A Geometric Distribution for Backoff Time in IEEE 802.11 DCF: An Analytical Study

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Abstract: Today's networks, including WLANs, transport different classes of services. A service differentiation is then essential to provide QoS. However, IEEE 802.11 for WLANs was primarily designed for best effort traffic and did not provide QoS specifications. IEEE 802.11e MAC has been then described to support QoS in WLAN. In this paper, we propose a new scheme for service differentiation which is based on the 802.11 standard and requires minor modifications. In fact, we act on DCF which uses the backoff procedure to solve contention in WLANs. For this scheme, we use, instead of the uniform distribution, a geometric distribution for random backoff time selection. Using a multi-class system, we propose three parameterizations of the geometric distribution which imply different dynamic differentiation modes and we provide an analytical study, using a Markov chain model, to compare our differentiation modes. We discuss our numerical results which give the performances evaluation of the proposed mechanism in term of throughput and delay.

Keywords: WLAN, 802.11 DCF, Markov chain, service differentiation, QoS.

1. Introduction

Today, network traffic has become more and more diversified, and each type of traffic has its own Quality of Service (QoS) requirements. Service differentiation is so essential for systems of different traffic classes in order to provide QoS. However, the IEEE 802.11 was primarily designed for best effort traffic and did not provide QoS specifications. IEEE 802.11e [2] has been then described to support QoS in WLANs (Wireless Local Area Networks) in introducing priority mechanism. IEEE 802.11e supports service differentiation by assigning data traffic with different priorities based on their QoS requirements.

IEEE 802.11 MAC [1] defines two different access mechanisms, the mandatory Distributed Coordination Function (DCF) which provides distributed channel access based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), and the optional Point Coordination Function (PCF) which provides centrally controlled channel access through polling.

A backoff procedure is necessary in DCF to avoid collision because of the CSMA/CA. Stations sharing the same medium have to wait, in addition to the DIFS (DCF Inter-Frame Space) time period, a random backoff time prior to the transmission if the medium is sensed busy, or was busy just before the station started waiting the DIFS period.

The random backoff value is uniformly chosen from the interval $[0,CW]$, called the Contention Window. CW is initialized to the minimum size CW_{min} and doubled after each unsuccessful transmission, until it reaches the maximum Contention Window size, CW_{max}. CW is reset to CW_{min} after every successful transmission. The selection of the random backoff time doesn't take into consideration the type of traffic circulating in the medium, and thus, the service differentiation is not addressed.

In order to differentiate services, we propose in this paper, a novel scheme which requires minor change from DCF. Instead of the uniform distribution of the random backoff time selection, we use a geometric distribution which takes into account various classes of services.

This paper is organized as follows. Section 2 gives a description of the IEEE 802.11 DCF and discusses related research. Section 3 gives the problem formulation and describes our proposition. We present in the same section three interesting modes of the new scheme operation. In section 4, we give the analytical study using a Markov model and in Section 5 we show our performance evaluation results. Section 6 concludes the paper.

2. Background and Related Research

Before describing our new scheme and proceeding with the problem formulation, it is appropriate to recall the DCF principle on which our new scheme is based. This section gives thus a description of DCF and outlines some proposed schemes to introduce QoS on MAC Level.

2.1. 802.11 Distributed Coordination Function

IEEE 802.11 MAC [1] uses two schemes for channel access: DCF and PCF. DCF is a contention based function that uses CSMA/CA to transmit frames. It can use either the basic access mode in which DATA frames are acknowledged by ACK control frames, or a channel reservation mechanism in which RTS (Request To Send)/CTS (Clear To Send) frames are exchanged before DATA/ACK exchange in order to reduce frame collisions introduced by the hidden terminal problem. In this paper we only consider the basic access mode.

The time is divided into slots. At a slot, a station wishing to transmit a frame has to sense the medium activity. If the medium is busy, the station defers its transmission until the medium is sensed idle for a DIFS (Distributed InterFrame Space) period if the last frame was received correctly. The medium has to be sensed idle for a EIFS (Extended InterFrame Space) period if the last received frame contained an error. At the end of this waiting period, the station adds another waiting period by invoking the BEB (Binary Exponential Backoff) procedure if it is not already invoked.

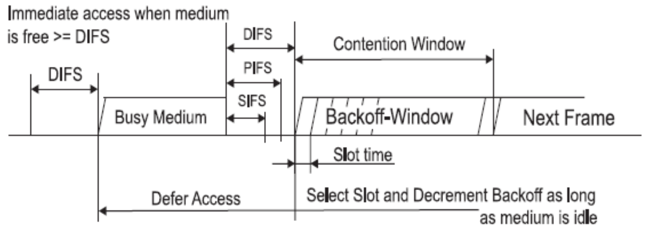


Figure 1. DCF: Basic Access Method

At the beginning of that backoff procedure, a station sets its *backoff* stage to 0, and arms a backoff timer by drawing a uniformly distributed random backoff time (expressed in slots) from an initial contention window of size CW_{min}. The backoff timer is decremented when there is no medium activity, otherwise it is frozen. The backoff timer decrement is resumed if the channel is sensed idle again for a DIFS/EIFS time. The station transmits its frame when the backoff timer reaches zero. If an ACK frame is not received for the transmitted frame, a collision is detected and the station retries to transmit the frame by moving to the next backoff stage where the contention window size is doubled. After the m'^{th} backoff stage, the transmission attempts do not affect the contention window. this latter remains constant with size equal to CW_{max}. The frame is dropped if its transmission is incorrect after the maximum retry limit m.

During the backoff procedure, when an ACK frame is received, the station resets its backoff stage and its contention window to their initial values in order to invoke the backoff procedure for the next frame to be transmitted. This is done also at the backoff stage m whether the transmission is successful or not.

A SIFS (Short InterFrame Space) time is used for ACK frames. If a DATA frame is correctly received, the receiver station waits for a SIFS time before sending the ACK frame. If the ACK frame is not received during an ACK Timeout interval, a collision is assumed to have occurred.

2.2. MAC Level QoS: Related Work

There were many research papers that focused on service differentiation for 802.11 DCF. Some works, as in [3], [4], used a DIFS based differentiation. By giving a smaller DIFS period to the high priority class, stations of that class can access quickly to the medium compared to the low priority class stations.

Service differentiation has been also addressed at backoff procedure level. This is made by differentiating one or more parameters of that procedure as the minimal contention window and the maximal contention window [8], the backoff increase factor [3], the maximum backoff stage [9], [10].

There were also works that have proposed service differentiation at the backoff time selection level. This is done, as in [6], by dividing the backoff interval into sub-intervals where the classes select their backoff time. In [4] classes select the backoff time according to different probability distributions.

The backoff interval in [6] is divided into disjoint subintervals. Each of them corresponds to a class of the network. Each class selects its backoff time only in its own backoff sub-interval. Therefore, as obviously the smallest backoff subinterval corresponds to the highest priority class, then if that class is inactive, it implies that the smallest backoff subinterval will never be chosen due to that strict differentiation. In this paper, our proposition is more flexible, in such a way that all slots are accessible for stations, but with different probabilities depending of the stations classes. If there are no active stations of high priority classes, low priority classes stations are still likely to select earlier slots.

In [4], the authors propose a service differentiation scheme for two classes, using an exponential backoff time selection distribution for the high priority class and a uniform backoff time selection distribution for the low priority class. But using a continuous distribution is not well suited because the backoff time is expressed in term of discrete slots.

Moreover, for the priority implementation in [4], authors change distribution parameter for the high priority class at each backoff stage. That is superfluous because it affects very slightly the backoff time selection for that class in comparison to the evolution of the backoff time selection of the low priority class over the backoff stages. In addition, both [6] and [4] use only simulations to analyze performances of their propositions.

In [9] and [10] authors propose similar multi-class analytical models based on the Markov chains in [5]. Those models provide an analytical framework for service differentiation and include almost all the previous schemes.

In this paper, in order to provide service differentiation, we use a discrete distribution for random backoff time selection that covers all the values of the backoff interval, and that can, at each backoff stage, accelerate or decelerate the access to the medium depending to the priority. Also, we propose an accurate Markov model to evaluate the performances of our proposition in term of throughput and delay.

3. Proposed Scheme Description

Let consider a system of C classes. The idea is that each station of a class $c; c \in [0, C-1]$, will draw a backoff time from a truncated geometric distribution of a parameter α_c in the current backoff interval. We will choose this parameter in such a way that a high priority class will have more chance to select a small backoff time and less chance to select a large backoff time in comparison with a low priority class.

In the following, we define our priority based backoff selection model and propose three modes for priority adaptation to the backoff stage.

3.1. Geometric Backoff Time Distribution

Let W_i denote the backoff interval size at the i^{th} backoff stage. We have:

$$W_i = \begin{cases} 2^i W_0 & i \in [0, m'-1] \\ 2^{m'} W_0 & i \in [m', m] \end{cases} \quad (1)$$

where m' is the backoff stage after which the backoff interval remains constant, m is the maximum retry limit and W_0 is the size of the initial backoff interval.

Instead of uniform random backoff time selection in the backoff interval [0, W_i -1], we propose a non-uniform random backoff time selection which we model by using a truncated geometric distribution defined in [0, W_i -1] where i is the actual backoff stage.

Let ω denote the *pdf* (probability density function) of this distribution.

$$\omega_{c,i,k} = \alpha_c^k \frac{1-\alpha_c}{1-\alpha_c^{W_i}} \quad ; \quad i \in [0,m], k \in [0, W_i - 1], c \in [0, C-1] \tag{2}$$

The parameter $\alpha_c \in \mathbb{R}^{+\star}$ defines the shape and the increase/decrease of the distribution *pdf* of a given class *c*.

Table 1 presents the variation of $\omega_{c,i,k}$ for α_c belonging to different intervals.

From Table 1, we notice that the proposed backoff time selection using a truncated geometric distribution can be taught as a generalization of which the uniform backoff time selection, the no-backoff mode and the maximum backoff time selection are particular cases.

The parameter α_c defines the priority of class *c*. $\alpha_c < \alpha_{c'}$ means that class *c* has more priority than class *c'*, for $c, c' \in [0, C-1]$. We can see that:

$$\alpha_c < \alpha_{c'} \Rightarrow \begin{cases} \omega_{c,i,k} > \omega_{c',i,k} & k \in [0, k_T) \\ \omega_{c,i,k} < \omega_{c',i,k} & k \in (k_T, W_i - 1] \end{cases}$$

where k_T is the point in which the two *pdfs* intersect.

This means that the class *c* has more (resp. less) chance to select the earlier (resp. latter) slots in the range $[0, k_T)$ (resp. $(k_T, W_i - 1]$) than the class *c'*.

Let $E[\omega_{c,i}]$ denote the average backoff time for a class *c* at backoff stage *i*:

$$E[\omega_{c,i}] = \sum_{k=0}^{W_i - 1} k\omega_{c,i,k} = \frac{\alpha_c}{1-\alpha_c} - W_i \frac{\alpha_c^{W_i}}{1-\alpha_c^{W_i}} \tag{3}$$

It can be easily proven that:

$\alpha_c < \alpha_{c'} \Leftrightarrow E[\omega_{c,i}] < E[\omega_{c',i}]$ and

$\alpha_{c'} = \frac{1}{\alpha_c} \Leftrightarrow E[\omega_{c',i}] = W_i - 1 - E[\omega_{c,i}]$

for $i \in [0, m]$ and $c, c' \in [0, C-1]$.

Table 1. $\omega_{c,i,k}$ variations

	$\omega_{c,i,k}$ for $k \in [0, W_i - 1]$	Comment
$\alpha_c \to 0$	$\lim_{\alpha_c \to 0} \alpha_c^k \frac{1-\alpha_c}{1-\alpha_c^{W_i}} = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases}$	Max. priority (no backoff) The probability of selecting slot 0 is sure
$\alpha_c \in (0, 1)$	$\alpha_c^k \frac{1-\alpha_c}{1-\alpha_c^{W_i}}$ ↘ (decreasing *pdf*)	High priority Early slots have more chance to be selected than latter slots.
$\alpha_c \to 1$	$\lim_{\alpha_c \to 1} \alpha_c^k \frac{1-\alpha_c}{1-\alpha_c^{W_i}} = \frac{1}{W_i}$	No priority (uniform) Discrete uniform distribution defined over $[0, W_i - 1]$
$\alpha_c \in (1, +\infty)$ $\alpha'_c = \frac{1}{\alpha_c} \in (0, 1)$	$\alpha_c'^{W_i - 1 - k} \frac{1-\alpha'_c}{1-\alpha_c'^{W_i}}$; ↗ (increasing *pdf*)	Low priority Latter slots have more chance to be selected than early slots.
$\alpha_c \to +\infty$ $\alpha'_c = \frac{1}{\alpha_c} \to 0$	$\lim_{\alpha'_c \to 0} \alpha_c'^{W_i - 1 - k} \frac{1-\alpha'_c}{1-\alpha_c'^{W_i}} = \begin{cases} 1 & k = W_i - 1 \\ 0 & k \neq W_i - 1 \end{cases}$	Min. priority (max. wait. time) The probability of selecting slot $W_i - 1$ is sure.

Let the priority of a class *c* be defined as the fraction of the class *c* average backoff time over the maximum backoff time value at backoff stage *i*:

$$prio_{c,i} = \frac{E[\omega_{c,i}]}{W_i - 1} \qquad (4)$$

Figure 2 plots the class priority as defined in (4) for two classes and their opposites.

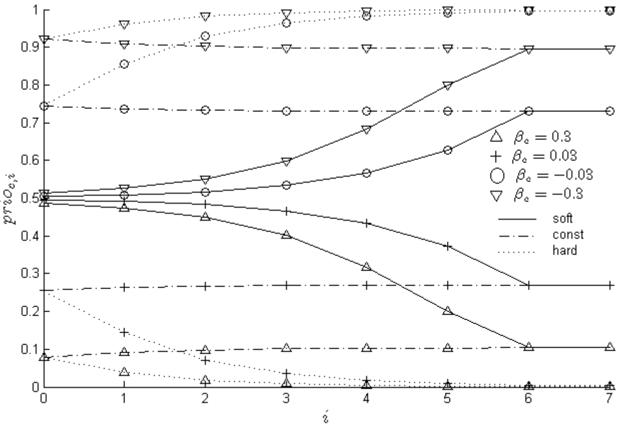


Figure 2. Class priority as a function of the backoff stage (*m'=6* and *m=7*)

3.2. Distribution Parameterization

For sake of symmetric study, we introduce a second parameter $\beta_c \in [-1,1]$. Let the class "basic priority shape" (*bps*) be defined as the shape of the *pdf* of a class *c* with parameter $\alpha_c = \frac{1-\beta_c}{1+\beta_c}$ at backoff stage 0.

In the following, we propose three priority differentiation modes in order to provide QoS guarantees.

3.2.1 Soft Differentiation Mode

$$\alpha_c = \frac{2^{m'} - \beta_c}{2^{m'} + \beta_c} \qquad (5)$$

At the first backoff stage, the classes' distributions are uniform. When the backoff stage increases, they become more differentiated until reaching their *bps* at backoff stage *m'* as in figure 3(b).

3.2.2 Constant Differentiation Mode

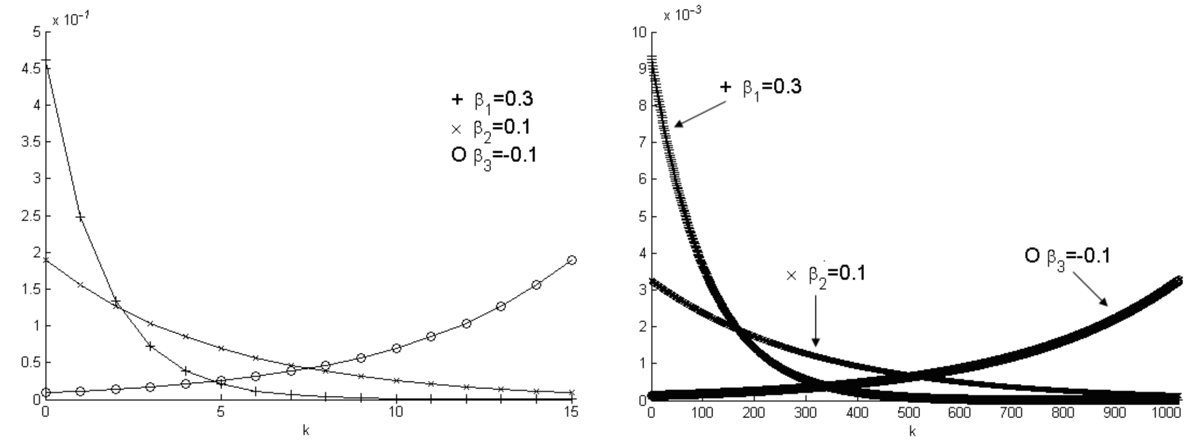
$$\alpha_{c,i} = \begin{cases} \dfrac{2^i - \beta_c}{2^i + \beta_c} & i \in [0, m' - 1] \\ \dfrac{2^{m'} - \beta_c}{2^{m'} + \beta_c} & i \in [m', m] \end{cases} \qquad (6)$$

At the first backoff stage, the classes are differentiated according to their *bps* as in figure 3(a). The distribution shapes are scaled in function of the backoff stage *i* in such a way that, at the *m'*[th] backoff stage (Figure 3(b)), they remain similar to the *bps*.

3.2.3 Hard Differentiation Mode

$$\alpha_c = \frac{1-\beta_c}{1+\beta_c} \qquad (7)$$

The classes are differentiated at the first backoff stage according to their *bps* as in Figure 3(a) When the backoff stage increases, a class distribution shape tends to no backoff mode (resp. maximum waiting time) if its parameter β_c is positive (resp. negative).



(a) $\omega_{c,0,k}$ **(b)** $\omega_{c,6,k}$

Figure 3. *pdf* of three classes at two backoff stages (*m'=6*)

By using the soft differentiation mode, a class will start its backoff procedure using the uniform distribution, and will gain or lose priority depending on the sign of its parameter β_c as the contention in the network increases. Thus low priority classes will not suffer from differentiation when the contention is low since differentiation is applied after contention.

Constant differentiation mode can be applied when the QoS requirements are met and have to be preserved.

Hard differentiation mode can be applied in order to accelerate the access to the medium for high priority classes (i.e. classes with positive β_c parameter) as the contention increases. Those classes will have their backoff times selected in earlier backoff slots, tending to no backoff mode. When this mode is used for low priority classes (i.e. classes with negative β_c parameter), their waiting time increases by forcing them to select high backoff time values, tending to maximum waiting time.

For classes with β_c parameter of the same sign, only one class should use the hard differentiation mode because there is no more differentiation between those classes as the contention increases.

All these differentiation modes are dynamic in such a way that the priority depends on the backoff stage.

4. Analytical Model

We consider a network of n contending stations in ideal channel conditions. The network is divided into classes of n_c nodes, $c \in [0, C-1]$ where C is the number of classes.

In our analysis, we follow the methodology in [5]. Let $b(t)$ (resp. $s(t)$) be the stochastic process representing the backoff counter (resp. stage) for a station of class c at a time t. The time scale is discrete such that t and $t+1$ correspond to the beginning of two consecutive slot times.

Let p_c denote the probability that a station of class c senses the channel busy due to a collision or due to a transmission. p_c is considered to be constant and independent of the past retransmissions.

Figure 4 shows a discrete-time Markov chain which we use to model the bidimensional process $\{s(t), b(t)\}$ for a class c. For readability in figure 4, the probability $\omega_{c,i,k}; i \in [0,m], k \in [0, W_i - 1]$ is denoted by $\omega_{i,k}$.

In order to deal with non-saturated traffic, an artificial state $\{-1, 0\}$ is introduced to model the probability λ of having a frame ready for transmission at the head of the transmission queue of the station at the beginning of a slot.

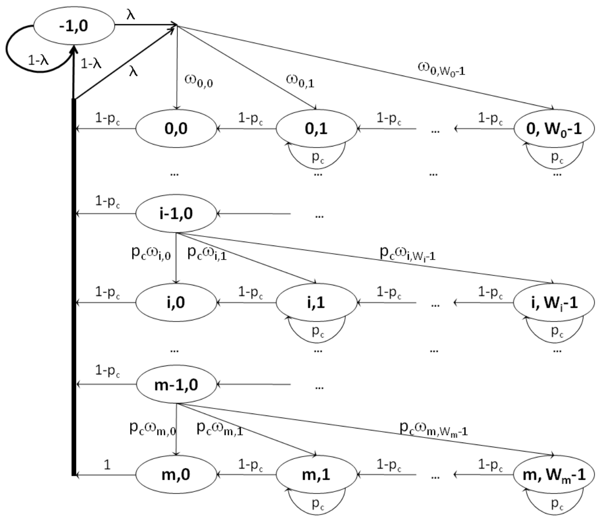


Figure 4. Markov chain model for class c

The non-null transitions probabilities for class c are[1]:

$$P_c\{-1,0|-1,0\} = P_c\{-1,0|m,0\} = 1-\lambda$$

$$P_c\{-1,0|i,0\} = (1-\lambda)(1-p_c),\ i \in [0, m-1]$$

$$P_c\{i,k|i,k\} = p_c, \quad k \in [1, W_i - 1], \quad i \in [0,m]$$

$$P_c\{i,k|i,k+1\} = 1-p_c, \quad k \in [0, W_i - 2], \quad i \in [0,m]$$

$$P_c\{0,k|i,0\} = \lambda(1-p_c)\omega_{c,0,k}, \quad k \in [0, W_0 - 1], \quad i \in [0, m-1]$$

$$P_c\{0,k|m,0\} = P_c\{0,k|-1,0\} = \lambda\omega_{c,0,k}, \quad k \in [0, W_0 - 1]$$

$$P_c\{i,k|i-1,0\} = p_c\omega_{c,i,k}, \quad k \in [0, W_i - 1], \quad i \in [1,m]$$

Let $b_{c,i,k} = \lim_{t\to\infty} P_c\{s(t) = i, b(t) = k\}$ be the stationary distribution of the chain. First, note that, for $c \in [0, C-1]$ we have:

$$b_{c,i,0} = p_c b_{c,i-1,0}; i \in [1,m] \Rightarrow b_{c,i,0} = p_c^i b_{c,0,0}; i \in [0,m]$$

$$b_{c,0,0} = (1-p_c)\sum_{i=0}^{m-1} b_{c,i,0} + b_{c,m,0}$$

Owing to the chain regularities, for each $i \in [0,m]$, we have:

$$b_{c,i,k} = \begin{cases} \dfrac{p_c^i}{1-p_c}\dfrac{\alpha_{c,i}^k - \alpha_{c,i}^{W_i}}{1-\alpha_{c,i}^{W_i}} b_{c,0,0} & k \in [1, W_i - 1] \\ p_c^i\, b_{c,0,0} & k = 0 \end{cases} \quad (8)$$

$b_{c,0,0}$ is determined by imposing normalization condition as follows:

[1] We adopt the short notation:

$$P_c\{i_1, k_1 | i_0, k_0\} =$$
$$P_c\{s(t+1) = i_1, b(t+1) = k_1 | s(t) = i_0, b(t) = k_0\}$$

$$1 = \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{c,i,k} + b_{c,-1,0}$$
$$= b_{c,0,0}\left[\frac{1}{1-p_c}\sum_{i=0}^{m} p_c^i\left(-p_c+\sum_{k=0}^{W_i-1}\frac{\alpha_{c,i}^k-\alpha_{c,i}^{W_i}}{1-\alpha_{c,i}^{W_i}}\right)+\frac{1-\lambda}{\lambda}\right]$$

After some algebraic manipulations we obtain:

$$b_{c,0,0} = \frac{\lambda(1-p_c)}{\lambda\sum_{i=0}^{m} p_c^i\left(-p_c+\frac{1}{1-\alpha_{c,i}}-W_i\frac{\alpha_{c,i}^{W_i}}{1-\alpha_{c,i}^{W_i}}\right)+(1-\lambda)(1-p_c)} \quad (9)$$

Transmissions occur when the backoff counter is equal to 0, then we can express the probability τ_c that a station of class c transmits in a randomly chosen slot time:

$$\tau_c = \sum_{i=0}^{m} b_{c,i,0} = b_{c,0,0}\frac{1-p_c^{m+1}}{1-p_c} \quad ; \quad i\in[0,m] \quad (10)$$

4.1. Throughput Analysis

A transmitted frame of class c collides if at least one node also transmits during the same slot time. The probability p_c that a node of class c senses the channel busy is:

$$p_c = 1-(1-\tau_c)^{n_c-1}\prod_{i=0,i\neq c}^{C-1}(1-\tau_i)^{n_i} \quad (11)$$

Equations (10) and (11) form a nonlinear system of $2C$ unknowns. This nonlinear system can be solved using numerical methods.

Let p_B denotes the probability that the channel is busy (i.e. at least one transmission is occurring in the channel):

$$p_B = 1-\prod_{i=0}^{C-1}(1-\tau_i)^{n_i} \quad (12)$$

Let $p_{S,c}$ denote the transmission probability for class c and let p_S denote the transmission probability for the system.

$$p_{S,c} = n_c\tau_c(1-\tau_c)^{n_c-1}\prod_{i=0,i\neq c}^{C-1}(1-\tau_i)^{n_i} \; ; \quad (13)$$

$$p_S = \sum_{c=0}^{C-1} p_{S,c} \quad (14)$$

The throughput is the fraction of time the channel is used to successfully transmit payload bits. Then, the throughput S_c for class c equal to the following ratio:

$$S_c = \frac{E(\text{payload transmission time in a slot for class c})}{E(\text{length of a slot time})}$$

$$S_c = \frac{p_{S,c}E(P)}{(1-p_B)\sigma + p_S T_S + (p_B - p_S)T_C} \quad (15)$$

where $E(P)$ is the average frame payload size. The denominator is the average duration of a slot, which can be idle, due to a successful transmission, or busy, due to a collision. T_S is the duration of a successful transmission, T_C is the duration of a collision and σ is the average duration of a slot. Thus the system throughput is:

$$S = \sum_{c=0}^{C-1} S_c = \frac{p_S E(P)}{(1-p_B)\sigma + p_S T_S + (p_B - p_S)T_C} \quad (16)$$

For the basic access mechanism, T_S and T_C are written as follow:

$$T_S = T_{DATA} + SIFS + \delta + T_{ACK} + \delta + DIFS$$
$$T_C = T_{DATA}^{*} + \delta + EIFS \quad (17)$$

where T_{DATA} is the transmission duration of a frame of size $E(P)$, T_{ACK} is the transmission duration of an ACK frame. T^*DATA is the average time to send $E(P^*)$ bytes, which is the average length of the longest frame payload involved in a collision. When all the frames have the same size, $E(P) = E(P^*) = P$. δ is the propagation delay.

4.2. Delay Analysis

We follow [9] to calculate the average delay for each class.

Let $X_c; c\in[0,C-1]$ denote the random variable representing the total number of backoff slots which a frame of class c encounters without considering the case when the counter freezes.

$$E(X_c) = \sum_{i=0}^{m}\left[\frac{p_c^i(1-p_c)}{1-p_c^{m+1}}\sum_{j=0}^{i} E[\omega_{c,j}]\right] \quad (18)$$

where $E[\omega_{c,j}]$ is the average backoff time of class c at the j^{th} backoff stage as calculated in [2].

Let $B_c; c\in[0,C-1]$ denote the random variable representing the total number of slots which a frame encounters for the class c when the counter freezes.

$$E(B_c) = \frac{E(X_c)}{1-p_c}\, p_c \quad (19)$$

Let $N_{c,m}; c\in[0,C-1]$ denote the average number of retries for the class c.

$$E(N_{c,m}) = \sum_{i=0}^{m}\frac{i p_c^i(1-p_c)}{1-p_c^{m+1}} \quad (20)$$

Let $D_c; c\in[0,C-1]$ denote the frame delay for the class c. We have:

$$E(D_c) = E(X_c)\sigma + E(B_c)\left(\frac{p_S}{p_B}T_S + \frac{p_B-p_S}{p_B}T_C\right) + E(N_{c,m})(T_C+T_O) + T_S \quad (21)$$

where T_O denote the time that a station has to wait when its frame transmission collides before it senses the channel again, and $T_{ACKtimeout}$ denote the duration of the ACK timeout. $T_O = SIFS + T_{ACKtimeout}$

Thus, the system average delay is equal to:

$$E(D) = \frac{1}{C}\sum_{c=0}^{C-1} E(D_c) \quad (22)$$

5. Performance Results

5.1. Parameters

We implemented our service differentiation model in Matlab in order to obtain the throughput and delay for an IEEE 802.11a network.

Table 2. System Parameters

Frame size	8184 bits	$T_{ACK_{timeout}}$	300 μs
802.11a Data rate	6 Mbps	CWmin	16
802.11a Modulation	BPSK	CWmax	1024
Slot time	9 μs	m'	6
Symbol duration	4 μs	m	10
SIFS	16 μs	$\beta_c = -\beta_{c'}$	0.15

Here, we consider two classes of opposite parameters, a high priority class *c* with parameter β_c and a low priority class *c'* of parameter $\beta_{c'}$. At each time, both classes use the same differentiation mode. There are *n* stations in the system divided in *n/2* stations for each class (Table 2 for parameters values used for calculations).

T_{DATA} and T_{ACK} in (17) are calculated according to 802.11a PHY layer, as in [7].

5.2. Throughput and Delay Analysis

We calculate classes throughput gain $Gain_{Th,c}$ and delay gain $Gain_{Del,c}$ expressed as follows:

$$Gain_{Th,c} = \frac{S_c - \frac{S}{2}}{\frac{S}{2}} \quad ; \quad Gain_{Del,c} = \frac{E(D) - E(D_c)}{E(D)}$$

where *S* and *E(D)* (resp. S_c and $E(D_c)$) are obtained from equations (16) and (22) (resp. (15) and (21)).

Figure 5 (resp. Figure 6) plots *S* and $Gain_{Th,c}$ (resp. *E(D)* and $Gain_{Del,c}$). Solid (resp. dashed) lines represent a traffic load of $\lambda = 0.1$ (resp. saturated traffic $\lambda = 1$). The symbols "△", "▽", "×" represent class *c*, class *c'*, the system respectively.

Since $\beta_c = -\beta_{c'} = 0.15$, we notice that class *c* throughput (resp. delay) gain is equal to class *c'* throughput (resp. delay) loss.

Table 3 provides some numerical values that allow the comparison of class *c* throughput gain (class *c'* throughput loss) using our differentiation modes for different values of the network size and traffic loads.

Table 3. Throughput gain for class c

	$\lambda = 0.1$		$\lambda = 1$	
Soft	$n = 2$	$n = 100$	$n = 2$	$n = 100$
	0.78%	32.8%	2.22%	34.24%
Const.	$n = 2$	$n = 100$	$n = 2$	$n = 100$
	32.86%	60.3%	78.96%	61.66%
Hard	$n = 2$	$n = 20$	$n = 2$	$n = 20$
	34.07%	93.16%	82.02%	96.21%

In Figure 5(a) for λ=0.1, $Gain_{Th,c}$ and $Gain_{Th,c'}$ evolve following the soft differentiation mode. For a network of small size, $Gain_{Th,c}$ and $Gain_{Th,c'}$ are almost null because both class *c* and class *c'* select their backoff times following the uniform distribution. When the size of the network increases, $Gain_{Th,c}$ increases and $Gain_{Th,c'}$ decreases. This is because, the contention increases with the network size. Thus, the stations of class *c* and class *c'* reach higher backoff stages where they become more differentiated.

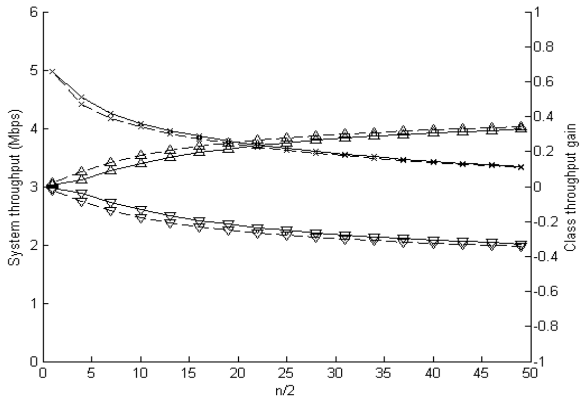
For λ=1, $Gain_{Th,c}$ and $Gain_{Th,c'}$ evolve in a same manner as with λ=0.1. Moreover, as the traffic load is saturated, the stations are more likely to reach higher backoff stages for smaller network size compared to a traffic load of λ=0.1. Thus, $Gain_{Th,c}$ (resp. $Gain_{Th,c'}$) is larger (resp. smaller) than with a traffic load of λ=0.1. Moreover, at larger network size, $Gain_{Th,c}$ and $Gain_{Th,c'}$ for both traffic loads tend to be similar since the system saturation point is nearly reached.

In Figure 5(b) for λ=0.1, $Gain_{Th,c}$ and $Gain_{Th,c'}$ evolve following the constant differentiation mode. For a network of small size, $Gain_{Th,c}$ (resp. $Gain_{Th,c'}$) is positive (resp. negative) because, according to that differentiation mode, class *c* and class *c'* are differentiated even at the first backoff stage. When the size of the network increases, $Gain_{Th,c}$ and $Gain_{Th,c'}$ tend to be constant. This is because, even if the contention increases with the network size, class *c* priority $prio_{c,i}$ and class *c'* priority $prio_{c',i}$ stay constant relatively to the backoff stage *i*. Thus, $Gain_{Th,c}$ and $Gain_{Th,c'}$ do not change when the network size increases.

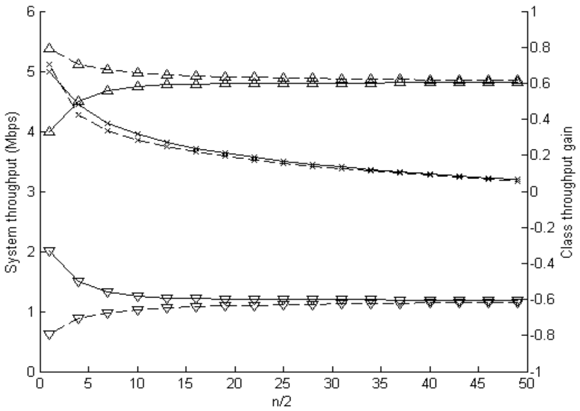
For λ=1, $Gain_{Th,c}$ and $Gain_{Th,c'}$ evolve in a same manner as with λ=0.1. Moreover, as in Figure 5(a), for small network size, the stations of class *c* and class *c'* are more likely to reach higher backoff stages even at smaller network size, that is due to traffic saturation. Thus, $Gain_{Th,c}$ (resp. $Gain_{Th,c'}$) is larger (resp. smaller) than with a traffic load of λ=0.1. Moreover, as in Figure 5(a), at larger network size, $Gain_{Th,c}$ and $Gain_{Th,c'}$ for both traffic loads tend to be similar since the system saturation point is nearly reached.

In Figure 5(c) for λ=0.1, $Gain_{Th,c}$ and $Gain_{Th,c'}$ evolve following the hard differentiation mode. For a network of small size, $Gain_{Th,c}$ (resp. $Gain_{Th,c'}$) is positive (resp. negative) as in Figure 5(b), because according to that differentiation mode, class *c* and class *c'* are differentiated even at the first backoff stage.

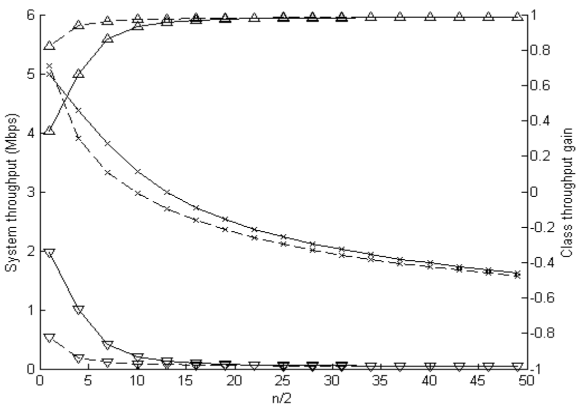
When the size of the network increases, $Gain_{Th,c}$ tends to be *100%* and $Gain_{Th,c'}$ tends to be *-100%*. This is because, the contention increases with the network size. Thus, the stations of class *c* tend to no backoff mode and class *c'* tends to maximum waiting time when selecting the backoff time.



(a) Soft Differentiation Mode



(b) Constant Differentiation Mode

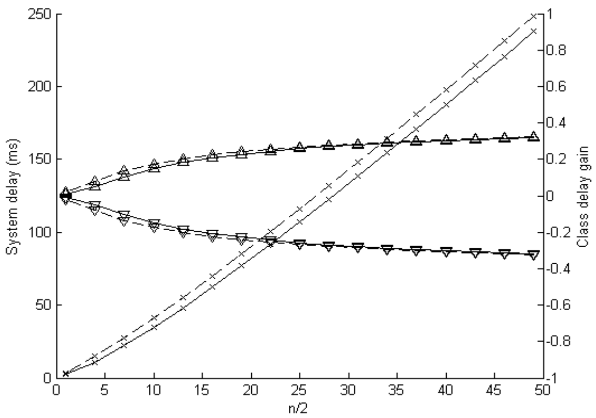


(c) Hard Differentiation Mode

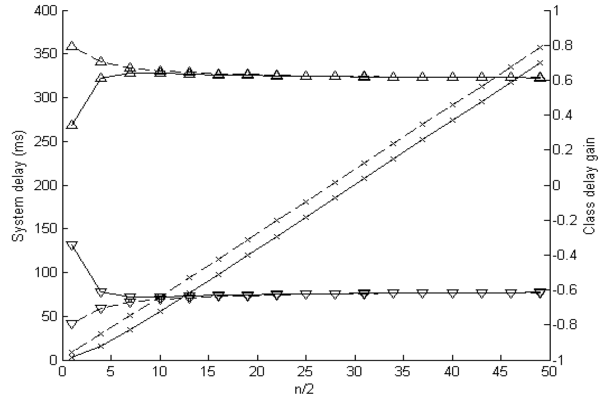
Figure 5. Throughput

For λ=1, $Gain_{Th,c}$ and $Gain_{Th,c'}$ evolve in a same manner as with λ=0.1. Moreover, for small network size, as in Figures 5(a) and 5(b) the stations of class *c* and class *c'* are more likely to reach higher backoff stages at smaller network size compared to a traffic load of λ=0.1. Thus, $Gain_{Th,c}$ (resp. $Gain_{Th,c'}$) is larger (resp. smaller) than with a traffic load of λ=0.1.

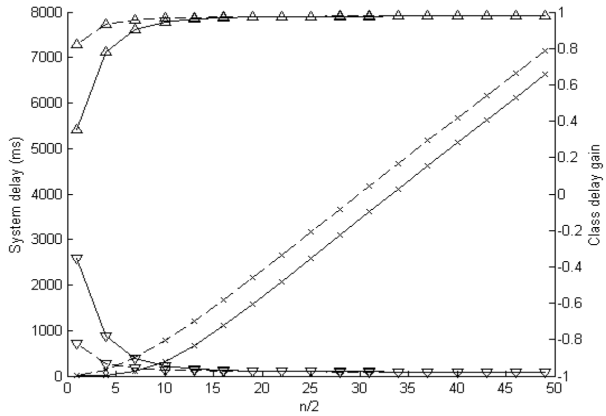
Moreover, using the hard differentiation mode in Figure 5(c), the whole system throughput *S* degrades more in comparison to the differentiation modes used in Figures 5(a) and 5(b). This is because, class *c* backoff time selection tends to no backoff mode and class *c'* backoff time selection tends to maximum waiting time. Thus, the contention is not resolved even at small network size.



(a) Soft Differentiation Mode



(b) Constant Differentiation Mode



(c) Hard Differentiation Mode

Figure 6. Average Delay

For both traffic loads λ=0.1 and λ=1, using the three differentiation modes, the system throughput *S* starts from a value equal to *5Mbps* (see Figure 5(a), 5(b) and 5(c)) when the size of the network is minimal and equal to $n = 2$. And, when the soft or the constant differentiation modes are used, the system throughput becomes equal to *3.4Mbps* (see Figures 5(a) and 5(b)) for $n = 100$. But using the hard differentiation mode, the system throughput degrades more to reach a value of *1.6Mbps* (see Figure 5(c)) when $n = 100$.

In Figure 6, we see that the impact of applying the different differentiation modes on class delay gain is similar to the impact of applying those modes on class throughput gain shown in Figure 5.

Table 4 shows the average delay for both class *c* and *c'* using the differentiation modes at different traffic loads when the network size is 20. Class *c'*, of parameter $\beta_{c'} = -0.15$, suffers from delay degradation when it uses the hard differentiation mode along with class *c* of opposite parameter $\beta_c = 0.15$.

Table 4. Delay (n=20)

	$\lambda = 0.1$		$\lambda = 1$	
	$E(D_c)$	$E(D_{c'})$	$E(D_c)$	$E(D_{c'})$
Soft	$29.42ms$	$39.69ms$	$33.97ms$	$48.16ms$
Const.	$19.89ms$	$90.24ms$	$25.01ms$	$119.8ms$
Hard	$17.18ms$	$0.62s$	$28.88ms$	$1.52s$

The delay of class *c'* becomes of the order of seconds from a network size of $n = 24$ stations when λ=0.1 and a network size of $n = 16$ stations when λ=1.

6. Conclusions

In this paper, we proposed a new scheme for service differentiation in WLANs. This new scheme is based on the 802.11 DCF which uses the backoff procedure to solve contention in WLANs. Our new scheme uses a geometric distribution for random backoff time selection instead of the uniform distribution used by DCF standard. The introduction of a new parameter allows managing the access to the shared media of different types of traffic and gives a level of priority of each type of traffic. High priority traffic have more chance to select a small backoff time and less chance to select a large backoff time in comparison with a low priority traffic.

To study our proposal, we used three interesting parameterizations of the backoff time distribution applied on a multi-class system. We gave an analytical study based on Markov model to evaluate performances of the proposed scheme in term of throughput and delay. Our numerical results showed the impact of applying the different differentiation modes on class delay gain and on class throughput gain.

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