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A Synthetic model of IEEE 802.11e EDCA

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Abstract—This paper proposes a very simple reduced abstract model of the behavior of the EDCA (Enhanced Distributed Channel Access) access mode with respect to an access category under saturation. This model is derived from a Markov chain model of EDCA using reduction techniques. Closed-form expressions of common performance metrics (i.e. mean throughput, mean access delay and packet drop probability of an access category) are given and insight into the potential applications of this model are briefly presented.

I. INTRODUCTION

The IEEE 802.11e work group [1] introduced QoS (Quality of Service) mechanisms into the MAC layer (Medium Access Control) of the legacy IEEE 802.11 standard. This mainly consisted in the definition of a new access function: HCF (Hybrid Access Control) which combines two access modes, one of these is EDCA (Enhanced Distributed Channel Access) which is an enhancement of DCF (Distributed Coordination Function based on a CSMA/CA scheme). EDCA is the area of interest of our work. With respect to DCF, EDCA introduces the traffic differentiation concept, thus defining four access categories (AC), each corresponding to a different queue within the station. A CSMA/CA scheme is implemented by each AC . This scheme is based on the arbitration (characterized by the AIFS parameter (Arbitration Inter Frame Space)) and on the backoff procedure (characterized by the contention window (CW) and the range $[CW_{min}, CW_{max}]$). AIFS and CW play the same role as DIFS and CW in DCF. The choice of AIFS and CW allow to prioritize the AC traffic (the smaller the AIFS and CW , the higher the access probability). Due to the presence of several queues within a station, EDCA introduces, in addition to real collisions (physical collisions in the channel involving queues from different stations), a new kind of collisions, named virtual collisions. These latter take place when at least two queues from the same station try to access the medium at the same time after their backoff period. It results in granting the access to the highest priority queue and penalizing the others (by widening the CW in the same manner as a real collision). EDCA involves several complex mechanisms, those are not always clearly specified thus inducing a lot of questioning among the people working on it. The use of formal methods is of great interest to help the understanding and guide the analysis and the performance evaluation of the protocol. Some models have already been proposed in the literature [2], [3], models which assume a

saturation regime (thus frequent collisions) and which are mainly inspired by the Bianchi model of DCF [4]. Zhu and Chlamtac [2] proposed a two dimensional model of an EDCA AC which considers neither the virtual collision aspect nor the time elapsing during a transmission on the medium. The model of Kong et. al. [3] captures this latter aspect (at a cost of a new dimension in the model - the overall model of EDCA is a three dimensional discrete Markov chain). However it does not describe explicitly the virtual collision nor does it represent all the mechanisms described in the standard [1], [5].

In [6], we have addressed these issues and proposed a new Markov chain model that describes precisely (with respect to the 802.11e amendment) the behavior of an EDCA access category under saturation. The work presented in this paper completes this previous work. It presents closed-form expressions for the most important metrics that describe the performance perceived by the AC , namely Mean access delay, throughput and packet drop probability. These were derived from a very simple abstract model statistically equivalent to the initial model of [6] that we obtained by applying iteratively Beizer's rules [7].

This paper is organized as follows: section 2 and 3 describe briefly the Markov chain model that we proposed in [6]. The former presents the modeling methodology while the latter describes its different components. Section 4 presents the main contribution of this paper, i.e. the abstract model and the closed-form expressions of the performance metrics. Section 5 gives some insight on the potential use of the model. Finally, section 6 concludes the paper.

II. GUIDES FOR THE MODELING

A. AC_i behavioral view

We give an abstract view of an AC_i 's behavior ($i \in (0, 1, 2, 3)$ in descending priority order) in figure 1. The transmission of a packet is implemented through a series of access attempts. Each is based, at first, on the sequence of two processes (AIFS and backoff), defining the medium idleness test before the actual transmission attempt, and then on the actual transmission attempt (i.e. the decision to make a transmission). The result of each actual transmission is either a successful transmission (following which the sending of a new packet is considered) or a collision (following which the packet's retransmission is considered). Note that contention windows in EDCA, as it is in DCF, are managed as a Binary Exponential Backoff. The

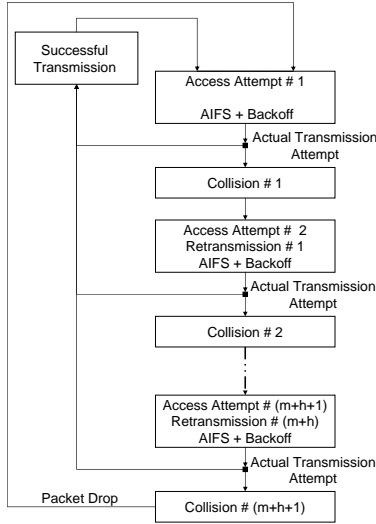


Fig. 1. Behavior of an AC_i

maximum value of a contention window CW_{max} is attained after m attempts, this value will be used for h additional retransmissions before reaching the Retransmission Threshold ($m + h$) after which the collided packet is dropped. *This abstract view highlights the basic patterns for the modeling: AIFS procedure, Backoff procedure, actual transmission attempt procedure and their results.*

B. The basic patterns

1) *AIFS procedure*: Any transmission attempt starts with the random choice of the value of the Backoff Counter ($B_C[AC_i]$) within the current contention window range $[0, CW[AC_i]]$ (this value defines the backoff time which will be used at the end of the AIFS period). The AIFS procedure consists in the necessity to observe the medium idleness during the AIFS period. If, during the AIFS period (We call A its duration in terms of time slots), the medium becomes busy, we have the AIFS decrementing freeze during the medium occupation time (we call N the mean value of this duration in terms of time slots) after which the AIFS countdown is reset. At the end of the last slot of AIFS, if the medium is still idle, two outputs are possible: if $B_C[AC_i] = 0$, the AC will directly attempt a transmission; if $B_C[AC_i] > 0$, the value of $B_C[AC_i]$ is decremented by one, thus initiating the backoff procedure.

2) *Backoff procedure*: A backoff procedure will mainly consist in decrementing the value of $B_C[AC_i]$ while the medium is idle. The value of $B_C[AC_i]$ is decremented until it reaches 0, one slot after which a transmission is directly attempted if the medium is still idle. If during the backoff counter decrementing, the medium becomes busy, the decrementing procedure is stopped and frozen during a time which is the sum of the medium occupation time and an AIFS period (this time has the value $N + A$), if during the AIFS period, the medium is busy again, the process is repeated. At the end of the last slot of AIFS, if the medium is still

idle, two outputs are possible: if $B_C[AC_i] = 0$, the AC will directly attempt a transmission; if $B_C[AC_i] > 0$, the value of $B_C[AC_i]$ is decremented, thus resuming the backoff procedure.

3) *Actual transmission attempt*: When an AC_i decides to initiate a transmission attempt, either it is the only one within the station that wants to transmit, in which case it will directly access the medium, or there is at least another AC within the station also wishing to transmit, in which case both AC s will go into a virtual collision. Within the virtual collision handler, the AC winner of the virtual collision (thus accessing the medium) is the higher priority AC . If AC_i loses the virtual collision, then the medium will be accessed by an AC , virtually colliding with AC_i and having a higher priority. An actual transmission attempt is followed by three outcomes:

- 1) The transmission was successful, in which case AC_i occupied the medium for a duration $[T_s]$ ($[T_s]$ is the smallest integer -in time slots- higher than T_s the duration of a successful transmission) and a new packet transmission is then taken into consideration.
- 2) AC_i suffered a real collision, in which case AC_i occupied the medium for a collided transmission time $[T_c]$ and the packet may be retransmitted within the retry threshold limit.
- 3) AC_i lost a virtual collision, in which case AC_i will not occupy the medium, a higher priority AC within the station will transmit (either suffering a collision thus occupying the medium for $[T_c]$ or transmitting successfully thus occupying the medium for $[T_s]$). AC_i 's packet may be retransmitted within the retry threshold limit.

Situations 2 and 3 above define globally, what we call, the collision situation for AC_i .

III. AC_I MODELING

A. Basics for the modeling

a) *AC_i Behavior*: We represent it by a discrete-time Markov chain where the state must be represented without ambiguity. A state of the discrete Markov chain must specify both *the packet access attempts* (we have to distinguish on one hand the successive attempts and their corresponding collisions and on the other hand a successful transmission), *the backoff counter* (we have to distinguish on one hand the backoff procedure where the backoff counter is meaningful and on the other hand the situations where the backoff counter is meaningless) and *the remaining time to the end of the different timed actions* (AIFS, medium occupancy, collision, successful transmission). Therefore a state of the discrete Markov chain is represented by a triplet (j, k, d) with j representing the state of the packet attempt, k the backoff counter and d the remaining time. We consider the following values for each of the components:

- j : $0 \leq j \leq m + h$ for the successive attempts ($j = 0$ for the first attempt and $1 \leq j \leq m + h$ for the following retransmission attempts), each value of j is associated to all the states of the AIFS period before the

backoff, the stage of the backoff procedure where the value of the contention window $CW[AC_i]$ is noted W_j , and the collision situation; the successful transmission is represented by $j = -1$.

- k : $0 \leq k \leq W_j$ for stage j of the backoff procedure; in the other cases where k is meaningless we take a negative value for k (different negative values should be taken, for triplet uniqueness reasons, depending on the situation as we explain after the specification of the values of d).
- d : $1 \leq d \leq \lceil T_s \rceil$ for the duration of a successful transmission of AC_i or after a virtual collision of AC_i (where AC_k , winner of the virtual collision, successfully transmits); $1 \leq d \leq \lceil T_c \rceil$ for the duration of a collision (of either AC_i or AC_k winner of the virtual collision); $1 \leq d \leq A$ for the AIFS duration; $A + 1 \leq d \leq N + A$ for the medium occupancy duration occurring during an AIFS period or during backoff counter decrementing. We consider $\lceil T_c \rceil < \lceil T_s \rceil$.

As for each attempt j the AIFS period before the backoff and the collision situation (in both situations the backoff counter is meaningless) can have remaining time values which can be identical, it is necessary, in order to avoid state ambiguity, to distinguish these states by a different negative value of k ; we choose: $k = -1$ for the collision situation and $k = -2$ for the AIFS period. The value of k for the successful transmission period is not problematic because of the different value of j , we thus choose $k = -1$.

b) Transition probabilities: Before defining the different pattern models forming the whole model, we must define the probabilities that will be associated to the transitions. At first we define the following basic probabilities:

- The probability of the medium becoming busy (p_b) or staying idle ($1 - p_b$).
- The probabilities related to the access attempt of AC_i , whether competing or not with the other access categories within the station (leading in the first case to a virtual collision situation): \overline{p}_i^v is the probability for AC_i not to go into a virtual collision when attempting to access, p_i^{wv} is the probability for AC_i to go into a virtual collision and win it and p_i^{lv} is the probability for AC_i to go into a virtual collision and lose it. Note that $\overline{p}_i^v + p_i^{wv} + p_i^{lv} = 1$.
- The probability for AC_i to suffer a real collision during its actual access to the medium (i.e. either AC_i went into a virtual collision and won it or did not go into a virtual collision at all): p_i^r . We have $p_i^r + \overline{p}_i^r = 1$.
- The probability (after the loss of a virtual collision by AC_i) for the AC winning the virtual collision (let AC_k be it) to suffer a real collision: p_k^r . We have $p_k^r + \overline{p}_k^r = 1$.
- The probability of the random choice of the Backoff Counter ($B_C[AC_i]$) within the contention window for the j^{th} retransmission is $\frac{1}{W_j + 1}$.

Based on those basic probabilities, we define the probabilities characterizing the collision situation:

- $p_i^{(2)}$ is the probability of an unsuccessful transmission attempt resulting in a $\lceil T_c \rceil$ slot occupation of the medium,

i.e. either AC_i suffered a real collision or AC_i lost a virtual collision and AC_k , winner of this virtual collision suffers a real collision: $p_i^{(2)} = (\overline{p}_i^v + p_i^{wv})p_i^r + p_i^{lv}p_k^r$.

- $p_i^{(3)}$ is the probability of an unsuccessful transmission attempt resulting in a $\lceil T_s \rceil$ slot occupation of the medium, i.e. AC_i loses a virtual collision and AC_k , winner of the virtual collision, successfully transmits: $p_i^{(3)} = p_i^{lv}\overline{p}_k^r$.
- p_i is the probability of a collision of AC_i (a real collision or a lost virtual collision): $p_i = p_i^{(2)} + p_i^{(3)}$.

B. Models of the basic patterns

We at first present the graphs of each model, we then indicate how to get the global model from these graphs. In each of the following models we represent the input and output states in bold line type and the internal states in normal line type. The states that do not belong to the presented pattern (which either lead to an input state of the pattern or are led to from an output state) are represented in dotted line type (note that those external states are necessarily output/input states of other patterns). All the transitions are labelled with the transition probabilities presented in section III-Ab.

1) *Pattern: AIFS procedure and outputs:* The model is given in figure 2. The different states of the pattern are self explanatory. We added to each of the transitions from the output state $(j, -2, 1)$ a Predicate/Transition type label. The predicate is the value of the Backoff Counter ($B_C[AC_i]$) that has been randomly chosen at the beginning of the AIFS procedure (see section II-B1). If $B_C[AC_i] = 0$, there will be a transmission attempt at the end of the last slot of AIFS if the medium is still idle, the transmission attempt will either lead to a successful transmission (state $(-1, -1, \lceil T_s \rceil)$) or to a collision (state $(j, -1, \lceil T_s \rceil)$ in case AC_i loses a virtual collision and AC_k , winner of the virtual collision, transmits successfully, or state $(j, -1, \lceil T_c \rceil)$ in case AC_i collides or in case it loses a virtual collision and AC_k collides). If $B_C[AC_i] > 0$, the chain transits into one of the states $[(j, 0, 0), (j, 1, 0) \dots (j, W_j - 1, 0)]$ representing the beginning of the backoff procedure.

2) *Pattern: Backoff procedure and outputs:* The model is given in figure 3. The input states of the model are $[(j, 0, 0), (j, 1, 0) \dots (j, W_j - 1, 0)]$. The transitions between these states represent the decrementing of the backoff counter while the medium is idle (probability $1 - p_b$). If the medium goes busy (probability p_b), the decrementing will be frozen during the medium occupancy and an AIFS period (represented by the subset of states above each counter decrementing state). From the output states $((j, 0, 0)$ or $(j, 0, 1))$, a transmission is attempted if the medium is idle. The transmission attempt will lead into one of the states $(-1, -1, \lceil T_s \rceil)$, $(j, -1, \lceil T_s \rceil)$, $(j, -1, \lceil T_c \rceil)$ (as in section III-B1 - case where $B_C[AC_i] = 0$).

3) *Pattern: Actual transmission attempt:* The model is given in figure 4. The states $(j, -2, 1)$, $(j, 0, 1)$ and $(j, 0, 0)$ are respectively the output states in the model "AIFS Procedure" for the first one and "Backoff procedure" for the two others. Those are the states leading to a transmission attempt and

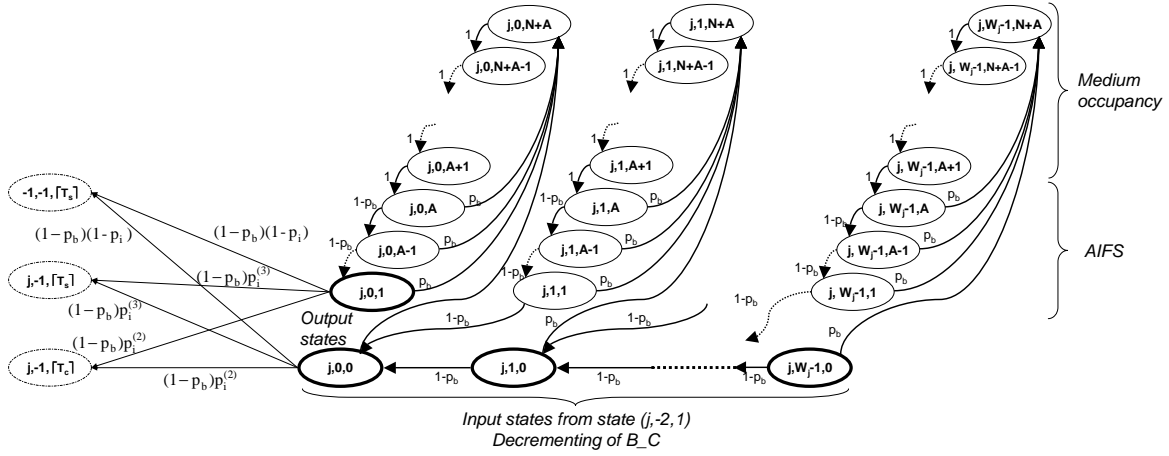


Fig. 3. Backoff Procedure pattern: $0 \leq j \leq m + h$

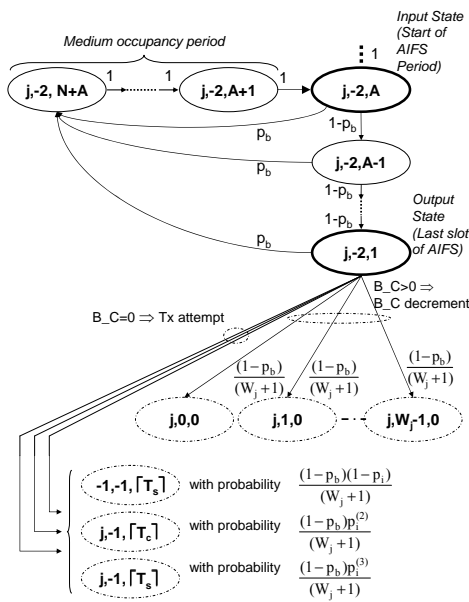


Fig. 2. AIFS procedure pattern: $0 \leq j \leq m + h$

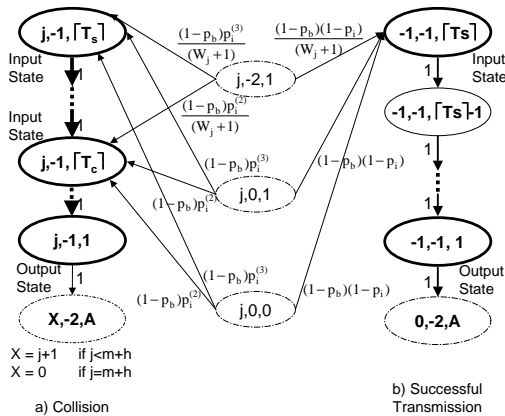


Fig. 4. Outcomes of an actual transmission attempt: $0 \leq j \leq m + h$

resulting in either a successful transmission (right part of the figure) or a collision (left part of the figure). In case of a collision, two different entry states are possible (both leading to state $(j, -1, 1)$ meaning two different medium occupancy time):

- states $(j, -1, [T_s])$ for a $[T_s]$ occupancy time in case AC_i lost a virtual collision and AC_k , winner of the virtual collision, successfully transmits;
- $(j, -1, [T_c])$ for a $[T_c]$ occupancy time either in case AC_i accesses the medium and collides or in case AC_i loses a virtual collision and AC_k , winner of the virtual collision, collides.

Once the process is finished it will lead:

- in case of a successful transmission, a new packet is taken into consideration, we thus go to its first access attempt (state $(0, -2, A)$);
- in case of a collision, if the retry threshold has not been reached, the packet will go into a new transmission attempt (state $(j + 1, -2, A)$), if the retry threshold has been reached, the packet is dropped and a new packet is taken into consideration (state $(0, -2, A)$).

C. Global model

The global model is got by connecting the models of the different "Access Attempts" following the guide of figure 1 (with $j = 0, 1, 2 \dots m, \dots m + h$).

IV. GETTING AN ABSTRACTION OF THE MODEL

The abstraction focuses on three important states (Start of the first access attempt, successful transmission and packet drop) and on the transition probabilities and durations of these states. It is obtained using the Beizer rules [7] on probabilistic and timed state graphs (a link between two states a and b is labelled with the transition probability P_{ab} and the conditional sojourn time T_{ab}). In the following sections we present the rules used in order to achieve the abstraction of the initial model, we then describe the process of abstraction and the final result.

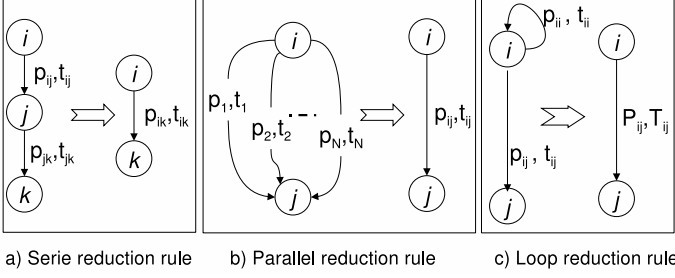


Fig. 5. Beizer reduction rule

A. The Beizer Rules

In [7], Beizer detailed several rules used to replace nodes in a probabilistic and timed state graph with links that are statistically equivalent to them. The rules correspond to the three situations which can occur: series links, parallel links and loops. The procedure used is iterative: it consists in choosing a node to replace, replace it with the equivalent links (using the series link replacement rule), then combining the parallel links and finally removing loops.

1) *The "series" rule:* It consists in replacing a linear chain of links by one statistically identical link. In figure 5-a, $p_{ik} = p_{ij} \times p_{jk}$ and $t_{ik} = t_{ij} + t_{jk}$.

2) *The "parallel" rule:* It consists in replacing several links linking two nodes by one statistically identical link. In figure 5-b, $p_{ij} = \sum_{k=1}^N p_k$ and $t_{ij} = \frac{\sum_{k=1}^N p_k \times t_k}{\sum_{k=1}^N p_k}$.

3) *The "loops" rule:* It consists in integrating a loop link of a node into the links excident to the looping node. In figure 5-c, $P_{ij} = \frac{p_{ij}}{1-p_{ii}}$ and $T_{ij} = t_{ij} + \frac{t_{ii} \times p_{ij}}{1-p_{ii}}$.

B. On the abstraction process of the model

We will refrain from detailing the tedious work needed to accomplish all the transformations necessary in order to attain the abstract view of the model both for lack of space and for it being out of scope in this paper. The details can be checked in the technical report [8]. We will present one intermediary model because of the interest it holds before presenting the final equivalent abstract model.

1) *Intermediary model:* The intermediary model of the abstraction we present in figure 6 mainly represents the behavior of the Binary Exponential Backoff essential for the Collision Avoidance of the CSMA/CA scheme. We present this intermediary model for two main reasons: first it shows the different collision stages a transmission may go through. This may be practical for a study of the collisions. The second, more visual, is that the intermediate model corresponds to the abstract view we presented earlier in this paper (figure 1), thus helping the reader to put into context both the complete model and the abstract model we present in the next section. In figure 6, states $\{j, -2, A\}$ (with $1 \leq j \leq m+h$) represent the different AIFS deference states that follow a collision. State $\{0, -2, A\}$ represents the beginning of the first attempt to send a packet. States $\{j, -2, 1\}$ (with $0 \leq j \leq m+h$) represent the different backoff stages. These are followed

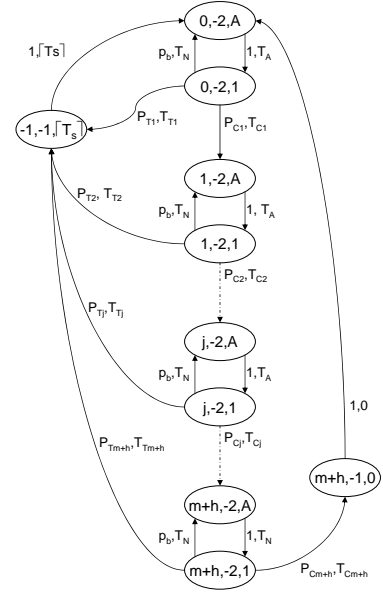


Fig. 6. Intermediary model

either by a collision (transiting to state $\{j+1, -2, A\}$) or by a successful transmission (represented by state $\{-1, -1, [T_s]\}$). If the backoff state $\{m+h, -2, 1\}$ is followed by a collision, the packet is dropped. We introduced a new state labelled $\{m+h, -1, 0\}$ to represent the packet drop situation. Transiting from states $\{-1, -1, [T_s]\}$ and $\{m+h, -1, 0\}$ to state $\{0, -2, A\}$ represents the decision to send a new packet after respectively the successful transmission or the drop of the previous packet. The expressions of the different durations and probabilities [8] and their meanings are:

$$T_A = A - 1 + \frac{\sum_{l=1}^{A-1} (N+1)p_b(1-p_b)^{l-1}}{(1-p_b)^{A-1}}$$

T_A represents the duration of the first AIFS period per transmission attempt, taking into account the possible busy medium periods during the AIFS period.

$$T_N = N + 1$$

T_N represents the medium busy duration when detected during the AIFS period.

$$T_{tj} = \frac{1}{W_j+1} \left[1 + \frac{W_j^2+W_j}{2} T_o + W_j \right]$$

T_{tj} represents the duration of the backoff time before starting a successful transmission.

$$T_{cj} = \frac{1}{W_j+1} \left[1 + \frac{W_j^2+W_j}{2} T_o + W_j \right] + \frac{[T_s]p_i^{(3)} + [T_c]p_i^{(2)}}{p_i}$$

T_{cj} represents the duration of the backoff time before starting a collision to which is added the collision duration.

$$T_o = \frac{(1+(N+A)p_b)(1-p_b)^A + \sum_{l=1}^A (N+l)p_b^2(1-p_b)^{(l-1)}}{(1-p_b)^A}$$

T_o represents the time it takes to decrement the backoff counter (of one unit: e.g. from state $\{j, 1, 0\}$ to state $\{j, 1, 0\}$ in figure 3), taking into account the possible busy medium periods during the process.

$$P_{tj} = (1-p_b)(1-p_i) \text{ and } P_{cj} = (1-p_b)p_i$$

Note that T_{tj} and T_{cj} both depend on the backoff stage (since they both are function of W_j) with $0 \leq j \leq m+h$. W_j being constant for $j \geq m$, T_{tj} and T_{cj} remain constant.

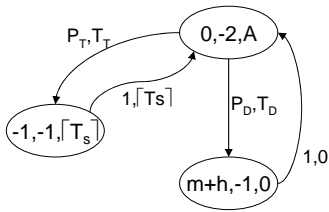


Fig. 7. Abstract model of EDCA

2) *Abstract Model*: Figure 7 represents the final abstract model which is gotten from the intermediary model in figure 6. The behavior of EDCA is reduced to a three state model. The remaining states are those relevant from the point of view of a user wishing to know the results of an attempt to transmit a packet: Access Attempt state $\{0, -2, A\}$ called state 1, successful transmission state $\{-1, -1, \lceil T_s \rceil\}$ called state 2 and the packet drop state $\{m + h, -1, 0\}$ called state 3.

The probabilities P_D and P_T respectively represent the probability for a packet to be dropped or successfully transmitted.

$P_D = p_i^{m+h+1}$, a packet is dropped if it suffers a collision at each of the $(m+h+1)$ transmission attempts.

$P_T = 1 - p_i^{m+h+1}$ which is the complement of P_D .

T_D and T_T represent respectively the duration between the beginning of the access attempt of a packet until either its drop or the beginning of its successful transmission.

$$T_D = \sum_{j=0}^{m+h} (T_A + \frac{(T_A+T_N)p_b}{1-p_b} + T_{c_j})$$

T_D is the sum of all the collision durations $(m + h + 1)$ collision in total, to which are added all the AIFS periods and the possible busy medium periods.

$$T_T = \frac{1-p_i}{1-p_i^{m+h+1}} \sum_{j=0}^{m+h} [p_i^j (T_A + \frac{(T_A+T_N)p_b}{1-p_b} + T_{t_j}) + \sum_{l=0}^{j-1} (T_A + \frac{(T_A+T_N)p_b}{1-p_b} + T_{cl})]$$

T_T integrates for all the values of j ($0 \leq j \leq m + h$) two terms: the duration before a successful transmission at the j^{th} attempt begins and the duration of the collisions that preceded.

From the transition probability matrix of the graph of figure 7, we get the equilibrium state probabilities of states 1, 2 and 3: ($\Pi_1 = \frac{1}{2}$; $\Pi_2 = \Pi_1 P_T$; $\Pi_3 = \Pi_1 P_D$).

3) *Derived performances*: This graph leads to the following performance metrics, essential from the user's point of view:

a) *The throughput*:

$$\text{Throughput}_i = \frac{\Pi_2 T_s}{\Pi_1 (P_T T_T + P_D T_D) + \Pi_2 T_s + \Pi_3 \times 0} \quad (\text{the sojourn time in state 3 is null}). \text{ Thus we finally have:}$$

$$\text{Throughput}_i = \frac{P_T \lceil T_s \rceil}{P_T T_T + P_D T_D + P_T \lceil T_s \rceil}$$

b) *The mean access delay*: The mean access delay of a packet is the mean time between it first comes into consideration and its successful transmission which is equivalent to T_T .

c) *The packet drop probability*: Similarly, the packet drop probability is P_D

4) *Validation*: The model has been validated against simulation. It has shown to particularly fit the simulation when the collision probabilities are exact. For space reasons, the

validation process is not presented in this paper. The interested reader can refer to [8].

V. APPLICATION

The synthetic model can be used in several different contexts : performance analysis of EDCA or more interestingly as the basis of an admission control algorithm for QoS provision in a 802.11e BSS (Basic Service Set). The idea is to use the closed-form expressions of section IV-B3 in order to derive the achievable throughput and mean delay of an *AC* in a specific network context (values of medium occupation probability and mean collision probability representing the network condition are retrieved by measurement means). Admission decisions would be based on an evaluation of the achievable performances compared to the requested ones. Such an algorithm will take advantage in using our proposed model since thanks to the closed-form expressions of IV-B3 the numerical resolution of the Markov chain is no longer needed. The computation implied by admission control are significantly reduced which is very important in an embedded context (admission control being embedded in the access point).

VI. CONCLUSIONS

In this paper we presented an abstract model of the Markov chain model of EDCA. The obtained model is synthetic and integrates closed-form expressions of common performance metrics. When contrasted to simulation, it gave a good match especially when the collision probabilities were precise. We are now working on an admission control algorithm which relies on the synthetic model presented in this paper. By injecting some network condition measures (collision probabilities, ..) into the model, the achievable throughput and delay that can be provided to a new arriving flow can be easily assessed and contrasted to its requirements.

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