packet. This is similar to a well-known "CTS-to-self" mechanism widely used in presence of different physical layers. E-VSTA is backward compatible as CG packet transmission can be switched off with $Q = 1$ to provide original L-VSTA operation.

The collision probability ξ_E for E-VSTA is given by the following expression (details in [20])

$$\xi_E = (1-\zeta_L)^{\kappa_L} \times \frac{1 - (1-\zeta_E)^{\kappa_E - 1}}{Q}. \tag{9}$$

Equation (9) states that voice packets of E-VSTAs cannot encounter collision when L-VSTAs transmit in the same slot time used for CG packet transmission (due to defer process). Given that "no" L-VSTAs transmit in a selected slot time, voice packet collision among E-VSTAs is reduced by the collision avoidance window factor "Q." Despite small CW sizes, ECA scheme effectively reduces collisions between voice packets transmitted through AC_VO queues.

Equations (1)-(9) are used to solve for all the unknown quantities. The following parameters are defined for throughput calculations.

Probability that at least one out of κ VSTAs transmit in a randomly chosen slot time, represented by P_{TX}^{OV}, is given by

$$P_{TX}^{OV} = 1 - (1-\zeta_L)^{\kappa_L}(1-\zeta_E)^{\kappa_E}. \tag{10}$$

Given that a transmission occurred, probability that an L-VSTA successfully transmitted its voice packet, P_S^L, is given by

$$P_S^L = (1-\zeta_E)^{\kappa_E} \times \frac{\kappa_L \zeta_L (1-\zeta_L)^{\kappa_L - 1}}{P_{TX}^{OV}}. \tag{11}$$

Probability of collision between two or more L-VSTAs, P_C^L, is then simply

$$P_C^L = \frac{(1-\zeta_E)^{\kappa_E}}{P_{TX}^{OV}}\sum_{n=2}^{\kappa_L}\binom{\kappa_L}{n}\zeta_L^n(1-\zeta_L)^{\kappa_L - n}. \tag{12}$$

Probability that an E-VSTA successfully transmits its voice packet P_S^E is conditional on q_z [20]

$$\begin{aligned}P_S^E\big/_{q_z} = \frac{(1-\zeta_L)^{\kappa_L}}{P_{TX}^{OV}}\Bigg\{&\kappa_E \zeta_E (1-\zeta_E)^{\kappa_E - 1} \\ &+ \sum_{n=2}^{\kappa_E}\kappa_E n \zeta_E^n\left[\frac{Q-z-1}{Q}\right]^{n-1}(1-\zeta_E)^{\kappa_E - n}\Bigg\},\end{aligned} \tag{13}$$

where "q_z" denotes collision avoidance counter "q" taking value "z" in range $[0, Q-1]$. The second term in (13) states that it is possible to have a successful transmission also when two or more E-VSTAs simultaneously transmit CG packet. Collision between voice packets transmitted by two or more E-VSTAs, P_C^E, is also conditional on q_z:

$$P_C^E/_{q_z} = \frac{(1-\zeta_L)^{\kappa_L}}{P_{TX}^{OV}} \times \sum_{n=2}^{\kappa_E} \binom{\kappa_E}{n} \zeta_E^n (1-\zeta_E)^{\kappa_E - n} \left[1 - \left(\frac{Q-z-1}{Q}\right)^{n-1}\right]. \tag{14}$$

Probability of collision between at least one E-VSTA and one L-VSTA, $P_C^{E,L}$, is given by

$$P_C^{E,L} = 1 - P_S^L - P_C^L - P_S^E - P_C^E. \tag{15}$$

Probability that the channel is idle because VSTAs choose not to transmit during a slot time P_{idle} is simply

$$P_{idle} = 1 - P_{TX}^{OV}. \tag{16}$$

Equations (11)-(16) provide the probabilities of observing all possible events on the channel. The length of a slot time depends on the type of event happening during that slot time. The following notations are used: $\diamond$ τ_0—length of idle slot time, $\diamond$ $\tau_s^E/_{q_z}$—average length of slot time for successful transmission by E-VSTA, for each q_z, $\diamond$ τ_s^L—average length of slot time for successful transmission by L-VSTA, $\diamond$ $\tau_c^E/_{q_z}$—average length of slot time for collision between two or more E-VSTAs, for each q_z, $\diamond$ τ_c^L—average length of slot time for collision between two or more L-VSTAs, $\diamond$ $\tau_c^{E,L}$—average length of slot time for collision between at least one L-VSTA and one E-VSTA. The idle slot time "τ_0" is a constant for a given physical layer. Average lengths of other slot times for basic access mechanism are

$$\tau_s^L = \frac{PHY_{hdr}}{R_{basic}} + \frac{(MAC_{hdr} + E[L])}{R_{data}} + \delta + SIFS + \frac{ACK}{R_{basic}} + \delta + DIFS, \tag{17}$$

$$\tau_c^L = \frac{PHY_{hdr}}{R_{basic}} + \frac{(MAC_{hdr} + E[L])}{R_{data}} + \delta + EIFS, \tag{18}$$

$$\tau_s^E/_{q_z} = \frac{(PHY_{hdr} + CG)}{R_{basic}} + \delta + QIFS_z + \frac{PHY_{hdr}}{R_{basic}} + \frac{(MAC_{hdr} + E[L])}{R_{data}} + \delta + SIFS + \frac{ACK}{R_{basic}} + \delta + DIFS, \tag{19}$$

$$\tau_c^E/_{q_z} = \frac{(PHY_{hdr} + CG)}{R_{basic}} + \delta + QIFS_z + \frac{PHY_{hdr}}{R_{basic}} + \frac{(MAC_{hdr} + E[L])}{R_{data}} + \delta + EIFS, \tag{20}$$

$$\tau_c^{E,L} = \tau_c^L, \text{(as ECA defers)}, \tag{21}$$

where $SIFS, DIFS$, and $EIFS$ denote short, distributed, and extended interframe spaces, respectively [18]. The size of CG packet is represented by CG, whereas PHY_{hdr} and MAC_{hdr} represent the length of the physical (PHY) and the media access control (MAC) layer headers. The average size of voice packet is $E[L]$, the size of acknowledgment packet is ACK. In general, R_{basic} and R_{data} represent basic and supported data rates on the channel. Propagation delay is δ. Interval $QIFS_z$ is "observation period" corresponding to q_z. Intervals $QIFS_z$ and $EIFS$ are given by

$$QIFS_z = SIFS + z \times \tau_0, \quad z \in [0, Q-1], \tag{22}$$

$$EIFS = SIFS + \frac{ACK}{R_{basic}} + DIFS. \tag{23}$$

Probabilities of observing these different slot times are

$$Pr\{\tau_0\} = P_{idle} = 1 - P_{TX}^{OV}, \tag{24}$$

$$Pr\{\tau_s^L\} = P_{TX}^{OV} P_S^L, \tag{25}$$

$$Pr\{\tau_c^L\} = P_{TX}^{OV} P_C^L, \tag{26}$$

$$Pr\{\tau_s^E/_{q_z}\} = P_{TX}^{OV} P_S^E/_{q_z} Pr\{q_z\}, \tag{27}$$

$$Pr\{\tau_c^E/_{q_z}\} = P_{TX}^{OV} P_C^E/_{q_z} Pr\{q_z\}, \tag{28}$$

$$Pr\{\tau_c^{E,L}\} = P_{TX}^{OV} P_C^{E,L}, \tag{29}$$

where $Pr\{q_z\} = 1/Q$. Average length of slot time "$E[\tau]$" is

$$E[\tau] = Pr\{\tau_0\}\tau_0 + Pr\{\tau_s^L\}\tau_s^L + Pr\{\tau_c^L\}\tau_c^L + \sum_{z=0}^{Q-1}\left[Pr\{\tau_s^E/_{q_z}\}\tau_s^E/_{q_z} + Pr\{\tau_c^E/_{q_z}\}\tau_c^E/_{q_z}\right] + Pr\{\tau_c^{E,L}\}\tau_c^{E,L}. \tag{30}$$

Total throughput of all "κ_L" L-VSTAs transmitting on the channel is given by

$$U^L = \frac{P_{TX}^{OV} P_S^L E[L]}{E[\tau]} \tag{31}$$

and the total throughput of all "κ_E" E-VSTAs on the channel is given by

$$U^E = \frac{1}{Q}\sum_{z=0}^{Q-1} \frac{P_{TX}^{OV} P_S^E/_{q_z} E[L]}{E[\tau]}. \tag{32}$$

3.2 MM—Multimedia Scenario

To study performance of ECA scheme in multimedia traffic scenarios, lower three priority queues "$i \in [1, 3]$" are included along with AC_VO queue. Throughput model for QoS-enabled station (QSTA) contains four priority queues ($P = 4$), where each queue is represented by a Markov chain model. Markov chain model for each queue can be described in the same way as discussed for AC_VO queue. For simplicity, network now contains all κ stations belonging either to legacy EDCA-based QSTAs (L-QSTAs, $p = L$ for AC_VO) or ECA-enabled QSTAs (E-QSTAs, $p = E$ for AC_VO). Throughput model presented is applicable to both original EDCA protocol and proposed ECA-EDCA scheme.

A priority i queue uses (1) to calculate CW size for its rth retransmission attempt. If α_i^* and ξ_i^* are defer and collision probabilities for priority i queue, then

$$\langle \alpha_i^*; \xi_i^* \rangle = \begin{cases} \langle \alpha_E^*; \xi_E^* \rangle & i = 0, \quad \text{and} \quad p = E, \\ \langle 0; \xi_i^* \rangle & i = 0, \quad \text{and} \quad p = L, \\ \langle 0; \xi_i^* \rangle & i \in [1, P-1], \end{cases} \tag{33}$$

that means, when throughput model represents legacy EDCA protocol, defer probability α_i^* is "zero" for all four queues. When the same model represents ECA-EDCA scheme, α_i^* is "zero" only for lower three priority queues. As defer and collision probabilities for AC_VO queue in ECA-EDCA scheme have to be calculated separately, they are denoted by α_E^* and ξ_E^* (instead of α_i^* and ξ_i^*).

Priority i queue in a QSTA is described by a tuple (r_i, β_i). Representing $\upsilon_i^*(r_i, \beta_i)$—as probability of a priority i queue being in state (r_i, β_i), and $\upsilon_i^*(r_i^{\{d\}}, \beta_i)$—as probability of a priority i queue being in a deferred state $(r_i^{\{d\}}, \beta_i)$,

$$\upsilon_i^*(r_i, \beta_i) = \left[\frac{\omega_{r,i} + 1 - \beta_i}{\omega_{r,i} + 1}\right] \left[\frac{\xi_i^*}{1 - \alpha_i^*}\right]^r \upsilon_i^*(0,0) \qquad \beta_i \in [0, \omega_{r,i}], \tag{34}$$

$$\upsilon_i^*(r_i^{\{d\}}, \beta_i) = \left[\frac{\omega_d + 1 - \beta_i}{\omega_d + 1}\right] \left[\frac{\alpha_i^*}{1 - \alpha_i^*}\right] \left[\frac{\xi_i^*}{1 - \alpha_i^*}\right]^r \upsilon_i^*(0,0) \qquad \beta_i \in [0, \omega_d], \tag{35}$$

where $i \in [0, P-1]$. The probability of priority i queue being in $(0,0)$ state—$\upsilon_i^*(0,0)$, is given by

$$\upsilon_i^*(0,0) = \frac{2}{(\omega_d + 2) \sum_{r=0}^{m} \left[\frac{\xi_i^*}{1-\alpha_i^*}\right]^r \left[\frac{\alpha_i^*}{1-\alpha_i^*} + \frac{\omega_{r,i}+2}{\omega_d+2}\right]}. \tag{36}$$

If ζ_i^* represents the transmission probability of a priority i queue, it can be obtained in the same way as (5):

$$\zeta_i^* = \frac{1}{1 - \alpha_i^*} \sum_{r=0}^{m} \left[\frac{\xi_i^*}{1 - \alpha_i^*}\right]^r \upsilon_i^*(0,0). \tag{37}$$

A virtual collision may occur when more than one queue within a QSTA selects a particular slot time for transmission. These collisions are resolved internally within a QSTA, where it allows a higher priority queue (involved in virtual collision) to transmit. Taking virtual collisions into account, effective transmission probability $\widehat{\zeta}_i$—probability of actual transmission by a priority i queue on the channel, is given by

$$\widehat{\zeta}_i = \zeta_i^* \prod_{j=0}^{i-1} (1 - \zeta_j^*). \tag{38}$$

A lower priority queue in a QSTA can transmit only when higher priority queues (of that QSTA) do not transmit in that particular slot time. The overall transmission probability of a QSTA, represented by $\widehat{\zeta}$, is the sum of effective transmission probabilities of all four priority queues:

$$\widehat{\zeta} = \bigcup_{i=0}^{P-1} \widehat{\zeta}_i = \sum_{i=0}^{P-1} \widehat{\zeta}_i. \tag{39}$$

State and transmission probabilities of each queue in a QSTA can be calculated if their defer and collision probabilities are known. The defer probability α_E^* and collision probability ξ_E^* for AC_VO queue in ECA-EDCA are calculated by taking into account the defer process in ECA scheme [20]:

$$\alpha_E^* = 1 - (1 - \widehat{\zeta})^{\kappa-1} - \frac{1}{Q} \sum_{z=0}^{Q-1} \sum_{n=1}^{\kappa-1} \binom{\kappa-1}{n} \left[\frac{Q-z}{Q}\right]^n \widehat{\zeta}_0^{\,n} (1 - \widehat{\zeta})^{\kappa-1-n}. \tag{40}$$

Looking at (40), $\alpha_E^* = 0$ when: $\diamond Q = 1$ and lower three priority queues are absent (i.e., when $\widehat{\zeta} = \widehat{\zeta}_0$), $\diamond \kappa = 1$. In all other situations, AC_VO queue in a QSTA defers with a nonzero probability α_E^*. The collision probability ξ_E^* for AC_VO queue in QSTA using ECA scheme is

$$\xi_E^* = \frac{1}{Q} \sum_{n=1}^{\kappa-1} \binom{\kappa-1}{n} \widehat{\zeta}_0^{\,n} (1 - \widehat{\zeta})^{\kappa-1-n}, \tag{41}$$

when $\widehat{\zeta} = \widehat{\zeta}_0$, probability of collision between AC_VO queues is reduced by the collision avoidance window factor Q.

Let a variable ξ^* represent the probability of collision due to simultaneous transmissions by two or more QSTAs. As QSTAs transmit with probability $\widehat{\zeta}$, the expression for ξ^* is simply

$$\xi^* = 1 - (1 - \widehat{\zeta})^{\kappa-1}. \tag{42}$$

Then the probability of collision experienced by a priority i queue, $p \neq E$ when $i = 0$, is given by

$$\xi_i^* = \xi^* \bigcup \left[\bigcup_{j=0}^{i-1} \zeta_j^*\right] = 1 - (1 - \xi^*) \prod_{j=0}^{i-1} (1 - \zeta_j^*), \qquad i \in [0, P-1] \quad \text{and} \quad p \neq E. \tag{43}$$

Equations (1), (33)-(43) are used to solve for all the unknown quantities for throughput calculations.

Let $\widehat{P}_{TX}^{MM}$ be the probability that at least one of κ QSTAs transmit during a randomly chosen slot:

$$\widehat{P}_{TX}^{MM} = 1 - (1 - \widehat{\zeta})^{\kappa}. \tag{44}$$

The probability that a priority i queue ($p \neq E$ when $i = 0$) successfully transmits in a chosen slot time—$\widehat{P}_S^i$, provided that a transmission has occurred, is given by

$$\widehat{P}_S^i = \frac{1}{\widehat{P}_{TX}^{MM}} \kappa \widehat{\zeta}_i (1 - \widehat{\zeta})^{\kappa-1}, \qquad i \in [0, P-1] \quad \text{and} \quad p \neq E. \tag{45}$$

Probability that AC_VO using ECA scheme will successfully transmit during a randomly chosen slot time $\widehat{P}_S^E$ is conditional on the value of collision avoidance counter q_z. The expression for $\widehat{P}_S^E/_{q_z}$ is given as (see details in [20])

$$\widehat{P}_S^E/_{q_z} = \frac{1}{\widehat{P}_{TX}^{MM}} \left\{ \kappa \widehat{\zeta}_0 (1 - \widehat{\zeta})^{\kappa-1} + \sum_{n=2}^{\kappa} \binom{\kappa}{n} \widehat{\zeta}_0^{\,n} \left[\frac{Q-z-1}{Q}\right]^{n-1} (1 - \widehat{\zeta})^{\kappa-n} \right\}. \tag{46}$$

The second term in (46) indicates that it is possible to have a successful transmission with collision avoidance counter q, even if two or more AC_VO queues (using ECA scheme) transmit a CG packet during the same slot time.

When a collision occurs on the channel, it ispossible that more than one priority i queue is involved in transmission. The length of a collision depends on various priority i queues involved in collision. The probability of collision between AC_VO queues using ECA scheme, $\widehat{P}_C^E$, is conditional on q_z. Other possible types of collisions are: $\diamond\widehat{P}_C^i$-probability of collision between priority i queues ($p \neq E$ when $i=0$), $\diamond\widehat{P}_C^{i,j}$—probability of collision between two different priority queues, $\diamond\widehat{P}_C^{i,j,k}$—probability of collision between three different priority queues, and $\diamond\widehat{P}_C^{i,j,k,l}$—probability of collision due to transmission from all four different priority queues. The probabilities of all these different collisions are given by

$$\widehat{P}_C^E/_{q_z} = \frac{1}{\widehat{P}_{TX}^{MM}} \sum_{n=2}^{\kappa} \binom{\kappa}{n} \widehat{\zeta}_0{}^n (1-\widehat{\zeta})^{\kappa-n} \times \left[1 - \left[\frac{Q-z-1}{Q}\right]^{n-1}\right], \tag{47}$$

$$\widehat{P}_C^i \frac{1}{\widehat{P}_{TX}^{MM}} \sum_{n=2}^{\kappa} = \binom{\kappa}{n} \widehat{\zeta}_i{}^n (1-\widehat{\zeta})^{\kappa-n}, \quad i \in [0, P-1] \quad \text{and} \quad p \neq E, \tag{48}$$

$$\widehat{P}_C^{i,j} = \frac{1}{\widehat{P}_{TX}^{MM}} \sum_{n=2}^{\kappa} \binom{\kappa}{n} \left[(\widehat{\zeta}_i + \widehat{\zeta}_j)^n - \widehat{\zeta}_i{}^n - \widehat{\zeta}_j{}^n\right] \times (1-\widehat{\zeta})^{\kappa-n}, \quad i \in [0, P-2], j \in [i+1, P-1], \tag{49}$$

$$\widehat{P}_C^{i,j,k} = \frac{1}{\widehat{P}_{TX}^{MM}} \sum_{n=3}^{\kappa} \binom{\kappa}{n} \begin{bmatrix} (\widehat{\zeta}_i + \widehat{\zeta}_j + \widehat{\zeta}_k)^n \\ -(\widehat{\zeta}_i + \widehat{\zeta}_j)^n \\ -(\widehat{\zeta}_j + \widehat{\zeta}_k)^n \\ -(\widehat{\zeta}_i + \widehat{\zeta}_k)^n \\ +\widehat{\zeta}_i{}^n + \widehat{\zeta}_j{}^n + \widehat{\zeta}_k{}^n \end{bmatrix} \times (1-\widehat{\zeta})^{\kappa-n}, \quad i \in [0, P-3], \; j \in [i+1, P-2], k \in [j+1, P-1], \tag{50}$$

$$\widehat{P}_C^{i,j,k,l} = \frac{1}{\widehat{P}_{TX}^{MM}} \sum_{n=4}^{\kappa} \binom{\kappa}{n} \begin{bmatrix} (\widehat{\zeta}_i + \widehat{\zeta}_j + \widehat{\zeta}_k + \widehat{\zeta}_l)^n \\ -(\widehat{\zeta}_i + \widehat{\zeta}_j + \widehat{\zeta}_k)^n \\ -(\widehat{\zeta}_i + \widehat{\zeta}_j + \widehat{\zeta}_l)^n \\ -(\widehat{\zeta}_i + \widehat{\zeta}_k + \widehat{\zeta}_l)^n \\ -(\widehat{\zeta}_j + \widehat{\zeta}_k + \widehat{\zeta}_l)^n \\ +(\widehat{\zeta}_i + \widehat{\zeta}_j)^n \\ +(\widehat{\zeta}_i + \widehat{\zeta}_k)^n \\ +(\widehat{\zeta}_i + \widehat{\zeta}_l)^n \\ +(\widehat{\zeta}_j + \widehat{\zeta}_k)^n \\ +(\widehat{\zeta}_j + \widehat{\zeta}_l)^n \\ +(\widehat{\zeta}_k + \widehat{\zeta}_l)^n \\ -\widehat{\zeta}_i{}^n - \widehat{\zeta}_j{}^n \\ -\widehat{\zeta}_k{}^n - \widehat{\zeta}_l{}^n \end{bmatrix} \times (1-\widehat{\zeta})^{\kappa-n}, i \in [0, P-4], j \in [i+1, P-3] \; k \in [j+1, P-2], l \in [k+1, P-1]. \tag{51}$$

Equations (49)-(51) also include AC_VO queues using ECA scheme. Probability of idle channel is given by

$$\widehat{P}_{idle} = 1 - \widehat{P}_{TX}^{MM}. \tag{52}$$

Equations (45)-(52) provide the probabilities of observing all possible events on the channel. Different average slot lengths can be observed corresponding to each type of event happening on the channel. The length of idle slot time τ_0 is constant. For basic access mechanism, average lengths of slot times for successful transmission ($\widehat{\tau}_s^E/_{q_z}$) by AC_VO queue using ECA scheme and collisions between (only) this type of queues ($\widehat{\tau}_c{}^E/_{q_z}$) are given by (19) and (20), respectively, where $E[L]$ is now changed to $E[L_i]$ for priority i labeling ($i=0$). Similarly, average lengths of slot times for successful transmission ($\widehat{\tau}_s{}^i$) by a priority i queue (except for AC_VO queue using ECA scheme) and collisions between (only) this type queues ($\widehat{\tau}_c{}^i$) are given by (17) and (18), respectively, where $E[L]$ is changed to $E[L_i]$ for priority i labeling ($i=0,1,2,3$ and $p \neq E$). Average slot length due to collision between two different queues is $\widehat{\tau}_c{}^{i,j} = \max(\widehat{\tau}_c{}^i, \widehat{\tau}_c{}^j)$, where $i \in [0, P-2]$ and $j \in [i+1, P-1]$. Average slot length due to collision among three different queues is $\widehat{\tau}_c{}^{i,j,k} = \max(\widehat{\tau}_c{}^i, \widehat{\tau}_c{}^j, \widehat{\tau}_c{}^k)$, where $i \in [0, P-3], j \in [i+1, P-2]$, and $k \in [j+1, P-1]$. Average slot length due to collision among all four different queues is $\widehat{\tau}_c{}^{i,j,k,l} = \max(\widehat{\tau}_c{}^i, \widehat{\tau}_c{}^j, \widehat{\tau}_c{}^k, \widehat{\tau}_c{}^l)$, where $i \in [0, P-4], j \in [i+1, P-3]$, $k \in [j+1, P-2]$, and $l \in [k+1, P-1]$. Probabilities of observing these slot lengths, where $q_z = z \in [0, Q-1]$, are

$$Pr\{\widehat{\tau}_0\} = 1 - \widehat{P}_{TX}^{MM}, \tag{53}$$

$$Pr\{\widehat{\tau}_s^E/_{q_z}\} = \widehat{P}_{TX}^{MM} \widehat{P}_S^E/_{q_z} Pr\{q_z\}, \tag{54}$$

$$Pr\{\widehat{\tau}_s{}^i\} = \widehat{P}_{TX}^{MM} \widehat{P}_S^i, \tag{55}$$

$$Pr\{\widehat{\tau}_c^E/_{q_z}\} = \widehat{P}_{TX}^{MM} \widehat{P}_C^E/_{q_z} Pr\{q_z\}, \tag{56}$$

$$Pr\{\widehat{\tau}_c{}^i\} = \widehat{P}_{TX}^{MM} \widehat{P}_C^i, \tag{57}$$

$$Pr\{\widehat{\tau}_c{}^{i,j}\} = \widehat{P}_{TX}^{MM} \widehat{P}_C^{i,j}, \tag{58}$$

$$Pr\{\widehat{\tau}_c{}^{i,j,k}\} = \widehat{P}_{TX}^{MM} \widehat{P}_C^{i,j,k}, \tag{59}$$

$$Pr\{\widehat{\tau}_c{}^{i,j,k,l}\} = \widehat{P}_{TX}^{MM} \widehat{P}_C^{i,j,k,l}, \tag{60}$$

where $Pr\{q_z\} = 1/Q$. Average length of slot time $\widehat{\tau}$ is

$$\begin{aligned} E[\widehat{\tau}]^{(L)} = {} & Pr\{\widehat{\tau}_0\}\widehat{\tau}_0 \\ & + \sum_i \left[Pr\{\widehat{\tau}_s{}^i\}\widehat{\tau}_s{}^i + Pr\{\widehat{\tau}_c{}^i\}\widehat{\tau}_c{}^i\right] + \sum_{i,j} Pr\{\widehat{\tau}_c{}^{i,j}\}\widehat{\tau}_c{}^{i,j} \\ & + \sum_{i,j,k} Pr\{\widehat{\tau}_c{}^{i,j,k}\}\widehat{\tau}_c{}^{i,j,k} + \sum_{i,j,k,l} Pr\{\widehat{\tau}_c{}^{i,j,k,l}\}\widehat{\tau}_c{}^{i,j,k,l}, \end{aligned} \tag{61}$$

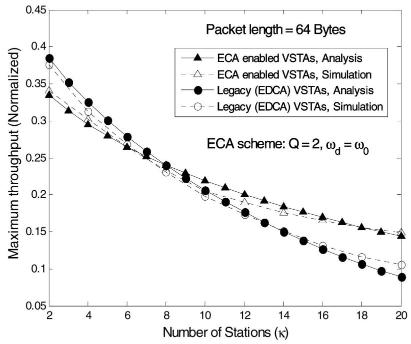


Fig. 5. ECA and EDCA throughput performance.

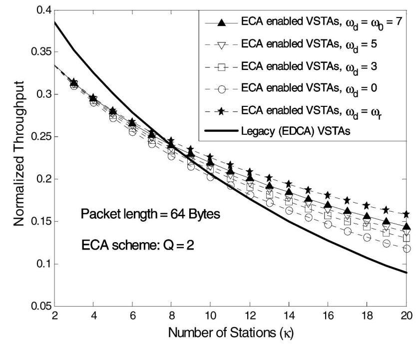


Fig. 6. Effect of defer process CW size "ω_d" in ECA scheme.

$$
\begin{aligned}
E[\widehat{\tau}]^{(E)} &= Pr\{\widehat{\tau}_0\}\widehat{\tau}_0 \\
&\quad + \sum_z \left[Pr\{\tau_s^E/_{q_z}\}\tau_s^E/_{q_z} + Pr\{\tau_c^E/_{q_z}\}\tau_c^E/_{q_z} \right] \\
&\quad + \sum_{i\neq 0} \left[Pr\{\widehat{\tau}_s^i\}\widehat{\tau}_s^i + Pr\{\widehat{\tau}_c^i\}\widehat{\tau}_c^i \right] + \sum_{i,j} Pr\{\widehat{\tau}_c^{i,j}\}\widehat{\tau}_c^{i,j} \\
&\quad + \sum_{i,j,k} Pr\{\widehat{\tau}_c^{i,j,k}\}\widehat{\tau}_c^{i,j,k} + \sum_{i,j,k,l} Pr\{\widehat{\tau}_c^{i,j,k,l}\}\widehat{\tau}_c^{i,j,k,l}.
\end{aligned} \tag{62}
$$

Equation (61) gives average length of slot $\widehat{\tau}$ when all QSTAs in the network use legacy EDCA protocol. Equation (62) gives the average length of slot $\widehat{\tau}$ when all QSTAs in the network use ECA-EDCA scheme.

Total throughput for each access category (i.e., priority i) queue in legacy EDCA protocol is obtained as

$$
\widehat{U}_i^{(L)} = \frac{\widehat{P}_{TX}^{MM}\widehat{P}_S^i E[L_i]}{E[\widehat{\tau}]^{(L)}} \quad i \in [0, P-1] \tag{63}
$$

and total throughput for each access category (i.e., priority i) queue in ECA-EDCA scheme is obtained as

$$
\widehat{U}_i^{(E)} = \begin{cases} \dfrac{1}{Q}\displaystyle\sum_{z=0}^{Q-1} \dfrac{\widehat{P}_{TX}^{MM}\widehat{P}_S^E/_{q_z} E[L_i]}{E[\widehat{\tau}]^{(E)}} & i = 0, \\ \dfrac{\widehat{P}_{TX}^{MM}\widehat{P}_S^i E[L_i]}{E[\widehat{\tau}]^{(E)}} & i \in [1, P-1]. \end{cases} \tag{64}
$$

4 Results and Discussion

Performance evaluation of ECA scheme is initially studied under voice scenarios, where all stations on the network send only voice traffic. Performance under mixed scenarios, where both E-VSTAs and L-VSTAs share a channel, is studied to verify coexistence. For comparison, EDCA-bound is defined, which is the maximum achievable throughput for AC_VO queue parameters. The channel bandwidth is initially assumed to be equal to 1 megabits per second (Mbps), in order to evaluate protocol efficiency as suggested in [12]. Protocol efficiency or normalized throughput is the fraction of total channel bandwidth used for actual data transmission. ECA performance is then studied under multimedia scenario, where all four access categories have backlogged traffic to transmit. Finally, performance in a low-load multimedia scenario is presented using simulations. All simulations presented in this work are performed in NS-2 network simulator [21]. All parameters used in the presented results are summarized in the end in the Appendix.

4.1 Only Voice Scenario

Consider two networks, Network-L and Network-E. These networks are identical to each other including the number of VSTAs, except Network-L contains only L-VSTAs and Network-E contains E-VSTAs. The throughput model presented in Section 3.1 analyzes these two networks. In Network-L (Network-E), the number of E-VSTAs (L-VSTAs) is "zero"—i.e., κ_E $(\kappa_L) = 0$. The value for Ω_{min} is selected as 31. The corresponding $\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$ sizes for AC_VO queue are $\omega_0 = 7$ and $\omega_{max} = 15$ (refer to Table 3). Total obtainable throughput in Network-L and Network-E is given by (31) and (32), respectively.

All VSTAs have backlogged traffic and transmit 64 bytes voice packets. ECA scheme initially uses a minimum possible value for collision avoidance window "Q" to perform defer process, which is 2. The CW size used for defer process "ω_d" is set equal to ω_0. Normalized throughput performance in these two network scenarios (Network-L and Network-E) is given in Fig. 5. It can be seen that when CW size for a network (of size κ) becomes smaller, ECA scheme provides improvement in throughput performance. It is seen that ECA performs better when network size increases beyond 8 VSTAs. This is also verified using NS-2 simulations as shown in Fig. 5. ECA reduces the effective collision probability when network contains large number of competing VSTAs.

Next, different values are used for ω_d in ECA scheme to see its effect on throughput performance. Same network scenarios are used as VSTAs send 64 bytes voice packets. Fig. 6 shows that as ω_d is reduced below ω_0, throughput performance of ECA scheme decreases. This is because more VSTAs are clustered around after minimum DIFS waiting period during defer process. This is particularly the case when ω_d is equal to 0. When $\omega_d = 0$, VSTAs in defer process transmit CG packet immediately when channel is idle for DIFS time. Throughput improves when the size of ω_d is set equal to the CW size corresponding to the backoff stage, i.e., equal to ω_r. However, for all values of ω_d, ECA scheme provides better throughput performance than legacy EDCA protocol for large networks.

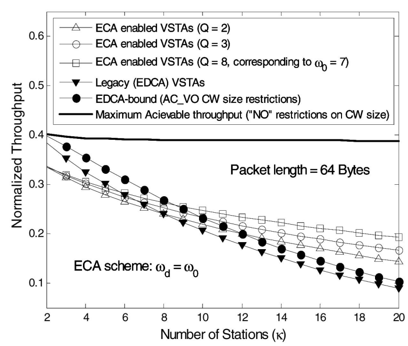


Fig. 7. Effect of collision avoidance window "Q" in ECA scheme.

In rest of the results presented, ECA parameter "ω_d" is set equal to "ω_0." Fig. 7 is plotted to verify the effect of collision avoidance window Q on ECA performance. The same network scenarios namely Network-L and Network-E are compared. As the value of Q increases, ECA throughput performance improves. The largest possible value of Q (Q_{max}) should ensure that deferred transmission starts within $EIFS$ duration. This allows contention to remain between VSTAs that have transmitted CG packet. The performance of ECA scheme for $Q = 3$ is "in between" the performances when ECA scheme uses the smallest possible value $Q = 2$ and a very large value $Q = 8$. When collisions among three or more VSTAs are less likely, $Q = 3$ is an appropriate value for collision avoidance window. Performance of ECA scheme is compared with "EDCA-bound," which is the maximum throughput that can be obtained by EDCA protocol under "AC_VO queue" CW size restrictions. EDCA-bound is well below the maximum achievable throughput when there are no CW size restrictions for backoff process as shown in Fig. 7. ECA scheme performs well above the EDCA-bound when network size gets larger than 8 VSTAs. For example, when $\kappa = 20$, ECA provides relative improvement in percentages equal to $38.86 (Q = 2)$, $61.04 (Q = 3)$, and $86.21 (Q = 8)$ corresponding to EDCA-bound.

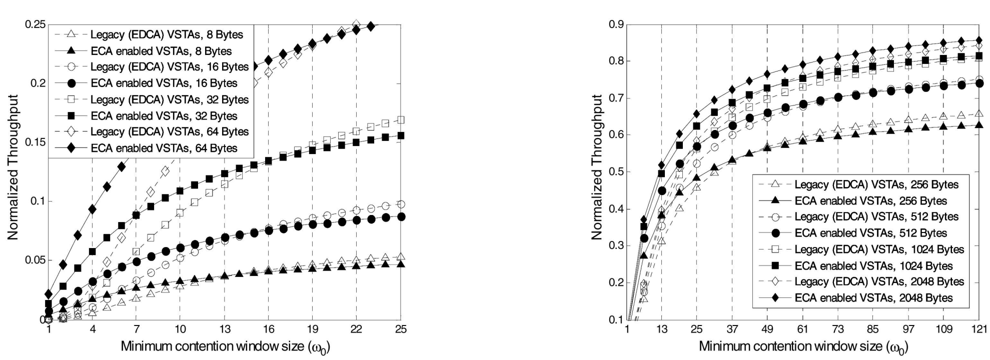
From now on, unless mentioned otherwise, consider that default ECA parameters $Q = 2$ and $\omega_d = \omega_0$ are used in all presented results. It is generally seen that ECA scheme provides performance improvement when CW range becomes inadequate for a network size. For example, consider performance when the network size is $\kappa = 20$ and voice packet length is 64 bytes. ECA scheme performed better than original EDCA protocol for AC_VO queue CW range [7,15]. In order to study different CW ranges over which ECA scheme provides improvement, the sizes of Network-L and Network-E are set to $\kappa = 20$ VSTAs. The maximum contention window size is set to $\omega_{max} = 2 \times (\omega_0 + 1) - 1$. Then ω_0 is varied to study throughput performance in these network scenarios, as shown in Figs. 8a and 8b. As expected, for smaller CW ranges, ECA performed better compared to original EDCA protocol irrespective of the packet length. When CW range increases, there is no need for ECA scheme. More interestingly, the range of supported CW values over which ECA performs better increases proportionally to the transmitted packet length. The supported CW ranges exceed the normally used CW ranges for AC_VO queue, for all possible voice packet sizes. Also, ECA scheme-supported CW ranges exceed commonly used CW ranges for AC_VI queues, which transmit video in EDCA protocol. For example, consider a 256-bytes video packet. ECA performance is better than EDCA protocol, for AC_VI queue CW range $[15, 31]$ corresponding to $\Omega_{min} = 31$ in Table 3.

4.2 Mixed Scenario

Performance of ECA scheme in a mixed network scenario (or a "mixed environment," which contains "κ_E" E-VSTAs and "κ_L" L-VSTAs) is presented to study coexistence. VSTAs send voice packets of constant length equal to 64 bytes. The throughput model presented in Section 3.1 is used to obtain performance results.

Consider that there are equal number of E-VSTAs and L-VSTAs (i.e., $\kappa_E = \kappa_L$) in a network. Normalized throughput obtained per station as a function of κ_E (or κ_L) is shown in Fig. 9a. For comparison, throughput that can be obtained in their respective "pure environments" (i.e., when the other VSTAs in the mixed network scenario are replaced by their likes) is also presented. E-VSTAs in mixed environment, at all times, achieve better throughput performance compared to L-VSTAs. This is seen in all other scenarios, studied but not presented due to space limitations. In this particular scenario, each E-STA benefits close to 30 percent more throughput relative to L-VSTA throughput.

As another example, performance of an E-VTSA and an L-VSTA in an unsymmetrical network scenario is presented in Fig. 9b. The number of E-VSTAs in the network is fixed



(a) (b)

Fig. 8. Effect of CW range on ECA performance ($Q = 2, \omega_d = \omega_0$). (a) Throughput performance for voice packets. (b) Throughput performance for video or data packets.

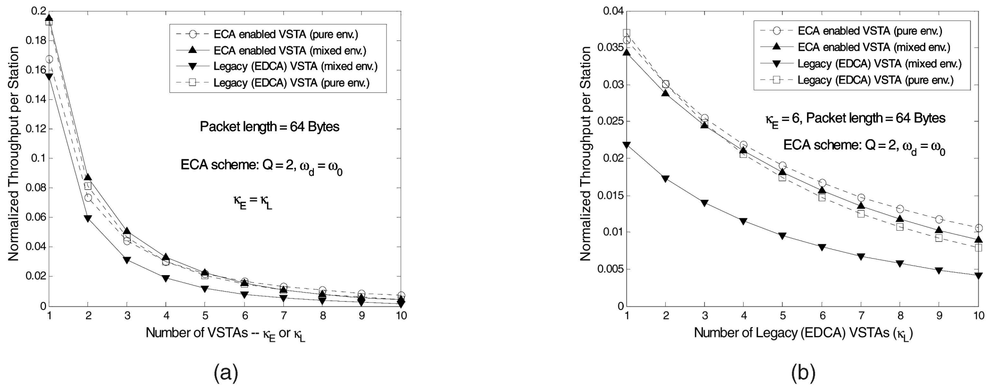


Fig. 9. Performance of ECA scheme under mixed environment. (a) E-VSTAs and L-VSTAs are equal. (b) E-VSTAs and L-VSTAs are unequal.

($\kappa_E = 6$). The throughput performance is studied by varying only the number of L-VSTAs, κ_L from 1 to 10. The throughput obtained by an E-VSTA and an L-VSTA under this mixed environment is shown in Fig. 9b. Performance of these VSTAs under their respective pure environments is also presented for comparison. As seen in previous mixed environment, at all times, performance of E-VSTA is always better than L-VSTA. The performance of an L-VSTA falls below its performance in its pure environment. The throughput performance of an E-VSTA in this mixed environment is very close and in between the performances in pure environments presented for both types of VSTAs.

From performances in the presented mixed environments, it is seen that E-VSTAs dominate in transmissions. The channel is now unfairly allocated. This can be addressed by assigning appropriate transmission opportunity (TXOP), a transmission scheme commonly used in EDCA protocol [18]. Basic idea is that a VSTA can send N number of voice packets (instead of just sending a single voice packet) for each acquired successful transmission opportunity. By limiting E-VSTAs and L-VSTAs to transmit N_E and N_L voice packets, respectively, it can be ensured that all VSTAs obtain equal share of the channel time.

Fairness performance is presented using the unsymmetrical network scenario discussed before. The mixed environment contains fixed number of E-VSTAs ($\kappa_E = 6$). The number of L-VSTAs, κ_L, is varied from 1 to 10. For each set $\{\kappa_E, \kappa_L\}$, it is possible to obtain approximate (but not unique) values N_E and N_L (summarized in Table 4), which provide relatively fair channel allocation. The values N_E and N_L corresponding to set $\{\kappa_E, \kappa_L\}$ do not depend on packet length (assuming that both types of VSTAs are sending voice packets of same size). The throughput performance of E-VSTA and L-VSTA for 64 and 10 bytes voice packet lengths, using their values for N given in Table 4, is presented in Figs. 10a and 10b, respectively. Both E-VSTA and L-VSTA achieve similar throughput performance. E-VSTAs send minimum of six voice packets in their acquired successful transmission opportunities. L-VSTAs send roughly double the number, at least 12 voice packets during their acquired successful transmission attempts. For comparison, their performance in pure environments when they send $N = 6$ voice packets (also $N = 12$ for L-VSTAs) is presented. Performance in mixed environment is maintained at what is achievable when they send $N = 6$ voice packets in their pure environments.

If the number of VSTAs κ_E and κ_L in a network can be estimated, it is easy to use a table similar to Table 4 to obtain corresponding values for N_E and N_L to maintain fairness.

4.3 Backlogged Multimedia Scenario

To evaluate the performance of ECA under multimedia traffic scenario, an ad hoc network is created with κ stations. The queues use CW sizes corresponding to $\Omega_{min} = 31$ and $\Omega_{max} = 1{,}023$ (use Table 3 for obtaining actual CW sizes for all four queues). The data packet lengths used are: "$L_0 = 64$ bytes" for AC_VO, "$L_1 = 1{,}000$ bytes" for AC_VI, "$L_2 = 1{,}200$ bytes" for AC_BE, and "$L_3 = 1{,}400$ bytes" for AC_BK queues. ECA scheme for AC_VO uses $Q = 2$ to assign values in the range $[0, Q-1]$ for collision avoidance counter q. All low-priority queues (AC_VI, AC_BE, and AC_BK) use basic access mechanism for transmission of their data packets. Throughput performance of all four access categories is shown in Fig. 11. The throughput model presented in Section 3.2 is used to obtain numerical results.

The total throughput on channel due to AC_VO queues is shown in Fig. 11a. It can be seen that ECA scheme improves voice throughput performance even when "Case 1" in Fig. 4 is used. The throughput performance of AC_VI is shown in Fig. 11b. ECA scheme presents additional overhead due to CG packet and deferred transmissions. Because of this, throughput of AC_VI access category decreases. Similar trend is seen for other two low-priority queues AC_BE and AC_BK as shown in Figs. 11c and 11d, respectively. It must be noted that in real network scenarios, AC_VO queues will only offer very light load on channel. Because of this, there will be little degradation in lot priority throughput.

TABLE 4
N for Fairness $\kappa_E = 6$, ECA Scheme $Q = 2, \omega_d = \omega_0$

κ_L	1	2	3	4	5	6	7	8	9	10
N_L	12	13	13	13	13	12	12	14	13	14
N_E	8	8	7	7	7	6	6	7	6	7

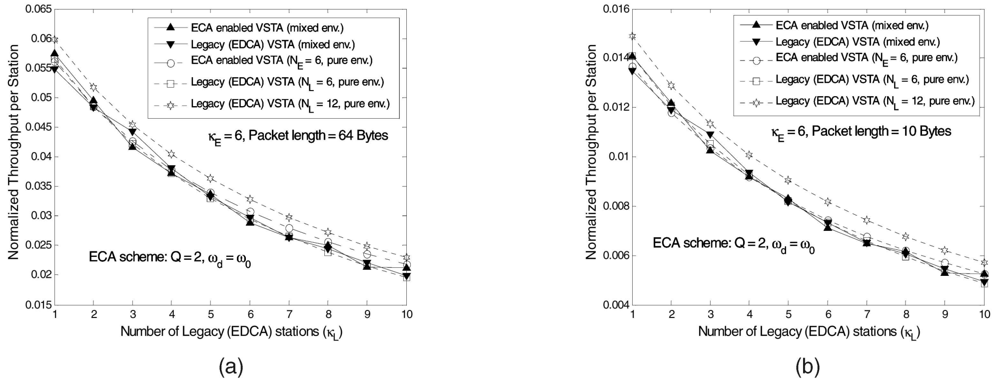


Fig. 10. Fairness under mixed environment. (a) Voice packet size—64 bytes. (b) Voice packet size—10 bytes.

4.4 Low-Load Multimedia Scenario

Performance of ECA scheme under low-load conditions is presented using NS-2 simulations. Control packets (CG, RTS, CTS, ACK) are now sent at 6 Mbps. Data (voice, video, data, and background) packets are sent at 54 Mbps, as supported by IEEE 802.11a (see Appendix A). Also TXOP and AIFS priority differentiations are used. Parameters $\Omega_{min} = 31$ and $\Omega_{max} = 1{,}023$ are used to obtain CW sizes for four access categories as given in Table 3.

Each QSTA in network transmits four types of traffic namely voice, video, data, and background to its adjacent node. Codec parameters for G. 711 are used for voice. The video (packet size, $\mathrm{P} = 1{,}280$ Bytes; bit rate, $\mathrm{R} = 640$ Kbps), data ($\mathrm{P} = 1{,}600$ Bytes; $\mathrm{R} = 1{,}024$ Kbps), and background ($\mathrm{P} = 1{,}000$ Bytes; $\mathrm{R} = 800$ Kbps) are also constant bit rate UDP sources. In this scenario, only basic access mechanism is applied for voice packets in EDCA protocol. The other traffic categories use both basic and RTS/CTS access mechanisms in both EDCA protocol and ECA-EDCA scheme. The throughput performance of all the different traffic is shown in Fig. 12. It can be seen that the performance of video, data, and background traffic in basic access mechanism is better than RTS/CTS access mechanism as RTS and CTS packets are sent at a lower transmission rate. Comparing the performance of ECA-EDCA and EDCA, it can readily be concluded that the performance degradation of other traffics due to ECA-EDCA scheme is minimal. However, the performance of

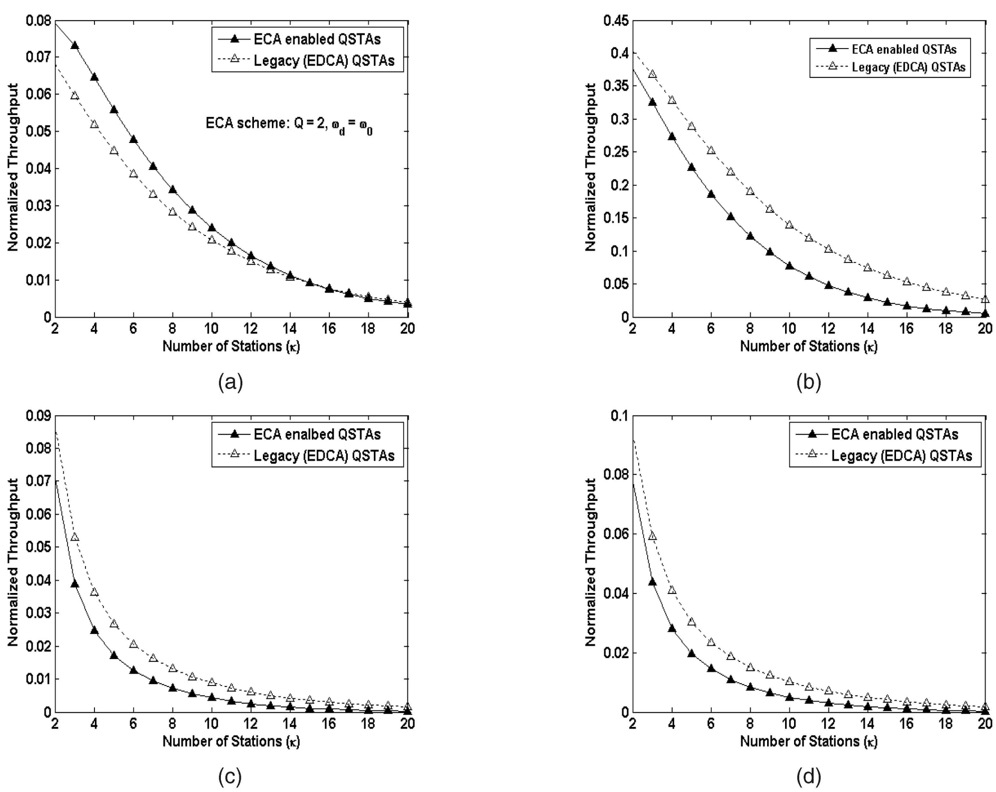
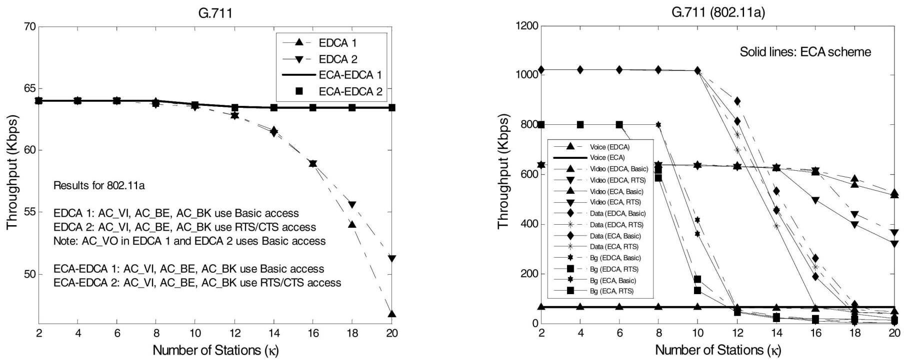


Fig. 11. Throughput performance of AC_VO, AC_VI, AC_BE, and AC_BK access categories. Packet lengths in bytes: $[L_0\ L_1\ L_2\ L_3] = [64\ 1{,}000\ 1{,}200\ 1{,}400]$. (a) Throughput of all AC_VO queues. (b) Throughput of all AC_VI queues. (c) Throughput of all AC_BE queues. (d) Throughput of all AC_BK queues.



(a) (b)

Fig. 12. Multimedia throughput performance in ad hoc network scenario. (a) Voice throughput (G. 711 codec for voice). (b) Throughput of all traffic (G. 711 codec for voice).

voice in ECA-EDCA is much better compared to EDCA. Voice throughput remains almost constant as the network size increases under ECA-EDCA scheme, while it deteriorates with EDCA protocol as the network size becomes larger. Additional performance results for delay and jitter are given in [7].

5 Conclusion

Backoff parameters, especially CW sizes, used for collision avoidance have profound effect on the performance of a CSMA/CA protocol. Optimal CW sizes are critical to ensure peak performance so that the total network throughput reaches the protocol capacity. However, IEEE 802.11e standard-based "enhanced distributed channel access (EDCA)" protocol uses different CW sizes for different ACs to provide priority differentiation. Though away from optimal values, the use of small CW sizes for high-priority traffic is very essential and cannot be avoided for frequent channel access. On the other hand, an obvious drawback of using small CW sizes in EDCA protocol is the increase in data packet loss due to large number of collisions. This results in a lower throughput performance for high-priority traffic such as voice. Unfortunately, no work in the past literature has addressed this problem in EDCA protocol.

This paper proposed an ECA scheme that alleviated intensive collisions between voice packets scheduled through AC_VO access category in EDCA protocol. The proposed ECA scheme maintained the same CW size restrictions as in EDCA protocol for providing traffic prioritization. The CG transmission mechanism in ECA scheme also protected voice traffic from other lower priority traffic such as video and data.

The performance of ECA scheme was studied in detail using Markov chain analysis and through simulations carried out in NS-2 network simulator. The proposed ECA scheme showed improvement in voice throughput performance for the same AC_VO queue CW sizes used in EDCA protocol. Though the ECA scheme was focused on voice traffic, it was found equally applicable for AC_VI access category in EDCA protocol.

In particular, the performance of ECA scheme was compared with original EDCA protocol under backlogged network conditions and also under practical low-load multimedia traffic scenarios. It was seen that ECA performance was similar to EDCA protocol under small network loads. The performance improvement of ECA over EDCA was evident from the study of larger and more congested network scenarios. Clearly, the ECA scheme provided better channel arbitration mechanism when probability of collision was high. Low-load multimedia performance results showed that the ECA scheme profoundly improved voice performance without much effect on lower priority traffic.

Finally, backward compatibility and coexistence of the proposed ECA scheme were shown through analysis in mixed environment containing both ECA and legacy EDCA stations. Performance analysis revealed that ECA stations dominated transmissions to get 30 percent more throughput relative to the same number of EDCA stations present in the network. For fairness, the transmission opportunities (TXOP) of ECA stations were adjusted to have equal share of network resources with EDCA stations.

Appendix

Summary of the Parameters used in Results

Parameters	Values
Data rates	1, 6, 54 Mbps
Preamble Length ($Preamble$)	72 bits
PLCP header Length ($PLCP_{hdr}$)	56 bits
$PHY_{hdr} = Preamble + PLCP_{hdr}$	128 bits
Idle slot time (τ_0)	9 μs
$SIFS$	16 μs
TXOP (AC_VO)	1.504 ms
TXOP (AC_VI)	3.008 ms
Voice packet Lengths	$8, \ldots, 64$ bytes
Video/Data packet Lengths	$256, \ldots, 2048$ bytes
MAC_{hdr}	240 bits
CG	8 bytes
Q	2, 3, 8
ω_d	$0, \ldots, 15$
RTS	$(160 + PHY_{hdr})$ bits
CTS, ACK	$(112 + PHY_{hdr})$ bits
Ω_{min}	15, 31
Ω_{max}	1023
CW size increase limiter (m')	5
Max retransmissions (m)	7
Propagation delay (δ)	2 μs

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