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Saturation Throughput Analysis of the 802.11e Enhanced Distributed Channel Access Function†

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***Abstract*—The IEEE 802.11e standard has recently been ratified. This standard provides Quality-of-Service (QoS) guarantees in the Medium Access Control (MAC) layer of 802.11 Wireless Local Area Networks (WLANs). In other words, the 802.11e standard updates the MAC layer of the former 802.11 standard for QoS. In particular, the Enhanced Distributed Channel Access (EDCA) function of 802.11e is an enhancement of the Distributed Coordination Function (DCF) of 802.11. In this paper, we present an analytical model for EDCA in saturation mode. Our model incorporates an accurate Contention Window (CW) and Arbitration Interframe Space (AIFS) differentiation. In addition, it provides virtual collision treatment for an Access Category (AC). Validating the theoretical results via simulations, we show that *i)* the proposed model accurately captures EDCA saturation throughput, and *ii)* this model is substantially more accurate than the models previously proposed in the literature.**

I. Introduction

The Distributed Coordination Function (DCF) of the IEEE 802.11 standard [1] provides best-effort service at the Medium Access Control (MAC) layer. On top of DCF, 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. 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 fundamental performance figure evaluated in this paper is the saturation (asymptotic) throughput. The saturation throughput is the limit reached by the system throughput in stable conditions when every station has always backlogged data ready to transmit in its buffer. Although the maximum throughput that can be achieved by the same system can be shown to be higher than the saturation throughput in many scenarios, the operation of a random access scheme at the state of maximum achievable throughput is shown to have unstable behavior [3]. Therefore, the saturation throughput is a practical asymptotic figure. The analysis of the saturation throughput provides in-depth understanding and insights into the random access schemes and the effects of different contention parameters on the performance. The results of such analysis can be employed in access parameter adaptation or in a call admission control algorithm.

We will first provide a summary of previous work for similar analysis from the literature. Bianchi [4] developed a simple Discrete-Time Markov Chain (DTMC) to model the behavior of the DCF in saturation. The saturation throughput is obtained by applying regenerative analysis to a generic slot time and assuming constant collision probability for each station. This model is improved in [5],[6] to include finite retry limits and in [7] to include the details of backoff suspension for DCF. Xiao [8] extended [4] to analyze only the CW differentiation. The backoff suspension procedure considering AC-specific AIFS completion time is modeled by Kong *et al.* [9] via a 3-dimensional DTMC. On the other hand, the treatment of varying collision probabilities at different AIFS slots due to varying number of contending stations is missed.

The varying collision probability among different AIFS slots has also previously been studied in the literature. Robinson *et al.* [10] proposed an average analysis on the collision probability for different contention zones during AIFS and employed calculated average collision probability on a 2-dimensional Markov Chain. This model assumes a much smaller timeout value than defined in [2] which results in a complex post collision treatment. Hui *et al.* [11] unified several major approaches into one approximate average model taking varying collision probability in different backoff subperiods (corresponds to contention zones in [10]). Zhu *et al.* [12] proposed another analytical EDCA Markov model averaging the transition probabilities based on the number and the

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parameters of high priority flows. Tantra *et al.* [13] specified an approximate saturation model for 2 AC case which includes AIFS differentiation for the lower priority AC, leaving the high priority AC model as in [4]. No guideline is given on creating the analytical model for a larger number of ACs. Battiti *et al.* [14] also proposes another approximate saturation model still leaving the high priority AC model as in [4].

In this paper, we propose an analytical model for the EDCA function in saturated Wireless LAN (WLAN) scenario. The key contribution of this paper is the accurate treatment of AIFS differentiation between the ACs in the EDCA Markov model. The Markov chain structure is specified such that *any* number of ACs with equal or varying EDCA parameters can be modeled analytically. The model also considers the difference in the DCF and the EDCA backoff countdown procedure as well as the treatment of virtual collisions [2]. Via simulations, the proposed model is shown to accurately predict EDCA saturation throughput. We also demonstrate the saturation throughput prediction errors of previously proposed models due to ignoring or approximating the details included in our model.

II. EDCA Overview

The IEEE 802.11e EDCA is a QoS extension of IEEE 802.11 DCF. The major enhancement to support QoS is that EDCA differentiates packets using different priorities and maps them to specific ACs that are buffered in separate queues at a station. Each AC$_i$ within a station ($0 \leq i \leq i_{max}$, $i_{max} = 3$ in [2]) having its own EDCA parameters contends for the channel independently of the others. Following the notation of [2], the larger the index i is, the higher the priority of the AC is. Levels of services are provided through different assignments of the AC specific EDCA parameters; AIFS, CW, and TXOP limits.

If there is a packet ready for transmission in the MAC queue of an AC, the EDCA function must sense the channel to be idle for a complete AIFS before it can start the transmission. The AIFS of an AC is determined by using the MAC Information Base (MIB) parameters as

$$AIFS = SIFS + AIFSN \times T_{slot}, \tag{1}$$

where $AIFSN$ is the AC-specific AIFS number, $SIFS$ is the length of the Short Interframe Space and T_{slot} is the duration of a time slot.

If the channel is idle when the first packet arrives at the AC queue, the packet can be directly transmitted as soon as the channel is sensed to be idle for AIFS. On the other hand, if the channel is busy or there are already packets buffered in the AC queue, in the transmission of this packet, a backoff procedure is completed following the completion of AIFS. A uniformly distributed random integer, namely a backoff value, is selected from the range $[0, W]$. The backoff counter is decremented at the slot boundary if the previous time slot is idle. Should the channel be sensed busy at any time slot during AIFS or backoff, the backoff procedure is suspended at the current backoff value. The backoff resumes as soon as the channel is sensed to be idle for AIFS again. When the backoff counter reaches zero, the packet is transmitted in the following slot.

The value of W depends on the number of retransmissions the current packet experienced. The initial value of W is set to the AC-specific CW_{min}. If the transmitter cannot receive an Acknowledgment (ACK) packet from the receiver in a timeout interval, the transmission is labeled as unsuccessful, and the packet is scheduled for retransmission. At each unsuccessful transmission, the value of W is doubled until the maximum AC-specific CW_{max} limit is reached. The value of W is reset to the AC-specific CW_{min} if the transmission is successful, or the retry limit is reached thus the packet is dropped.

An internal collision within a station is handled by granting the access to the AC with the highest priority. The ACs with lower priority that suffer from a virtual collision run the collision procedure as if an outside collision has occured.

It is also important to note the difference of EDCA and DCF in decrementing the backoff counter. In DCF, the backoff is decremented only when the channel is sensed to be idle in the previous backoff slot. However, in EDCA, the backoff counter is also decremented at the slot boundary after the last AIFS slot (AIFSN slot) if it is idle.

III. EDCA Discrete-Time Markov Chain Model

In EDCA, the AC-specific AIFS values result in a varying number of ACs contending for the channel depending on the number of previous consecutive idle slots after the last busy medium time. The main contribution of this work is that the state transitions as well as the corresponding transition probabilities in the discrete-time Markov model account for AIFS differentiation accurately under the assumption of constant transmission probability for each AC at an arbitrary backoff slot. Our model considers the varying number of contending stations thus varying collision probability over different AIFS and backoff slots.

We model the saturation behavior of each individual AC with a different 3-dimensional Markov process. We will start with the second dimension. The stochastic process $b_i(t)$, representing the backoff counter of AC$_i$, is the second dimension of the Markov process. Now we introduce the stochastic process $s_i(t)$ as the first dimension. It represents the backoff stage in order to overcome the non-Markovian property of $b_i(t)$, since the value of $b_i(t)$ depends on the size of the CW from which it is drawn. Finally, we are including the stochastic process $a_i(t)$ as the third dimension, representing the state of AC$_i$ during the AIFS$_i$ period. This structure extends the 2-dimensional per-station DCF Markov model introduced in [4] to accommodate the QoS features provided by EDCA. The 3-dimensional process $(s_i(t), b_i(t), a_i(t))$ of AC$_i$ can be represented as a discrete-time Markov chain using the assumption of independent collision probability at an arbitrary backoff slot.

At time t, the state of AC$_i$ is determined by (j, k, l), where j represents the current backoff stage, $0 \leq j \leq r-1$; k denotes the current backoff counter, $0 \leq k \leq W_{i,j}$; and l indicates the remaining AIFS time, $0 \leq l \leq A$. In these inequalities, we let r be the retransmission limit of a packet; $W_{i,j} = 2^{min(j,m)}(CW_{i,min}+1)-1$ be the CW size of AC$_i$ at the backoff stage j where $CW_{i,max} = 2^m(CW_{i,min}+1)-1$, $0 \leq m < r$; and $A = AIFS_0 - AIFS_{i_{max}}$ be the number of slots should the AC with the lowest priority wait more at AIFS when compared to the AC with the highest priority. Note that, we assume $AIFS_0 \geq AIFS_1 \geq ... \geq AIFS_{i_{max}}$. The third dimension representing the AIFS state excludes the backoff states corresponding to the period $AIFS_{i_{max}}$ since the backoff state does not change for any AC during this interval. Instead, as will be described in the sequel, this interval is included in (17) and (18).

Let $p_{b_{i,x}}$ denote the conditional probability that AC$_i$ detects the channel to be busy (there exists at least one transmission) in the current slot given that it has observed the medium idle for $AIFS_x$. Similarly, let $p_{c_{i,x}}$ denote the conditional probability that AC$_i$ experiences either an external or an internal collision given that it has observed the medium idle for $AIFS_x$ and transmits in the current slot (note $AIFS_x \geq AIFS_i$ should hold). Also, let $d_i = AIFS_i - AIFS_{i_{max}}$ (note $A = d_0$). 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 [4], are calculated as follows.

1) The AIFS of AC$_i$ is reset without a decrement in the backoff counter if there is a transmission from any AC$_{i'}$ where $AIFS_{i'} < AIFS_i$. Otherwise, remaining AIFS is decreased by one if the medium stays idle. Then, for $0 \leq j \leq r-1$, $0 \leq k \leq W_j$, and $A - d_i + 1 \leq l \leq A$,

$$P_i(j,k,A|j,k,l) = p_{b_{i,x}} \quad (2)$$

$$P_i(j,k,l-1|j,k,l) = 1 - p_{b_{i,x}} \quad (3)$$

where $x = \max\left(y \mid d_y = \max_z(d_z \mid d_z \leq A-l)\right)$ which shows that x is assigned the highest index value within a set of ACs that have AIFS values smaller than or equal to $A - l + AIFS_{i_{max}}$. This ensures that at AIFS state l, AC$_i$ has observed the medium for $AIFS_x$, and the transition probabilities in (2) and (3) fit the definition of $p_{b_{i,x}}$. Note also that if the stated inequalities for (j, k, l) are not satisfied, then the corresponding transition probabilities are 0.

2) The backoff of AC$_i$ is frozen after a decrement in the backoff counter and a reset in AIFS if there is a transmission from any AC$_{i'}$ where $AIFS_{i'} \geq AIFS_i$. If not, both the backoff counter and the remaining AIFS decrease by one. Then, for $0 \leq j \leq r-1$, $1 \leq k \leq W_j$, and $0 \leq l \leq A - d_i$,

$$P_i(j,k-1,A|j,k,l) = p_{b_{i,x}} \quad (4)$$

$$P_i(j,k-1,\max(l-1,0)|j,k,l) = 1 - p_{b_{i,x}} \quad (5)$$

where $x = \max\left(y \mid d_y = \max_z(d_z \mid d_z \leq A-l)\right)$. Note that these transitions account for the backoff countdown difference between DCF and EDCA which is discussed in Section II.

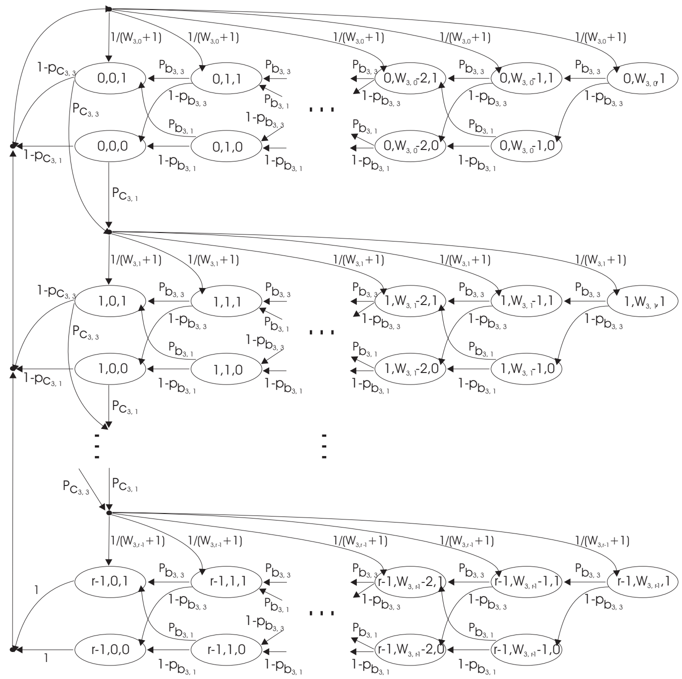

Fig. 1. Markov chain model for AC$_3$

3) After a successful transmission, AC$_i$ selects a new backoff value and starts AIFS. Otherwise when there is a collision, and the AC retries the transmission if the retransmission limit is yet not reached. Then, for $0 \leq j \leq r-2$, $0 \leq k \leq W_j$, and $0 \leq l \leq A - d_i$

$$P_i(0,k,A|j,0,l) = \frac{1 - p_{c_{i,x}}}{W_0 + 1} \quad (6)$$

$$P_i(j+1,k,A|j,0,l) = \frac{p_{c_{i,x}}}{W_{j+1} + 1} \quad (7)$$

where $x = \max\left(y \mid d_y = \max_z(d_z \mid d_z \leq A-l)\right)$. When the retry limit is reached, the packet is discarded. Therefore, for $j = r-1$, $0 \leq k \leq W_j$, and $0 \leq l \leq A-d_i$

$$P_i(0,k,A|r-1,0,l) = \frac{1}{W_0+1}. \quad (8)$$

Equations (2)-(8) define the nonzero state transition probabilities for the AC-specific Markov chain, taking the AIFS and CW differentiation between ACs into account. All these state transition probabilities are illustrated in Fig. 1 and Fig. 2 for an example scenario comprising stations with AC$_3$ and AC$_1$. Note that, for the specific example, AIFSN$_1$-AIFSN$_3$=1.

Note that in Fig. 1, the Markov chain model for AC$_3$ does not have the states $(j, W_{i,j}, 0)$, $0 \leq j \leq r-1$. Although one can add these states to the model and assign appropriate state transition probabilities using (4) and (5), these states are transient and have a corresponding steady-state probability of zero. Actually, the system can never be in those states, since the backoff counter cannot stay at its maximum value if AIFS has already passed. Generalizing this case to the models of larger number of ACs is straightforward.

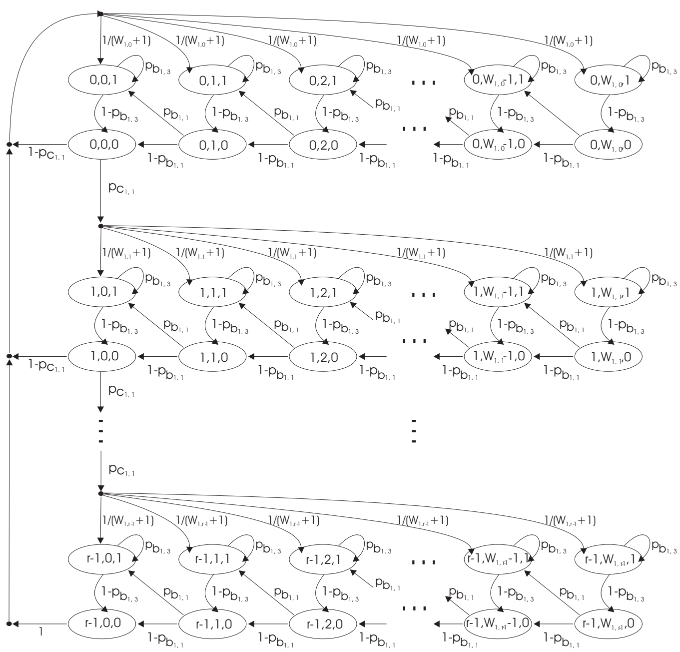

Fig. 2. Markov chain model for AC_1

A. Steady-State Solution

Adopting the same notation in [4], let $b_{j,k,l}$ be the steady-state probability of the state (j,k,l) which can be solved using (2)-(8) subject to $\sum_j \sum_k \sum_l b_{j,k,l} = 1$. Let τ_i be the probability that an AC_i transmits at an arbitrary backoff slot. Then,

$$\tau_i = \frac{\sum_{j=0}^{r-1} \sum_{l=0}^{A-d_i} b_{j,0,l}}{\sum_{j=0}^{r-1} \sum_{k=0}^{W_j} \sum_{l=0}^{A-d_i} b_{j,k,l}}. \quad (9)$$

One can define $\tau_{i,l'}$ separately for each AIFS slot l' by normalizing $\sum_{j=0}^{r-1} b_{j,0,l'}$ over $\sum_{j=0}^{r-1} \sum_{k=0}^{W_j} b_{j,k,l'}$. We have observed that τ_i is pretty close to $\tau_{i,l'}$ for $0 \leq l' \leq A - d_i$, confirming the validity of the basic assumption made, the independent and constant transmission probability at an arbitrary backoff slot.

Let the total number of stations that have flows using AC_i be N_i. If not stated otherwise, for the following, let each station have multiple saturated ACs. The basic independence assumption implies each transmission sees the system in the steady-state. Then $p_{b_{i,x}}$ can be defined as

$$p_{b_{i,x}} = \begin{cases} 1 - \prod\limits_{i':d_{i'} \leq d_x} (1-\tau_{i'})^{N_{i'}}, & \text{if } \mathrm{d_x < d_i} \\ 1 - \dfrac{\prod_{i':d_{i'} \leq d_x} (1-\tau_{i'})^{N_{i'}}}{(1-\tau_i)}, & \text{if } \mathrm{d_x \geq d_i}. \end{cases} \quad (10)$$

Similarly, taking the internal collisions into account, $p_{c_{i,x}}$ can be defined as

$$p_{c_{i,x}} = 1 - \prod_{i':d_{i'} \leq d_x} (1-\tau_{i'})^{N_{i'}-1} \prod_{i''>i} (1-\tau_{i''}). \quad (11)$$

Also note that for the heterogeneous scenario in which each station has only one AC, $p_{c_{i,x}}^{het}$ can be calculated using the same formula of $p_{b_{i,x}}$ for $AIFS_x \geq AIFS_i$ as in (10).

Together with the steady-state transition probabilities, (9)-(11) represent a nonlinear system which can be solved using numerical methods.

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,

$$S_i = \frac{p_{s_i} T_P}{p_I T_{slot} + \sum_{i'} p_{s_{i'}} T_s + (1 - p_I - \sum_{i'} p_{s_{i'}}) T_c} \quad (12)$$

where T_P is the average payload transmission time of AC_i which is assumed to be equal for any AC for simplicity (let T_P include the transmission time of MAC and PHY headers), p_I is the probability of the channel being idle at a slot, p_{s_i} is the conditional successful transmission probability of AC_i at a slot, and T_s and T_c are the average length of a successful transmission and a collision respectively.

The probability of a slot being idle, p_I, depends on the state of previous slots as well. For example, conditioned on the previous slot to be busy ($p_B = 1 - p_I$), p_I only depends on the transmission probability of the ACs with the smallest AIFS, since others have to wait extra AIFS slots. Generalizing this to all AIFS slots, p_I can be calculated as

$$p_I = \sum_{l=0}^{E[I]} q_l p_B (p_I)^l \cong \sum_{l=0}^{A-1} q_l p_B p_I^l + q_A p_I^A \quad (13)$$

where q_l denotes the probability of no transmission occuring at the $(l+1)^{th}$ AIFS slot after $AIFS_{i_{max}}$, and $E[I]$ denotes the expected number of idle slots before a transmission occurs. Substituting $q_l = q_A$ for $l \geq A$, and releasing the condition on the upper limit of summation, $E[I]$, to ∞, p_I can be approximated as in (13). As the results in Section IV imply, this approximation works well. For $l \in (0, A)$ and $x = \max\Big(y \mid d_y = \max\limits_z (d_z \mid d_z \leq l)\Big)$, q_l can be calculated as

$$q_l = \prod_{i:d_i \leq d_x} (1-\tau_i)^{N_i}. \quad (14)$$

The probabilities of successful transmission for AC_i, p_{s_i}, are conditioned on the states of the previous slots. This is again because the number of stations that can compete at an arbitrary backoff slot differs depending on the number of previous consecutive idle backoff slots. Therefore, taking the internal collisions into account, the probabilities p_{s_i} are calculated as in (15). Similarly, for the heterogeneous case, in which each station only has one AC, $p_{s_i}^{het}$ can be calculated as in (16).

To compute the normalized throughput, S_i, of AC_i, it is now only necessary to specify the corresponding values of T_s and T_c. Let δ be the propagation delay, ACK be the time required for acknowledgment packet (ACK) transmission, and $ACK\_Timeout$ be the retransmission timeout for the data frame if an ACK is not received. Then, for the basic access

$$p_{s_i} = \frac{N_i\tau_i}{(1-\tau_i)} \left(\sum_{x=d_i+1}^{A} \left(p_B p_I^{(x-1)} \prod_{x':0\leq d_{x'}\leq (x-1)} (1-\tau_{x'})^{N_{x'}-1} \prod_{i'>i} (1-\tau_{i'}) \right) + (p_i)^A \prod_{\forall x'} (1-\tau_{x'})^{N_{x'}-1} \prod_{i'>i}(1-\tau_{i'}) \right) \quad (15)$$

$$p_{s_i}^{het} = \frac{N_i\tau_i}{(1-\tau_i)} \left(\sum_{x=d_i+1}^{A} \left(p_B p_I^{(x-1)} \prod_{x':0\leq d_{x'}\leq (x-1)} (1-\tau_{x'})^{N_{x'}} \right) + (p_i)^A \prod_{\forall x'} (1-\tau_{x'})^{N_{x'}} \right) \quad (16)$$

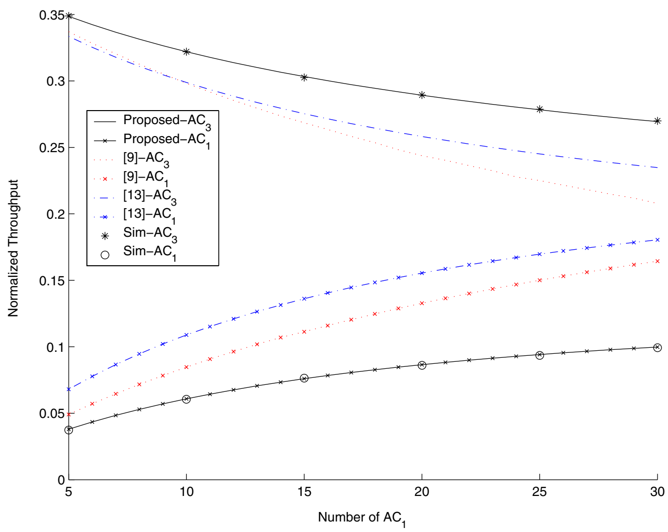

Fig. 3. Analytically calculated and simulated normalized throughput of each AC with a fixed N_3 of 10 and N_1 varied from 5 to 30 ($AIFSN_1 = 3$, $AIFSN_3 = 2$, $CW_{1,min} = 31$, $CW_{3,min} = 15$). Analytical results from [9] and [13] are also added for comparison.

scheme,

$$\begin{aligned} T_s^{bas} &= T_P + \delta + SIFS + ACK + \delta + AIFS_{i_{max}} \\ T_c^{bas} &= T_{P^*} + ACK\_Timeout + AIFS_{i_{max}} \end{aligned} \quad (17)$$

where T_{P^*} is the average transmission time of the longest packet payload involved in a collision [4]. Assuming the packet size to be equal for any AC, $T_{P^*} = T_P$. For the RTS/CTS access scheme

$$\begin{aligned} T_s^{rts} &= RTS + SIFS + CTS + SIFS + T_P + \delta + SIFS \\ &\quad + ACK + \delta + AIFS_{i_{max}} \\ T_c^{rts} &= RTS + CTS\_Timeout + AIFS_{i_{max}}. \end{aligned} \quad (18)$$

Being not explicitly specified in the standards, we set $ACK\_Timeout$ and $CTS\_Timeout$, using Extended Inter Frame Space (EIFS) in the calculation as $EIFS_i - AIFS_{i_{max}}$ [2], [15].

IV. Numerical and Simulation Results

We validate the accuracy of the numerical results calculated via the proposed EDCA model by comparing them to the simulation results obtained from ns-2 [17]. For the simulations, we employ the IEEE 802.11e HCF MAC simulation model for ns-2.28 that we developed [18]. This module implements all the EDCA and HCCA functionalities stated in [2].

As in all work on the subject in the literature, the simulations consider ACs that transmit fixed sized User Datagram Protocol (UDP) packets. Each AC has always buffered packets that are ready for transmission. Again, as in most of the work on the subject, the simulation results are reported for the wireless channel which is assumed to be not prone to any errors during transmission. All the stations are assumed to have 802.11g PHY using 54 Mbps and 6 Mbps as the data and basic rate respectively ($T_{slot} = 9\mu s$, $SIFS = 10\mu s$) [19]. Due to space limitations, we only report the performance for the heterogeneous case when each station has only one single AC active, either AC_3 or AC_1. For the proposed EDCA model, the analytical calculation uses the Markov models generated via the guidelines stated in Section III. For both ACs, the payload size is 1000 bytes. We set $m_1 = m_3 = 3$ and $r_1 = r_3 = 7$. The RTS/CTS threshold is set such that every transmission is assisted with an RTS/CTS exchange. The simulation runtime is 100 seconds.

For the first two sets of experiments, we set $AIFSN_1 = 3$, $AIFSN_3 = 2$, $CW_{1,min} = 31$, $CW_{3,min} = 15$. Fig. 3 shows the normalized throughput performance of each AC with a fixed N_3 of 10 and N_1 varied from 5 to 30. Similarly, Fig. 4 shows the normalized throughput performance of each AC with a fixed N_1 of 10 and N_3 varied from 5 to 30. The accordance of analytical results with simulation results suggests that our model is highly accurate, and shows no discernable trends toward error. The figures also highlight the importance of accurate collision probability treatment by comparing the results with [9] and [13]. The saturation throughput performance prediction error for [9] and [13] is significant for a scenario of 2 ACs with AIFSN difference of 1. We have also implemented the model in [11] for performance comparison. Although we are able to duplicate the results in [11], the solution of the nonlinear system of equations does not converge for the 2 AC scenarios considered in this paper.

For the third set of experiments, we set $AIFSN_3 = 2$, $CW_{3,min} = 15$, $N_1 = N_3 = 10$. Fig. 5 displays the normalized throughput performance of each AC when $AIFSN_1$ varies from 3 to 5 and $CW_{1,min}$ takes values from the set $\{15, 31, 63, 127, 255\}$. The saturation throughput prediction of our model closely follows the simulation results.

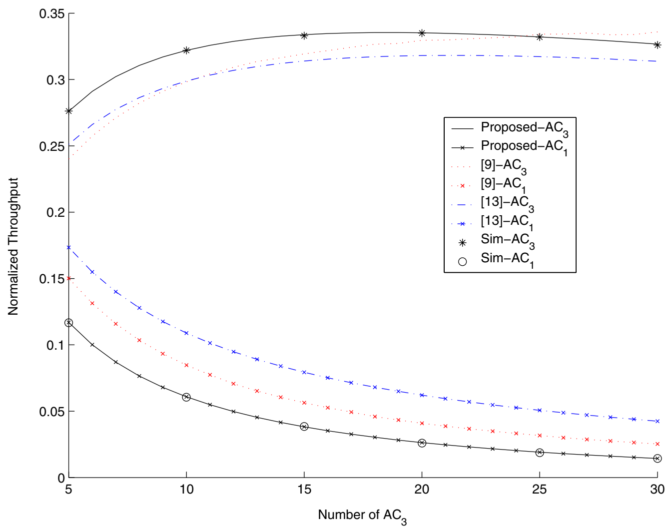

Fig. 4. Analytically calculated and simulated normalized throughput of each AC with a fixed N_1 of 10 and N_3 varied from 5 to 30 ($AIFSN_1 = 3$, $AIFSN_3 = 2$, $CW_{1,min} = 31$, $CW_{3,min} = 15$). Analytical results from [9] and [13] are also added for comparison.

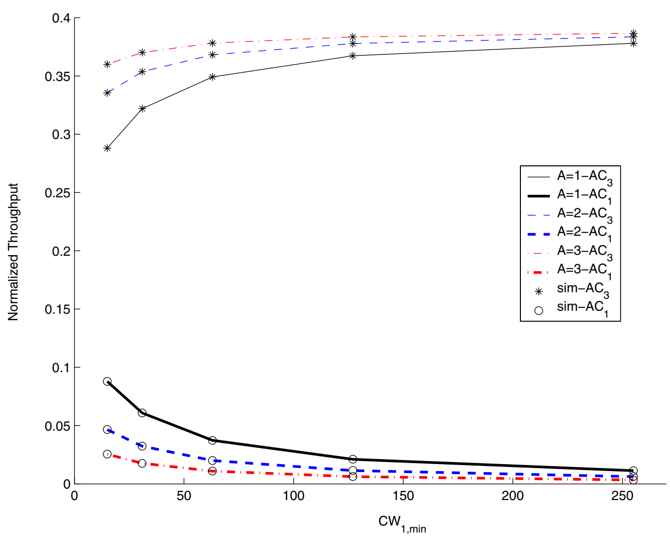

Fig. 5. Analytically calculated and simulated performance of each AC when $AIFSN_3 = 2$, $CW_{3,min} = 15$, $N_1 = N_3 = 10$, $AIFSN_1$ varies from 3 to 5, and $CW_{1,min}$ takes values from the set $\{15, 31, 63, 127, 255\}$. Note that $AIFSN_1 - AIFSN_3$ is denoted by A.

V. Conclusion

We have presented an accurate Markov model for analytically calculating the EDCA saturation throughput. The model accounts not only for AIFS and CW differentiation mechanisms, but also for the virtual collision procedure. The proposed model is valid and accurate for any number of ACs and arbitrary selection of EDCA parameters.

The key point is that the proposed Markov chain incorporates the varying probability of collision at different AIFS and backoff slots correctly. By comparing the results of our analysis with the simulation results as well as with the analytical results of the EDCA models in the literature, one can clearly see that including the correct treatment of AIFS differentiation in the model is vital for the accuracy of theoretical performance analysis.

The non-existence of a closed-form solution for the Markov model limits its practical use. On the other hand, the accurate saturation throughput analysis can highlight the strengths and the shortcomings of EDCA for varying scenarios and can provide invaluable insights. The model can effectively assist EDCA parameter adaptation or a call admission control algorithm for improved QoS support in the WLAN.

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