Modeling the 802.11e Enhanced Distributed Channel Access Function †

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***Abstract*—The Enhanced Distributed Channel Access (EDCA) function of IEEE 802.11e standard defines multiple Access Categories (AC) with AC-specific Contention Window (CW) sizes, Arbitration Interframe Space (AIFS) values, and Transmit Opportunity (TXOP) limits to support MAC-level Quality-of-Service (QoS). In this paper, we propose an analytical model for the EDCA function which incorporates an accurate CW, AIFS, and TXOP differentiation at any traffic load. The proposed model is also shown to capture the effect of MAC layer buffer size on the performance. Analytical and simulation results are compared to demonstrate the accuracy of the proposed approach for varying traffic loads, EDCA parameters, and MAC layer buffer space.**

I. INTRODUCTION

The IEEE 802.11 standard [1] defines the Distributed Coordination Function (DCF) which provides best-effort service at the Medium Access Control (MAC) layer of the Wireless Local Area Networks (WLANs). The IEEE 802.11e standard [2] specifies the Hybrid Coordination Function (HCF) which enables prioritized and parameterized Quality-of-Service (QoS) services at the MAC layer, on top of DCF. The HCF combines a distributed contention-based channel access mechanism, referred to as Enhanced Distributed Channel Access (EDCA), and a centralized polling-based channel access mechanism, referred to as HCF Controlled Channel Access (HCCA).

In this paper, we confine our analysis to the EDCA scheme, which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and slotted Binary Exponential Backoff (BEB) mechanism as the basic access method. The EDCA defines multiple Access Categories (AC) with AC-specific Contention Window (CW) sizes, Arbitration Interframe Space (AIFS) values, and Transmit Opportunity (TXOP) limits to support MAC-level QoS and prioritization [2].

The majority of analytical work on the performance of 802.11e EDCA (and of 802.11 DCF) assumes that every station has always backlogged data ready to transmit in its buffer anytime (in saturation) as will be discussed in Section II. The saturation analysis provides accurate and practical asymptotic figures. However, this assumption is unlikely to be valid in practice given the fact that the demanded bandwidth for most of the Internet traffic is variable with significant idle periods. Our main contribution in this paper is an accurate EDCA analytical model which releases the saturation assumption. The model is shown to predict EDCA performance accurately for the whole traffic load range from a lightly loaded non-saturated channel to a heavily congested saturated medium for a range of traffic models.

Furthermore, the majority of analytical work on the performance of 802.11e EDCA (and of 802.11 DCF) in non-saturated conditions assumes either a very small or an infinitely large MAC layer buffer space. Our analysis removes such assumptions by incorporating the finite size MAC layer queue (interface queue between Link Layer (LL) and MAC layer) into the model. The finite size queue analysis shows the effect of MAC layer buffer space on EDCA performance which we will show to be significant.

A key contribution of this work is that the proposed analytical model incorporates *all* EDCA QoS parameters, CW, AIFS, and TXOP. We present a Markov model the states of which represent the state of the backoff process and MAC buffer occupancy. To enable analysis in the Markov framework, we assume constant probability of packet arrival per state (for the sake of simplicity, Poisson arrivals). On the other hand, we have also shown that the results hold for a range of traffic types. Comparing with simulations, we show that our model can provide accurate results for any selection of EDCA parameters at any load.

II. RELATED WORK

Assuming constant collision probability for each station (slot homogeneity), Bianchi [3] developed a simple Discrete-Time Markov Chain (DTMC). The saturation throughput is obtained by applying regenerative analysis to a generic slot time. Xiao [4] extended [3] to analyze only the CW differentiation. Kong *et al.* [5] took AIFS differentiation into account. Robinson *et al.* [6] proposed an average analysis on the calculation collision probability for different contention zones. Hui *et al.* [7], Inan *et al.* [8], and Tao *et al.*[9] proposed extensions which provides accurate treatment of AIFS and CW differentiation between the ACs for the constant transmission probability assumption.

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Duffy *et al.* [10] and Alizadeh-Shabdiz *et al.* [11] proposed similar extensions of [3] for non-saturated analysis of 802.11 DCF. Due to specific structure of the proposed DTMCs, these extensions assume a MAC layer buffer size of one packet. We show that this assumption may lead to significant performance prediction errors for EDCA in the case of larger buffers. Cantieni *et al.* [12] extended the model of [11] assuming infinitely large station buffers and the MAC queue being empty with constant probability regardless of the backoff stage the previous transmission took place. Engelstad *et al.* [13] used a DTMC model to perform delay analysis for both DCF and EDCA considering queue utilization probability as in [12].

Tickoo *et al.* [14] modeled each 802.11 node as a discrete time G/G/1 queue to derive the service time distribution. Chen *et al.* [15] employed both G/M/1 and G/G/1 queueing models on top of [4]. Lee *et al.* [16] analyzed the use of M/G/1 queueing model while employing a simple non-saturated Markov model to calculate necessary quantities. Medepalli *et al.* [17] calculated individual queue delays using both M/G/1 and G/G/1 queueing models. Foh *et al.* [18] proposed a Markov framework to analyze the performance of DCF under statistical traffic. This framework models the number of contending nodes as an M/E_j/1/k queue. Tantra *et al.* [19] extended [18] to include service differentiation in EDCA while the analysis is only valid for a scenario where all nodes have a MAC queue size of one packet.

III. EDCA Discrete-Time Markov Chain Model

Assuming slot homogeneity, we propose a novel DTMC to model the behavior of the EDCA function of any AC at any load. The main contribution of this work is that the proposed model considers the effect of all EDCA QoS parameters (CW, AIFS, and TXOP) on the performance for the whole traffic load range from a lightly-loaded non-saturated channel to a heavily congested saturated medium. Although we assume constant probability of packet arrival per state (for the sake of simplicity, Poisson arrivals), we show that the model provides accurate performance analysis for a range of traffic types.

We model the MAC layer state of an AC_i, $0 \leq i \leq 3$, with a 3-dimensional Markov process, $(s_i(t), b_i(t), q_i(t))$. The definition of first two dimensions follow [3]. The stochastic process $s_i(t)$ represents the value of the backoff stage at time t. The stochastic process $b_i(t)$ represents the state of the backoff counter at time t. In order to enable the accurate non-saturated analysis considering EDCA TXOPs, we introduce another dimension which models the stochastic process $q_i(t)$ denoting the number of packets buffered for transmission at the MAC layer. Moreover, as the details will be described in the sequel, in our model, $b_i(t)$ does not only represent the value of the backoff counter, but also the number of transmissions carried out during the current EDCA TXOP (when the value of backoff counter is actually zero).

Using the assumption of independent and constant collision probability at an arbitrary backoff slot, the 3-dimensional process $(s_i(t), b_i(t), q_i(t))$ is represented as a DTMC with states (j, k, l) and index i. We define the limits on state variables as $0 \leq j \leq r_i - 1$, $-N_i \leq k \leq W_{i,j}$ and $0 \leq l \leq QS_i$. In these inequalities, we let r_i be the retransmission limit of a packet of AC_i; N_i be the maximum number of successful packet exchange sequences of AC_i that can fit into one $TXOP_i$; $W_{i,j} = 2^{min(j,m_i)}(CW_{i,min}+1)-1$ be the CW size of AC_i at the backoff stage j where $CW_{i,max} = 2^{m_i}(CW_{i,min}+1)-1$, $0 \leq m_i < r_i$; and QS_i be the maximum number of packets that can buffered at the MAC layer, i.e., MAC queue size. Moreover, a couple of restrictions apply to the state indices.

- When there are not any buffered packets at the AC queue, the EDCA function of the corresponding AC cannot be in a retransmitting state. Therefore, if $l = 0$, then $j = 0$ should hold. Such backoff states represent the postbackoff process [1],[2], therefore called as *postbackoff slots* in the sequel. The postbackoff procedure ensures that the transmitting station waits at least another backoff between successive TXOPs. Note that, when $l > 0$ and $k \geq 0$, these states are named *backoff slots*.
- The states with indices $-N_i \leq k \leq -1$ represent the negation of the number of packets that are successfully transmitted at the current TXOP rather than the value of the backoff counter (which is zero during a TXOP). For simplicity, in the design of the Markov chain, we introduced such states in the second dimension. Therefore, if $-N_i \leq k \leq -1$, we set $j = 0$. As it will be clear in the sequel, these states enable EDCA TXOP analysis.

Let p_{c_i} denote the average conditional probability that a packet from AC_i experiences a collision. Let $p_{nt}(l', T|l)$ be the probability that there are l' packets in the MAC buffer at time $t+T$ given that there were l packets at t and no transmissions have been made during interval T. Similarly, let $p_{st}(l', T|l)$ be the probability that there are l' packets in the MAC buffer at time $t + T$ given that there were l packets at time t and a transmission has been made during interval T. Note that since we assume Poisson arrivals, the exponential interarrival distributions are independent, and p_{nt} and p_{st} only depend on the interval length T and are independent of time t. Then, the nonzero state transmission probabilities of the proposed Markov model for AC_i, denoted as $P_i(j', k', l'|j, k, l)$ adopting the same notation in [3], are calculated as follows.

1) The backoff counter is decremented by one at the slot boundary. Note that we define the postbackoff or the backoff slot as Bianchi defines the slot time [3]. Then, for $0 \leq j \leq r_i - 1$, $1 \leq k \leq W_{i,j}$, and $0 \leq l \leq l' \leq QS_i$,

$$P_i(j, k-1, l'|j, k, l) = p_{nt}(l', T_{i,bs}|l). \qquad (1)$$

   Note that the proposed DTMC's evolution is not real-time and the state duration varies depending on the state. The average duration of a backoff slot $T_{i,bs}$ is calculated by (20) which will be derived. Also note that, in (1), we consider the probability of packet arrivals during $T_{i,bs}$.
2) We assume the transmitted packet experiences a collision with constant probability p_{c_i}. In the following, note that the cases when the retry limit is reached and when the MAC buffer is full are treated separately, since the tran-

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sition probabilities should follow different rules. Let $T_{i,s}$ and $T_{i,c}$ be the time spent in a successful transmission and a collision by AC$_i$ respectively which will be derived. Then, for $0 \leq j \leq r_i - 1$, $0 \leq l \leq QS_i - 1$, and $\max(0, l-1) \leq l' \leq QS_i$,

$$P_i(0,-1,l'|j,0,l) = (1-p_{c_i}) \cdot p_{st}(l', T_{i,s}|l) \quad (2)$$
$$P_i(0,-1,QS_i-1|j,0,QS_i) = 1-p_{c_i}. \quad (3)$$

For $0 \leq j \leq r_i - 2$, $0 \leq k \leq W_{i,j+1}$, and $0 \leq l \leq l' \leq QS_i$,

$$P_i(j+1,k,l'|j,0,l) = \frac{p_{c_i} \cdot p_{nt}(l', T_{i,c}|l)}{W_{i,j+1}+1}. \quad (4)$$

For $0 \leq k \leq W_{i,0}$, $0 \leq l \leq QS_i - 1$, and $\max(0, l-1) \leq l' \leq QS_i$,

$$P_i(0,k,l'|r_i-1,0,l) = \frac{p_{c_i}}{W_{i,0}+1} \cdot p_{st}(l', T_{i,s}|l) \quad (5)$$
$$P_i(0,k,QS_i-1|r_i-1,0,QS_i) = \frac{p_{c_i}}{W_{i,0}+1}. \quad (6)$$

Note that we use p_{nt} in (4) although a transmission has been made. On the other hand, the packet has collided and is still at the MAC queue for retransmission as if no transmission has occured. This is not the case in (2) and (5), since in these transitions a successful transmission or a drop occurs. When the MAC buffer is full, any arriving packet is discarded as (3) and (6) imply.

3) Once the TXOP is started, the EDCA function may continue with as many packet SIFS-separated exchange sequences as it can fit into the TXOP duration. Let $T_{i,exc}$ be the average duration of a successful packet exchange sequence for AC$_i$ which will be derived in (21). Then, for $-N_i + 1 \leq k \leq -1$, $1 \leq l \leq QS_i$, and $\max(0, l-1) \leq l' \leq QS_i$,

$$P_i(0,k-1,l'|0,k,l) = p_{st}(l', T_{i,exc}|l). \quad (7)$$

When the next transmission cannot fit into the remaining TXOP, the current TXOP is immediately concluded. By design, our model includes the maximum number of packets that can fit into one TXOP. Then, for $0 \leq k \leq W_{i,0}$ and $1 \leq l \leq QS_i$,

$$P_i(0,k,l|0,-N_i,l) = \frac{1}{W_{i,0}+1}. \quad (8)$$

The TXOP ends when the MAC queue is empty. Then, for $0 \leq k' \leq W_{i,0}$ and $-N_i \leq k \leq -1$,

$$P_i(0,k',0|0,k,0) = \frac{1}{W_{i,0}+1}. \quad (9)$$

Note that no time passes in (8) and (9), so these states and transitions are actually not necessary for accuracy. On the other hand, they simplify the DTMC structure.

4) If the queue is still empty when the postbackoff ends, the EDCA function enters the idle state until another packet arrives. Note (0,0,0) also represents the idle state. We make two assumptions; *i)* At most one packet arrives during T_{slot} (the duration of a physical layer time slot) with probability ρ_i, and *ii)* if the channel is idle when the packet arrives at an empty queue, the transmission will be successful at AIFS completion. These assumptions do not lead to any noticeable changes in the results while simplifying the model structure. Then, for $0 \leq k \leq W_{i,0}$ and $1 \leq l \leq QS_i$,

$$P_i(0,0,0|0,0,0) = (1-p_{c_i})(1-\rho_i) + p_{c_i} p_{nt}(0, T_{i,b}|0), \quad (10)$$

$$P_i(0,k,l|0,0,0) = \frac{p_{c_i}}{W_{i,0}+1} \cdot p_{nt}(l, T_{i,b}|0), \quad (11)$$

$$P_i(0,-1,l|0,0,0) = (1-p_{c_i}) \cdot \rho_i \cdot p_{nt}(l, T_{i,s}|0). \quad (12)$$

Let $T_{i,b}$ in (10) and (11) be the length of a backoff slot given it is not idle. Actually a successful transmission occurs in (12). On the other hand, the transmitted packet is not reflected in the initial queue size state which is 0. Therefore, p_{nt} is used instead of p_{st}.

Parts of the proposed DTMC model are illustrated in Fig. 1 for an arbitrary AC$_i$ with $N_i = 2$. Fig. 1(a) shows the state transitions for $l = 0$. Note that in Fig. 1(a) the states with $-N_i \leq k \leq -2$ can only be reached from the states with $l = 1$. Fig. 1(b) presents the state transitions for $0 < l < QS_i$ and $0 \leq j < r_i$. Note that only the transition probabilities and the states marked with rectangles differ when $j = r_i - 1$ (as in (5)). Due to space limitations, we do not include an extra figure for this case. Fig. 1(c) shows the state transitions when $l = QS_i$. Note also that the states marked with rectangles differ when $j = r_i - 1$ (as in (6)). The combination of these small chains for all j, k, l constitutes our DTMC model.

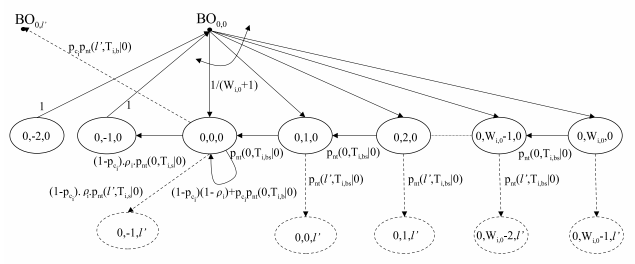
A. Steady-State Solution

Let $b_{i,j,k,l}$ be the steady-state probability of the state (j,k,l) of the proposed DTMC with index i which can be solved using (1)-(12) subject to $\sum_j \sum_k \sum_l b_{i,j,k,l} = 1$. Let τ_i be the probability that an AC$_i$ transmits at an arbitrary slot

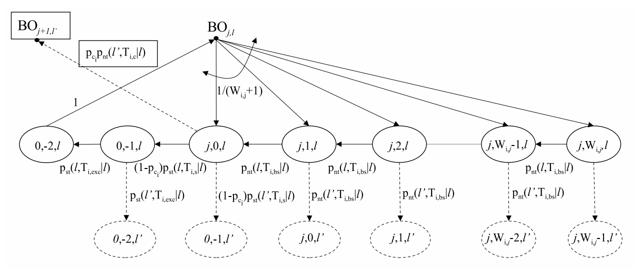
$$\tau_i = \frac{\left(\sum_{j=0}^{r_i-1} \sum_{l=1}^{QS_i} b_{i,j,0,l}\right) + b_{i,0,0,0} \cdot \rho_i \cdot (1-p_{c_i})}{\sum_{j=0}^{r_i-1} \sum_{k=0}^{W_{i,j}} \sum_{l=0}^{QS_i} b_{i,j,k,l}}. \quad (13)$$

Note that $-N_i \leq k \leq -1$ is not included in the normalization in (13), since these states represent a continuation in the TXOP rather than a contention for the access. As (13) implies, τ_i depends on p_{c_i}, $T_{i,bs}$, $T_{i,b}$, $T_{i,s}$, $T_{i,c}$, p_{nt}, p_{st}, and ρ_i. Once these are calculated, the non-linear system can be solved using numerical methods.

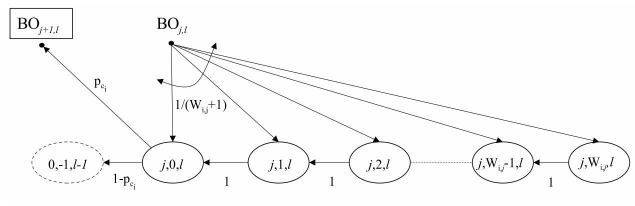
1) Average conditional collision probability p_{c_i}: The difference in AIFS of each AC in EDCA creates the so-called contention zones [6]. In each contention zone, the number of contending stations may vary. We can define $p_{c_{i,x}}$ as the conditional probability that AC$_i$ experiences a collision given that it has sensed the channel idle for $AIFS_x$ and transmits in the current slot. We assume $AIFS_0 \geq AIFS_1 \geq AIFS_2 \geq AIFS_3$. Let $d_i = AIFS_i - AIFS_3$. Also, let the total number



(a)



(b)



(c)

Fig. 1. Parts of the proposed DTMC model for N_i=2. The combination of these small chains for all j, k, l constitutes the proposed DTMC model. (a) $l = 0$. (b) $0 < l < QS_i$. (c) $l = QS_i$. Remarks: *i)* the transition probabilities and the states marked with rectangles differ when $j = r_i - 1$ (as in (5) and (6)), *ii)* the limits for l' follow the rules in (1)-(12).

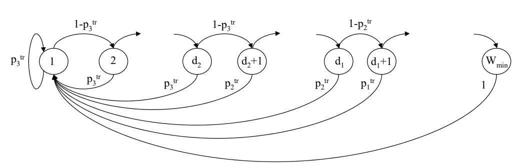


Fig. 2. Transition through backoff slots in different contention zones.

AC$_i$ flows be f_i. Then,

$$p_{c_{i,x}} = 1 - \frac{\prod\limits_{i':d_{i'} \le d_x} (1-\tau_{i'})^{f_{i'}}}{(1-\tau_i)}. \tag{14}$$

In this paper, we only investigate the situation when there is only one AC per station due to space limitations. We provide the case of larger number of ACs per station in [20].

We use the Markov chain shown in Fig. 2 to find the long term occupancy of contention zones. Each state represents the n^{th} backoff slot after completion of the AIFS$_3$ idle interval following a transmission period. The Markov chain model uses the fact that a backoff slot is reached if and only if no transmission occurs in the previous slot. Moreover, the number of states is limited by the maximum idle time between two successive transmissions which is $W_{min} = \min(CW_{i,max})$ for a saturated scenario. Although this is not the case for a non-saturated scenario, we do not change this limit. As the comparison with simulation results show, this approximation does not result in significant prediction errors. The probability that at least one transmission occurs in a backoff slot in contention zone x is

$$p_x^{tr} = 1 - \prod_{i':d_{i'} \le d_x} (1-\tau_{i'})^{f_{i'}}. \tag{15}$$

Note that the contention zones are labeled with x regarding the indices of d. In the case of equal AIFS values, the contention zone is labeled with the index of the AC with higher priority.

Let b'_n be the steady-state solution of the Markov chain in Fig. 2. The AC-specific average collision probability p_{c_i} is found by weighing zone specific collision probabilities $p_{c_{i,x}}$ according to the long term occupancy of contention zones (thus backoff slots)

$$p_{c_i} = \frac{\sum_{n=d_i+1}^{W_{min}} p_{c_{i,x}} \cdot b'_n}{\sum_{n=d_i+1}^{W_{min}} b'_n} \tag{16}$$

where $x = \max\Big(y \mid d_y = \max\limits_z(d_z \mid d_z \le n)\Big)$ which shows x is assigned the highest index value within a set of ACs that have AIFS smaller than or equal to $n + AIFS_3$.

2) The state duration $T_{i,s}$ and $T_{i,c}$: Let $T_{i,p}$ be the average payload transmission time for AC$_i$ ($T_{i,p}$ includes the transmission time of MAC and PHY headers), δ be the propagation delay, T_{ack} be the time required for acknowledgment packet (ACK) transmission. Then, for the basic access scheme, we define the time spent in a successful transmission $T_{i,s}$ and a collision $T_{i,c}$ for any AC$_i$ as

$$T_{i,s} = T_{i,p} + \delta + SIFS + T_{ack} + \delta + AIFS_i \tag{17}$$

$$T_{i,c} = T_{i,p^*} + ACK\_Timeout + AIFS_i \tag{18}$$

where T_{i,p^*} is the average transmission time of the longest packet payload involved in a collision [3]. For simplicity, we assume the packet size to be equal for any AC, then $T_{i,p^*} = T_{i,p}$. Being not explicitly specified in the standards, we set $ACK\_Timeout$, using Extended Inter Frame Space (EIFS) as $EIFS_i - AIFS_i$. Note that the extensions of (17) and (18) for the RTS/CTS scheme are straightforward [20].

3) The state duration $T_{i,bs}$ and $T_{i,b}$: We start with calculating the average duration of an EDCA TXOP for AC$_i$ $T_{i,txop}$ as in (19) where $T_{i,exc}$ is the duration of a successful packet exchange sequence within a TXOP. Since the packet exchanges within a TXOP are separated by SIFS,

$$T_{i,exc} = T_{i,s} - AIFS_i + SIFS, \tag{21}$$

$$N_i = \lfloor (TXOP_i + SIFS)/T_{i,exc} \rfloor. \tag{22}$$

Given τ_i and f_i, simple probability theory can be used to calculate the conditional probability of no transmission ($p_{x,i}^{idle}$), only one transmission from AC$_{i'}$ ($p_{x,i}^{suc_{i'}}$), or at least two

$$T_{i,txop} = \frac{\sum_{l=0}^{QS_i} b_{i,0,-N_i,l} \cdot ((N_i - 1) \cdot T_{i,exc} + T_{i,s}) + \sum_{k=-N_i+1}^{-1} b_{i,0,k,0} \cdot ((-k-1) \cdot T_{i,exc} + T_{i,s})}{\sum_{k=-N_i+1}^{-1} b_{i,0,k,0} + \sum_{l=0}^{QS_i} b_{i,0,-N_i,l}} \tag{19}$$

$$T_{i,bs} = \frac{1}{1 - \sum\limits_{x_i < x' \leq 3} p_{z_{x'}}} \sum_{\forall x'} (p_{x',i}^{idle} \cdot T_{slot} + p_{x',i}^{col} \cdot T_c + \sum_{\forall i'} p_{x',i'}^{suc_{i'}} \cdot T_{i',txop}) \cdot p_{z_{x'}} \tag{20}$$

transmissions ($p_{x,i}^{col}$) at the contention zone x given one AC$_i$ is in backoff [20]. Moreover, let x_i be the first contention zone in which AC$_i$ can transmit. Then, $T_{i,bs}$ is calculated as in (20), where p_{z_x} denotes the stationary distribution for a random backoff slot being in zone x. If we let $d_{-1} = W_{min}$,

$$p_{z_x} = \sum_{n=d_x+1}^{min(d_{x'}|d_{x'}>d_x)} b'_n. \tag{23}$$

The expected duration of a backoff slot given it is busy and one AC$_i$ is in idle state is calculated as

$$T_{i,b} = \sum_{\forall x'} \left(\frac{p_{x',i}^{col}}{1 - p_{x',i}^{idle}} \cdot T_c + \sum_{\forall i'} \frac{p_{x',i'}^{suc_{i'}}}{1 - p_{x',i'}^{idle}} \cdot T_{i',txop} \right) \cdot p_{z_{x'}}. \tag{24}$$

4) The conditional queue state transition probabilities p_{nt} and p_{st}: We assume the packets arrive at the AC queue according to a Poisson process. Using the probability distribution function of the Poisson process, the probability of k arrivals occuring in time interval t $\Pr(N_{t,i} = k)$ is calculated. Then, $p_{nt}(l', T|l)$ and $p_{st}(l', T|l)$ can be calculated considering the finite buffer space [20]. Also, note that $\rho_i = 1 - \Pr(N_{T_{slot},i} = 0)$.

B. Normalized Throughput Analysis

The normalized throughput of a given AC$_i$, S_i, is defined as the fraction of the time occupied by the successfully transmitted information. Then,

$$S_i = \frac{p_{s_i} N_{i,txop} T_{i,p}}{p_I T_{slot} + \sum_{i'} p_{s_{i'}} T_{i',txop} + (1 - p_I - \sum_{i'} p_{s_{i'}}) T_c} \tag{25}$$

where p_I is the probability of the channel being idle at a backoff slot, p_{s_i} is the conditional successful transmission probability of AC$_i$ at a backoff slot, and $N_{i,txop} = (T_{i,txop} - AIFS_i + SIFS)/T_{i,exc}$. The reader is referred to [20] for the simple derivations of p_I and p_{s_i}.

IV. Numerical and Simulation Results

We validate the accuracy of the numerical results by comparing them with the simulations results obtained from ns-2 [21]. For the simulations, we employ the 802.11e HCF MAC simulation model for ns-2.28 [22]. In simulations, we consider two ACs, one high priority and one low priority. Each station runs only one AC. Unless otherwise stated, the packets are generated according to a Poisson process with equal rate for both ACs. We set $AIFSN_1 = 3$, $AIFSN_3 = 2$, $CW_{1,min} = 15$, $CW_{3,min} = 7$, $TXOP_1 = 3.008$ ms, $TXOP_3 = 1.504$ ms, $m_1 = m_3 = 3$, $r_1 = r_3 = 7$. For both ACs, the payload size is 1034 bytes. The simulation results are reported for the wireless channel with no errors. All the stations use 54 Mbps and 6 Mbps as the data and basic rate respectively ($T_{slot} = 9$ μs, $SIFS = 10$ μs). The simulation runtime is 100 seconds.

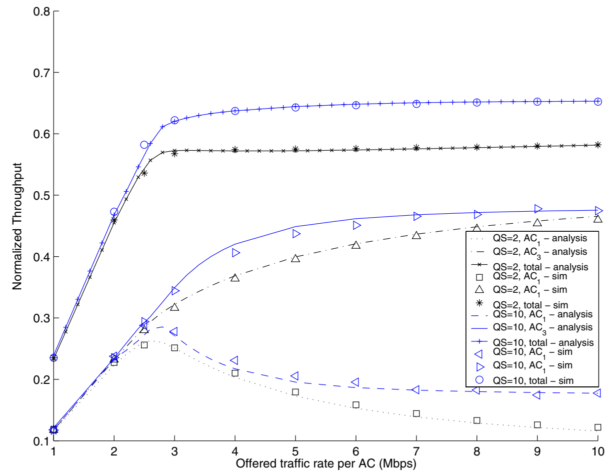


Fig. 3. Normalized throughput of each AC with respect to increasing load at each station.

In our first experiment, there are 5 stations for both ACs transmitting to an AP. Fig. 3 shows the normalized throughput per AC as well as the total system throughput for increasing offered load per AC. The analysis is carried out for maximum MAC buffer sizes of 2 packets and 10 packets. The results show that our model can accurately capture the linear relationship between throughput and offered load under low loads, the complex transition in throughput between under-loaded and saturation regimes, and the saturation throughput.The proposed model also captures the throughput variation with respect to the size of the MAC buffer. The results also show small interface buffer assumptions of previous models [10],[11],[19] can lead to considerable analytical inaccuracies.

Fig. 4 displays the differentiation of throughput when packet arrival rate is fixed to 2 Mbps per AC and the station number per AC is increased. We present the results for the MAC buffer size of 10 packets. The analytical and simulation results are well in accordance. As the traffic load increases, the differentiation in throughput between the ACs is observed.

We have also compared the throughput estimates obtained from the analytical model with the simulation results obtained

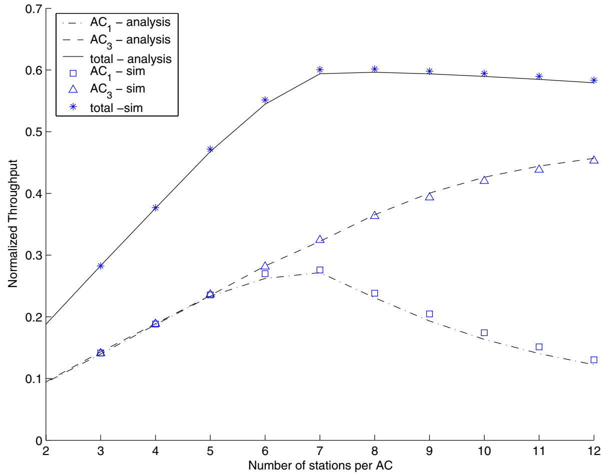


Fig. 4. Normalized throughput of each AC with respect to increasing number of stations when the total offered load per AC is 2 Mbps.

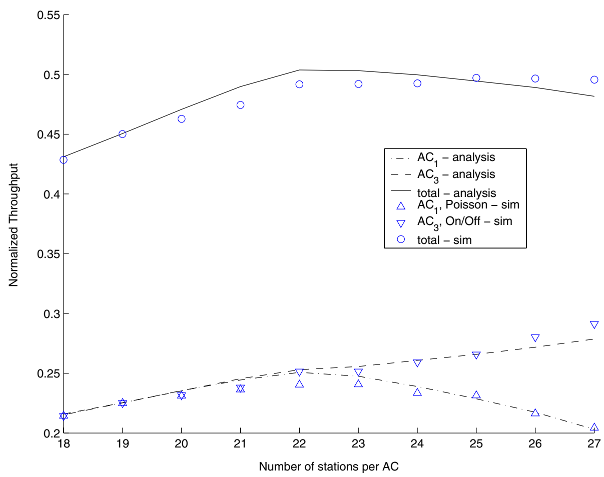


Fig. 5. Normalized throughput of each AC with respect to increasing number of stations when total offered load per AC is 0.5 Mbps. In simulations, AC_3 uses On/Off traffic rather than Poisson.

using an On/Off traffic model in Fig. 5. A similar study has first been made for DCF in [10]. We modeled the high priority with On/Off traffic model with exponentially distributed idle and active intervals of mean length 1.5 s. In the active interval, packets are generated with Constant Bit Rate (CBR). The low priority traffic uses Poisson distributed arrivals. The analytical predictions closely follow the simulation results for the given scenario. Although we do not include the results here, our model also provides a very good match in terms of the throughput for CBR traffic for any number of stations [20].

V. Conclusion

We have presented an accurate Markov model for analytically calculating the EDCA throughput at finite traffic load. The analytical model can incorporate any selection of AC-specific AIFS, CW, and TXOP values for any number of ACs. To the authors' knowledge this is the first demonstration of an analytic model including TXOP procedure for finite load.

We also show that the MAC buffer size affects the EDCA performance significantly between underloaded and saturation regimes (including saturation). Moreover, the comparison with simulation results shows that the throughput analysis is valid for a range of traffic types such as CBR and On/Off traffic (On/Off traffic model is a widely used model for voice and telnet traffic).

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