

# Performance Evaluation of Deadline Monotonic Policy over 802.11 protocol

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## ABSTRACT

Real time applications are characterized by their delay bounds. To satisfy the Quality of Service (QoS) requirements of such flows over wireless communications, we enhance the 802.11 protocol to support the Deadline Monotonic (DM) scheduling policy. Then, we propose to evaluate the performance of DM in terms of throughput, average medium access delay and medium access delay distribution. To evaluate the performance of the DM policy, we develop a Markov chain based analytical model and derive expressions of the throughput, average MAC layer service time and service time distribution. Therefore, we validate the mathematical model and extend analytical results to a multi-hop network by simulation using the ns-2 network simulator.

**Keywords:** Deadline Monotonic, 802.11 protocol, Performance evaluation, Medium access delay, Throughput, Probabilistic medium access delay bounds.

## 1 INTRODUCTION

Supporting applications with QoS requirements has become an important challenge for all communications networks. In wireless LANs, the IEEE 802.11 protocol [5] has been enhanced and the IEEE 802.11e protocol [6] was proposed to support quality of service over wireless communications.

In the absence of a coordination point, the IEEE 802.11 defines the Distributed Coordination Function (DCF) based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. The IEEE 802.11e proposes the Enhanced Distributed Channel Access (EDCA) as an extension for DCF. With EDCA, each station maintains four priorities called Access Categories (ACs). The quality of service offered to each flow depends on the AC to which it belongs.

Nevertheless, the granularity of service offered by 802.11e (4 priorities at most) can not satisfy the real time flows requirements (where each flow is characterized by its own delay bound).

Therefore, we propose in this paper a new medium access mechanism based on the Deadline Monotonic (DM) policy [9] to schedule real time flows over 802.11. Indeed DM is a real time scheduling policy that assigns static priorities to flow packets according to their deadlines; the packet with the shortest deadline being assigned the highest

priority. To support the DM policy over 802.11, we use a distributed scheduling and introduce a new medium access backoff policy. Therefore, we focus on performance evaluation of the DM policy in terms of achievable throughput, average MAC layer service time and MAC layer service time distribution. Hence, we follow these steps:

- First, we propose a Markov Chain framework modeling the backoff process of  $n$  contending stations within the same broadcast region [1]. Due to the complexity of the mathematical model, we restrict the analysis to  $n$  contending stations belonging to two traffic categories (each traffic category is characterized by its own delay bound).
- From the analytical model, we derive the throughput achieved by each traffic category.
- Then, we use the generalized Z-transforms [3] to derive expressions of the average MAC layer service time and service time distribution.
- As the analytical model was restricted to two traffic categories, analytical results are extended by simulation to different traffic categories.
- Finally, we consider a simple multi-hop scenario to deduce the behavior of the DM policy in a multi hop environment.

The rest of this paper is organized as follows. In section 2, we review the state of the art of the IEEE 802.11 DCF, QoS support over 802.11 mainly the IEEE 802.11e EDCA and real time scheduling over 802.11. In section 3, we present the distributed scheduling and introduce the new medium access backoff policy to support DM over 802.11. In section 4, we present our mathematical model based on Markov chain analysis. Section 5 and 6 present respectively throughput and the service time analysis. Analytical results are validated by simulation using the ns-2 network simulator [16]. In section 7, we extend our study by simulation, first to take into consideration different traffic categories, second, to study the behavior of the DM algorithm in a multi-hop environment where factors like interferences or routing protocols exist. Finally, we conclude in Section 8.

## 2 LITTERATURE REVIEWS

### 2.1 The 802.11 protocol

#### 2.1.1 Description of the IEEE 802.11 DCF

Using DCF, a station shall ensure that the channel is idle when it attempts to transmit. Then it selects a random backoff in the contention window  $[0, CW-1]$ , where  $CW$  is the current window size and varies between the minimum and the maximum contention window sizes. If the channel is sensed busy, the station suspends its backoff until the channel becomes idle for a Distributed Inter Frame Space (DIFS) after a successful transmission or an Extended Inter Frame Space (EIFS) after a collision. The packet is transmitted when the backoff reaches zero. A packet is dropped if it collides after maximum retransmission attempts.

The above described two way handshaking packet transmission procedure is called basic access mechanism. DCF defines a four way handshaking technique called Request To Send/ Clear To Send (RTS/CTS) to prevent the hidden station problem. A station  $S_j$  is said to be hidden from  $S_i$  if  $S_j$  is within the transmission range of the receiver of  $S_i$  and out of the transmission range of  $S_i$ .

#### 2.1.2 Performance evaluation of the 802.11 DCF

Different works have been proposed to evaluate the performance of the 802.11 protocol based on Bianchi's work [1]. Indeed, Bianchi proposed a Markov chain based analytical model to evaluate the saturation throughput of the 802.11 protocol. By saturation conditions, it's meant that contending have always packets to transmit.

Several works extended the Bianchi model either to suit more realistic scenarios or to evaluate other performance parameters. Indeed, the authors of [2] incorporate the frame retry limits in the Bianchi's model and show that Bianchi overestimates the

maximum achievable throughput. The native model is also extended in [10] to a non saturated environment. In [12], the authors derive the average packet service time at a 802.11 node. A new generalized Z-transform based framework has been proposed in [3] to derive probabilistic bounds on MAC layer service time. Therefore, it would be possible to provide probabilistic end to end delay bounds in a wireless network.

### 2.2 Supporting QoS over 802.11

#### 2.2.1 Differentiation mechanisms over 802.11

Emerging applications like audio and video applications require quality of service guarantees in terms of throughput delay, jitter, loss rate, etc. Transmitting such flows over wireless communications require supporting service differentiation mechanisms over wireless networks.

Many medium access schemes have been proposed to provide some QoS enhancements over the IEEE 802.11 WLAN. Indeed, [4] assigns different priorities to the incoming flows. Priority classes are differentiated according to one of three 802.11 parameters: the backoff increase function, Inter Frame Spacing (IFS) and the maximum frame length. Experiments show that all the three differentiation schemes offer better guarantees for the highest priority flow. But the backoff increase function mechanism doesn't perform well with TCP flows because ACKs affect the differentiation mechanism.

In [7], an algorithm is proposed to provide service differentiation using two parameters of IEEE 802.11, the backoff interval and the IFS. With this scheme high priority stations are more likely to access the medium than low priority ones. The above described researches led to the standardization of a new protocol that supports QoS over 802.11, the IEEE 802.11e protocol [6].

#### 2.2.2 The IEEE 802.11e EDCA

The IEEE 802.11e proposes a new medium access mechanism called the Enhanced Distributed Channel Access (EDCA), that enhances the IEEE 802.11 DCF. With EDCA, each station maintains four priorities called Access Categories (ACs). Each access category is characterized by a minimum and a maximum contention window sizes and an Arbitration Inter Frame Spacing (AIFS).

Different analytical models have been proposed to evaluate the performance of 802.11e EDCA. In [17], Xiao extends Bianchi's model to the prioritized schemes provided by 802.11e by introducing multiple ACs with distinct minimum and maximum contention window sizes. But the AIFS differentiation parameter is lacking in Xiao's model.

Recently Osterbo and Al. have proposed

different works to evaluate the performance of the IEEE 802.11e EDCA [13], [14], [15]. They propose a model that takes into consideration all the differentiation parameters of the EDFA especially the AIFS one. Moreover different parameters of QoS have been evaluated such as throughput, average service time, service time distribution and probabilistic response time bounds for both saturated and non saturated cases.

Although the IEEE 802.11e EDCA classifies the traffic into four prioritized ACs, there is still no guarantee of real time transmission service. This is due to the lack of a satisfactory scheduling method for various delay-sensitive flows. Hence, we need a scheduling policy dedicated to such delay sensitive flows.

### 2.3 Real time scheduling over 802.11

A distributed solution for the support of real-time sources over IEEE 802.11, called Blackburst, is discussed in [8]. This scheme modifies the MAC protocol to send short transmissions in order to gain priority for real-time service. It is shown that this approach is able to support bounded delays. The main drawback of this scheme is that it requires constant intervals for high priority traffic; otherwise the performance degrades very much.

In [18], the authors proposed a distributed priority scheduling over 802.11 to support a class of dynamic priority schedulers such as Earliest Deadline First (EDF) or Virtual Clock (VC). Indeed, the EDF policy is used to schedule real time flows according to their absolute deadlines, where the absolute deadline is the node arrival time plus the delay bound.

To realize a distributed scheduling over 802.11, the authors of [18] used a priority broadcast mechanism where each station maintains an entry for the highest priority packet of all other stations. Thus, stations can adjust their backoff according to other stations priorities.

The overhead introduced by the broadcast priority mechanism is negligible. This is due to the fact that priorities are exchanged using native DATA and ACK packets. Nevertheless, the authors of [18] propose a generic backoff policy which can be used by a class dynamic priority schedulers no matter if this scheduler targets delay sensitive flows or rate sensitive flows.

In this paper, we focus on delay sensitive flows and propose to support the fixed priority deadline monotonic scheduler over 802.11 to schedule delay sensitive flows. For instance, we use a priority broadcast mechanism similar to [5] and propose a new medium access backoff policy where the backoff value is inferred from the deadline

information.

## 3 SUPPORTING DEADLINE MONOTONIC (DM) POLICY OVER 802.11

With DCF all the stations share the same transmission medium. Then, the HOL (Head of Line) packets of all the stations (highest priority packets) will contend for the channel with the same priority even if they have different deadlines.

Introducing DM over 802.11 allows stations having packets with short deadlines to access the channel with higher priority than those having packets with long deadlines. Providing such a QoS requires distributed scheduling and a new medium access policy.

### 3.1 Distributed Scheduling over 802.11

To realize a distributed scheduling over 802.11, we introduce a priority broadcast mechanism similar to [18]. Indeed each station maintains a local scheduling table with entries for HOL packets of all other stations. Each entry in the scheduling table of node  $S_i$  comprises two fields  $(S_j, D_j)$  where  $S_j$  is the source node MAC address and  $D_j$  is the deadline of the HOL packet of node  $S_j$ . To broadcast the HOL packet deadlines, we propose to use the DATA/ACK access mode.

When a node  $S_i$  transmits a DATA packet, it piggybacks the deadline of its HOL packet. The nodes hearing the DATA packet add an entry for  $S_i$  in their local scheduling tables by filling the corresponding fields. The receiver of the DATA packet copies the priority of the HOL packet in ACK before sending the ACK frame. All the stations that did not hear the DATA packet add an entry for  $S_i$  using the information in the ACK packet.

### 3.2 DM medium access backoff policy

Let's consider two stations  $S_1$  and  $S_2$  transmitting two flows with the same deadline  $D_1$  ( $D_1$  is expressed as a number of 802.11 slots). The two stations having the same delay bound can access the channel with the same priority using the native 802.11 DCF.

Now, we suppose that  $S_1$  and  $S_2$  transmit flows with different delay bounds  $D_1$  and  $D_2$  such as  $D_1 < D_2$ , and generate two packets at time instants  $t_1$  and  $t_2$ . If  $S_2$  had the same delay bound as  $S_1$ , its packet would have been generated at time  $t'_2$  such as  $t'_2 = t_2 + D_{21}$ , where  $D_{21} = (D_2 - D_1)$ .

At that time,  $S_1$  and  $S_2$  would have the same priority and transmit their packets according to the

802.11 protocol.

Thus, to support DM over 802.11, each station uses a new backoff policy where the backoff is given by:

- The random backoff selected in  $[0, CW - 1]$  according to 802.11 DCF, referred as Basic Backoff (*BAB*).
- The DM Shifting Backoff (*DMSB*): corresponds to the additional backoff slots that a station with low priority (the HOL packet having a large deadline) adds to its BAB to have the same priority as the station with the highest priority (the HOL packet having the shortest deadline).

Whenever a station  $S_i$  sends an ACK or hears an ACK on the channel its *DMSB* is reevaluated as follows:

$$DMSB(S_i) = Deadline(HOL(S_i)) - DT_{min}(S_i) \quad (1)$$

Where  $DT_{min}(S_i)$  is the minimum of the HOL packet deadlines present in  $S_i$  scheduling table and  $Deadline(HOL(S_i))$  is the HOL packet deadline of node  $S_i$ .

Hence, when  $S_i$  has to transmit its HOL packet with a delay bound  $D_i$ , it selects a *BAB* in the contention window  $[0, CW_{min} - 1]$  and computes the *WHB* value as follows:

$$WHB(S_i) = DMSB(S_i) + BAB(S_i) \quad (2)$$

The station  $S_i$  decrements its *BAB* when it senses an idle slot. Now, we suppose that  $S_i$  senses the channel busy. If a successful transmission is heard, then  $S_i$  reevaluates its *DMSB* when a correct ACK is heard. Then the station  $S_i$  adds the new *DMSB* value to its current *BAB* as in equation (2). Whereas, if a collision is heard,  $S_i$  reinitializes its *DMSB* and adds it to its current *BAB* to allow colliding stations contending with the same priority as for their first transmission attempt.  $S_i$  transmits when its *WHB* reaches 0. If the transmission fails,  $S_i$  doubles its contention window size and repeats the above procedure until the packet is successfully transmitted or dropped after maximum retransmission attempts.

#### 4 MATHEMATICAL MODEL OF THE DM POLICY OVER 802.11

In this section, we propose a mathematical model to evaluate the performance of the DM policy using Markov chain analysis [1]. We consider the following assumptions:

##### Assumption 1:

The system under study comprises  $n$  contending stations hearing each other transmissions.

##### Assumption 2:

Each station  $S_i$  transmits a flow  $F_i$  with a delay bound  $D_i$ . The  $n$  stations are divided into two traffic categories  $C_1$  and  $C_2$  such as:

- $C_1$  represents  $n_1$  nodes transmitting flows with delay bound  $D_1$ .
- $C_2$  represents  $n_2$  nodes transmitting flows with delay bound  $D_2$ , such as  $D_1 < D_2$ ,  $D_{21} = (D_2 - D_1)$  and  $(n_1 + n_2) = n$ .

##### Assumption 3:

We operate in saturation conditions: each station has immediately a packet available for transmission after the service completion of the previous packet [1].

##### Assumption 4:

A station selects a *BAB* in a constant contention window  $[0, W - 1]$  independently of the transmission attempt. This is a simplifying assumption to limit the complexity of the mathematical model.

##### Assumption 5:

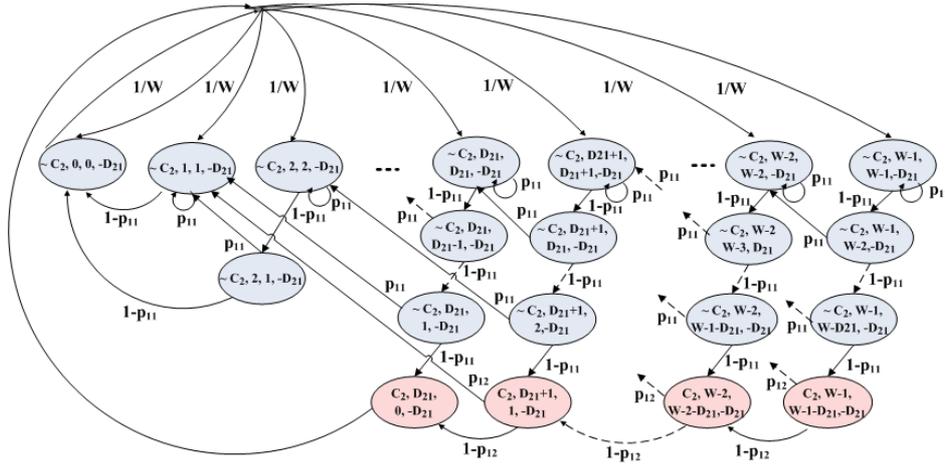
We are in stationary conditions, i.e. the  $n$  stations have already sent one packet at least.

Depending on the traffic category to which it belongs, each station  $S_i$  will be modeled by a Markov Chain representing its whole backoff (*WHB*) process.

#### 4.1 Markov chain modeling a station of category C1

Figure 1 illustrates the Markov chain modeling a station  $S_i$  of category  $C_1$ . The states of this Markov chain are described by the following quadruplet  $(R, i, i - j, D_{21})$  where:

- $R$ : takes two values denoted by  $C_2$  and  $\sim C_2$ . When  $R = \sim C_2$ , the  $n_2$  stations of category  $C_2$  are decrementing their shifting backoff (*DMSB*) during  $D_{21}$  slots and wouldn't contend for the channel. When  $R = C_2$ , the  $D_{21}$  slots had already been elapsed and stations of category  $C_2$  will contend for the channel..



**Figure 1:** Markov chain modeling a category  $C_1$  Station

- $i$  : the value of the BAB selected by  $S_1$  in  $[0, W - 1]$ .
- $(i - j)$  : corresponds to the current backoff of the station  $S_1$ .
- $D_{21}$  : corresponds to  $(D_2 - D_1)$ . We choose the negative notation  $-D_{21}$  for stations of  $C_1$  to express the fact that only stations of category  $C_2$  have a positive  $DMSB$  equal to  $D_{21}$ .

Initially  $S_1$  selects a random BAB and is in one of the states  $(\sim C_2, i, i, -D_{21})$ ,  $i = 0..W - 1$ . During  $(D_{21} - 1)$  slots,  $S_1$  decrements its backoff if none of the  $(n_1 - 1)$  remaining stations of category  $C_1$  transmits. Indeed, during these slots, the  $n_2$  stations of category  $C_2$  are decrementing their  $DMSB$  and wouldn't contend for the channel.

When  $S_1$  is in one of the states  $(\sim C_2, i, i - (D_{21} - 1), -D_{21})$ ,  $i = D_{21}..W - 1$  and senses the channel idle, it decrements its  $D_{21}^{th}$  slot. But  $S_1$  knows that henceforth the  $n_2$  stations of category  $C_2$  can contend for the channel (the  $D_{21}$  slots had been elapsed). Hence,  $S_1$  moves to one of the states  $(C_2, i, i - D_{21}, -D_{21})$ ,  $i = D_{21}..W - 1$ .

However, when the station  $S_1$  is in one of the states  $(\sim C_2, i, i - j, -D_{21})$ ,  $i = 1..W - 1$ ,  $j = 0..min(D_{21} - 1, i - 1)$  and at least one of the  $(n_1 - 1)$  remaining stations of category  $C_1$  transmits, then the stations of category  $C_2$  will reinitialize their  $DMSB$  and wouldn't contend for

channel during additional  $D_{21}$  slots. Therefore,  $S_1$  moves to the state  $(\sim C_2, i - j, i - j, -D_{21})$ ,  $i = 1..W - 1$ ,  $j = 0..min(D_{21} - 1, i - 1)$ .

Now, If  $S_1$  is in one of the states  $(C_2, i, i - D_{21}, -D_{21})$ ,  $i = (D_{21} + 1)..W - 1$  and at least one of the  $(n - 1)$  remaining stations (either a category  $C_1$  or a category  $C_2$  station) transmits, then  $S_1$  moves to one of the states  $(\sim C_2, i - D_{21}, i - D_{21}, -D_{21})$ ,  $i = (D_{21} + 1)..W - 1$ .

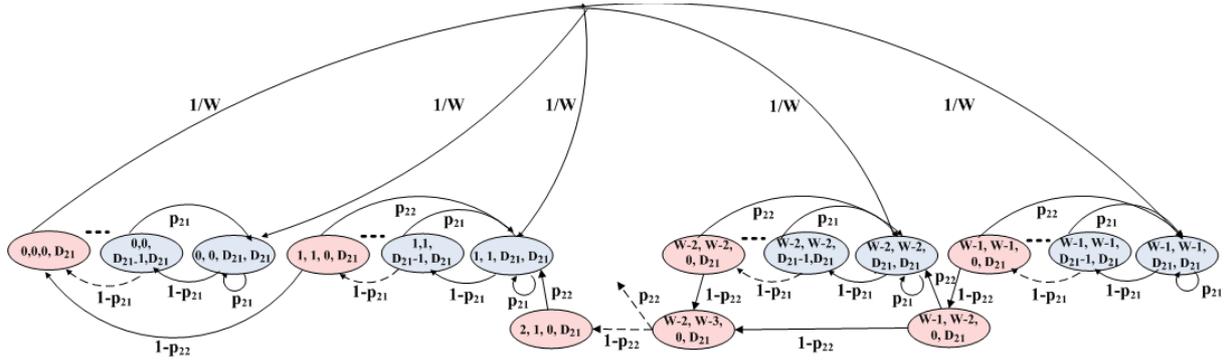
#### 4.2 Markov chain modeling a station of category $C_2$

Figure 2 illustrates the Markov chain modeling a station  $S_2$  of category  $C_2$ . Each state of  $S_2$  Markov chain is represented by the quadruplet  $(i, k, D_{21} - j, D_{21})$  where:

- $i$  : refers to the BAB value selected by  $S_2$  in  $[0, W - 1]$ .
- $k$  : refers to the current BAB value of  $S_2$ .
- $D_{21} - j$  : refers to the current  $DMSB$  of  $S_2$ ,  $j \in [0, D_{21}]$ .
- $D_{21}$  : corresponds to  $(D_2 - D_1)$ .

When  $S_2$  selects a  $BAB$ , its  $DMSB$  equals  $D_{21}$  and is in one of the states  $(i, i, D_{21}, D_{21})$ ,  $i = 0..W - 1$ . During  $D_{21}$  slots, only the  $n_1$  stations of category  $C_1$  contend for the channel.

If  $S_2$  senses the channel idle during  $D_{21}$  slots, it moves to one of the states  $(i, i, 0, D_{21})$ ,  $i = 0..W - 1$ , where it ends its shifting backoff.



**Figure 2:** Markov chain modeling a category  $C_2$  Station

When  $S_2$  is in one of the states  $(i, i, 0, D_{21})$ ,  $i = 0..W-1$ , the  $(n_2 - 1)$  other stations of category  $C_2$  have also decremented their DMSB and can contend for the channel. Thus,  $S_2$  decrements its BAB and moves to the state  $(i, i-1, 0, D_{21})$ ,  $i = 2..W-1$ , only if none of  $(n-1)$  remaining stations transmits.

If  $S_2$  is in one of the states  $(i, i-1, 0, D_{21})$ ,  $i = 2..W-1$ , and at least one of the  $(n-1)$  remaining stations transmits, the  $n_2$  stations of category  $C_2$  will reinitialize their DMSB and  $S_2$  moves to the state  $(i-1, i-1, 0, D_{21}, D_{21})$ ,  $i = 2..W-1$ .

#### 4.3 Blocking probabilities in the Markov chains

According to the explanations given in paragraphs 4.1 and 4.2, the states of the Markov chains modeling stations  $S_1$  and  $S_2$  can be divided into the following groups:

- $\xi_1$ : the set of states of  $S_1$  where none of the  $n_2$  stations of category  $C_2$  contends for the channel (blue states in figure 1).  
 $\xi_1 = \{(\sim C_2, i, i-j, -D_{21}), i = 0..W-1,$   
 $j = 0..min(max(0, i-1), D_{21}-1)\}$
- $\gamma_1$ : the set of states of  $S_1$  where stations of category  $C_2$  can contend for the channel (pink states in figure 1).  
 $\gamma_1 = \{(C_2, i, i-D_{21}, -D_{21}), i = D_{21}..W-1\}$
- $\xi_2$ : the set of states of  $S_2$  where stations of category  $C_2$  do not contend for the channel (blue states in figure 2).  
 $\xi_2 = \{(i, i, D_{21}-j, D_{21}), i = 0..W-1,$   
 $j = 0..(D_{21}-1)\}$

- $\gamma_2$ : the set of states of  $S_2$ , where stations of category  $C_2$  contend for the channel (pink states in figure 2).

$$\gamma_2 = \{(i, i, 0, D_{21}), i = 0..W-1$$

$$\cup (i, i-1, 0, D_{21}), i = 2..W-1\}$$

Therefore, when stations of category  $C_1$  are in one of the states of  $\xi_1$ , stations of category  $C_2$  are in one of the states of  $\xi_2$ . Similarly, when stations of category  $C_1$  are in one of the states of  $\gamma_1$ , stations of category  $C_2$  are in one of the states of  $\gamma_2$ .

Hence, we derive the expressions of  $S_1$  blocking probabilities  $p_{11}$  and  $p_{12}$  shown in figure 1 as follows:

- $p_{11}$ : the probability that  $S_1$  is blocked given that  $S_1$  is in one of the states of  $\xi_1$ .  $p_{11}$  is the probability that at least a station  $S'_1$  of the other  $(n_1 - 1)$  stations of  $C_1$  transmits given that  $S'_1$  is in one of the states of  $\xi_1$ .

$$p_{11} = 1 - (1 - \tau_{11})^{n_1 - 1} \quad (3)$$

where  $\tau_{11}$  is the probability that a station  $S'_1$  of  $C_1$  transmits given that  $S'_1$  is in one of the states of  $\xi_1$ :

$$\tau_{11} = Pr\{S'_1 \text{ transmits} \mid \xi_1\}$$

$$= \frac{\pi_1^{(\sim C_2, 0, 0, -D_{21})}}{\sum_{i=0}^{W-1} \left( \frac{\min(max(0, i-1), D_{21}-1)}{\sum_{j=0}^{\min(max(0, i-1), D_{21}-1)} \pi_1^{(\sim C_2, i, i-j, -D_{21})}} \right)} \quad (4)$$

$\pi_1^{(R, i, i-j, -D_{21})}$  is defined as the probability of the state  $(R, i, i-j, -D_{21})$ , in the stationary

conditions and  $\Pi_1 = \{\pi_1^{(R,i,i-j,-D_{21})}\}$  is the probability vector of a category  $C_1$  station.

- $p_{12}$  : the probability that  $S_1$  is blocked given that  $S_1$  is in one of the states of  $\gamma_1$ .  $p_{12}$  is the probability that at least a station  $S'_1$  of the other  $(n_1 - 1)$  stations of  $C_1$  transmits given that  $S'_1$  is in one of the states of  $\gamma_1$  or at least a station  $S'_2$  of the  $n_2$  stations of  $C_2$  transmits given that  $S'_2$  is in one of the states of  $\gamma_2$ .

$$p_{12} = 1 - (1 - \tau_{12})^{n_1 - 1} (1 - \tau_{22})^{n_2} \quad (5)$$

where  $\tau_{12}$  is the probability that a station  $S'_1$  of  $C_1$  transmits given that  $S'_1$  is in one of the states of  $\gamma_1$ .

$$\begin{aligned} \tau_{12} &= Pr[S'_1 \text{ transmits} / \gamma_1] \\ &= \frac{\pi_1^{(C_2, D_{21}, 0, -D_{21})}}{\sum_{i=D_{21}}^{W-1} \pi_1^{(C_2, i, i-D_{21}, -D_{21})}} \quad (6) \end{aligned}$$

and  $\tau_{22}$  the probability that a station  $S'_2$  of  $C_2$  transmits given that  $S'_2$  is in one of the states of  $\gamma_2$ .

$$\begin{aligned} \tau_{22} &= Pr[S'_2 \text{ transmits} / \gamma_2] \\ &= \frac{\pi_2^{(0,0,0,D_{21})}}{\sum_{i=0}^{W-1} \pi_2^{(i,i,0,D_{21})} + \sum_{i=2}^{W-1} \pi_2^{(i,i-1,0,D_{21})}} \quad (7) \end{aligned}$$

$\pi_2^{(i,k,D_{21}-j,D_{21})}$  is defined as the probability of the state  $(i,k,D_{21}-j,D_{21})$ , in the stationary condition.  $\Pi_2 = \{\pi_2^{(i,k,D_{21}-j,D_{21})}\}$  is the probability vector of a category  $C_2$  station.

In the same way, we evaluate  $p_{21}$  and  $p_{22}$  the blocking probabilities of station  $S_2$  as shown in figure 2:

- $p_{21}$  : the probability that  $S_2$  is blocked given that  $S_2$  is in one of the states of  $\xi_2$ .

$$p_{21} = 1 - (1 - \tau_{11})^{n_1} \quad (8)$$

- $p_{22}$  : the probability that  $S_2$  is blocked given that  $S_2$  is in one of the states of  $\gamma_2$ .

$$p_{22} = 1 - (1 - \tau_{12})^{n_1} (1 - \tau_{22})^{n_2 - 1} \quad (9)$$

The blocking probabilities described above allow deducing the transition state probabilities and having the transition probability matrix  $P_i$ , for a station of traffic category  $C_i$ .

Therefore, we can evaluate the state probabilities by solving the following system [11]:

$$\begin{cases} \Pi_i P_i = \Pi_i \\ \sum_j \pi_i^j = 1 \end{cases} \quad (10)$$

#### 4.4 Transition probability matrices

##### 4.4.1 Transition probability matrix of a category $C_1$ station

Let  $P_1$  be the transition probability matrix of the station  $S_1$  of category  $C_1$ .  $P_1\{i,j\}$  is the probability to transit from state  $i$  to state  $j$ . We have:

$$\begin{aligned} P_1\{(\sim C_2, i, i-j, -D_{21}), (\sim C_2, i, i-(j+1), -D_{21})\} \\ = 1 - p_{11}, i = 2..W-1, j = 0..min(i-2, D_{21}-2) \end{aligned} \quad (11)$$

$$\begin{aligned} P_1\{(\sim C_2, i, i, -D_{21}), (\sim C_2, 0, 0, -D_{21})\} = 1 - p_{11}, \\ i = 1..min(W-1, D_{21}-1) \end{aligned} \quad (12)$$

$$\begin{aligned} P_1\{(\sim C_2, i, i-D_{21}+1, -D_{21}), (C_2, i, i-D_{21}, -D_{21})\} \\ = 1 - p_{11}, i = D_{21}..W-1 \end{aligned} \quad (13)$$

$$\begin{aligned} P_1\{(\sim C_2, i, i-j, -D_{21}), (\sim C_2, i-j, i-j, -D_{21})\} \\ = p_{11}, i = 2..W-1, j = 1..min(i-1, D_{21}-1) \end{aligned} \quad (14)$$

$$\begin{aligned} P_1\{(\sim C_2, i, i, -D_{21}), (\sim C_2, i, i, -D_{21})\} = p_{11}, \\ i = 1..W-1 \end{aligned} \quad (15)$$

$$\begin{aligned} P_1\{(C_2, i, i-D_{21}, -D_{21}), (\sim C_2, i-D_{21}, i-D_{21}, -D_{21})\} \\ = p_{12}, i = (D_{21}+1)..W-1 \end{aligned} \quad (16)$$

$$\begin{aligned} P_1\{(C_2, i, i-D_{21}, -D_{21}), (C_2, (i-1), (i-1-D_{21}), -D_{21})\} \\ = 1 - p_{12}, i = (D_{21}+1)..W-1 \end{aligned} \quad (17)$$

$$\begin{aligned} P_1\{(\sim C_2, 0, 0, -D_{21}), (\sim C_2, i, i, -D_{21})\} = \frac{1}{W}, \\ i = 0..W-1 \end{aligned} \quad (18)$$

If  $(D_{21} < W)$  then:

$$P_1\{(C_2, D_{21}, 0, -D_{21}), (\sim C_2, i, i, -D_{21})\} = \frac{1}{W}, \quad (19)$$

$$i = 0..W - 1$$

By replacing  $p_{11}$  and  $p_{12}$  by their values in equations (3) and (5) and by replacing  $P_1$  and  $\Pi_1$  in (10) and solving the resulting system, we can express  $\pi_1^{(R, i, i - j, -D_{21})}$  as a function of  $\tau_{11}$ ,  $\tau_{12}$  and  $\tau_{22}$  given respectively by equations (4), (6) and (7).

#### 4.4.2 Transition probability matrix of a category $C_2$ station

Let  $P_2$  be the transition probability matrix of the station  $S_2$  belonging to the traffic category  $C_2$ . The transition probabilities of  $S_2$  are:

$$P_2\{(i, i, D_{21} - j, D_{21}), (i, i, D_{21} - (j + 1), D_{21})\} = 1 - p_{21}, i = 0..W - 1, j = 0..(D_{21} - 1) \quad (20)$$

$$P_2\{(i, i, D_{21} - j, D_{21}), (i, i, D_{21}, D_{21})\} = p_{21}, i = 0..W - 1, j = 0..(D_{21} - 1) \quad (21)$$

$$P_2\{(i, i, 0, D_{21}), (i, i - 1, 0, D_{21})\} = 1 - p_{22}, i = 2..W - 1 \quad (22)$$

$$P_2\{(1, 1, 0, D_{21}), (0, 0, 0, D_{21})\} = 1 - p_{22} \quad (23)$$

$$P_2\{(i, i, 0, D_{21}), (i, i, D_{21}, D_{21})\} = p_{22}, i = 1..W - 1 \quad (24)$$

$$P_2\{(i, i - 1, 0, D_{21}), (i - 1, i - 1, D_{21}, D_{21})\} = p_{22}, i = 2..W - 1 \quad (25)$$

$$P_2\{(i, i - 1, 0, D_{21}), (i - 1, i - 2, 0, D_{21})\} = 1 - p_{22}, i = 3..W - 1 \quad (26)$$

$$P_2\{(0, 0, 0, D_{21}), (i, i, D_{21}, D_{21})\} = \frac{1}{W}, i = 0..W - 1 \quad (27)$$

By replacing  $p_{21}$  and  $p_{22}$  by their values in equations (8) and (9) and by replacing  $P_2$  and  $\Pi_2$  in (10) and solving the resulting system, we can express  $\pi_2^{(i, k, D_{21} - j, D_{21})}$  as a function of  $\tau_{11}$ ,  $\tau_{12}$  and  $\tau_{22}$  given respectively by equations (4), (6) and (7). Moreover, by replacing  $\pi_1^{(R, i, i - j, -D_{21})}$  and  $\pi_2^{(i, k, D_{21} - j, D_{21})}$  by their values, in equations (4), (6) and (7), we obtain a system of non linear equations as follows:

$$\begin{cases} \tau_{11} = f(\tau_{11}, \tau_{12}, \tau_{22}) \\ \tau_{12} = f(\tau_{11}, \tau_{12}, \tau_{22}) \\ \tau_{22} = f(\tau_{11}, \tau_{12}, \tau_{22}) \\ \text{under the constraint} \\ \tau_{11} > 0, \tau_{12} > 0, \tau_{22} > 0, \tau_{11} < 1, \tau_{12} < 1, \tau_{22} < 1 \end{cases} \quad (28)$$

Solving the above system (28), allows deducing the expressions of  $\tau_{11}$ ,  $\tau_{12}$  and  $\tau_{22}$ , and deriving the state probabilities of Markov chains modeling category  $C_1$  and category  $C_2$  stations.

## 5 THROUGHPUT ANALYSIS

In this section, we propose to evaluate  $B_i$ , the normalized throughput achieved by a station of traffic category  $C_i$  [1]. Hence, we define:

- $P_{i,s}$ : the probability that a station  $S_i$  belonging to the traffic category  $C_i$  transmits a packet successfully. Let  $S_1$  and  $S_2$  be two stations belonging respectively to traffic categories  $C_1$  and  $C_2$ . We have:

$$\begin{aligned} P_{1,s} &= Pr[S_1 \text{ transmits successfully}/\xi_1] Pr[\xi_1] \\ &+ Pr[S_1 \text{ transmits successfully}/\gamma_1] Pr[\gamma_1] \\ &= \tau_{11}(1 - p_{11}) Pr[\xi_1] + \tau_{12}(1 - p_{12}) Pr[\gamma_1] \end{aligned} \quad (29)$$

$$\begin{aligned} P_{2,s} &= Pr[S_2 \text{ transmits successfully}/\xi_2] Pr[\xi_2] \\ &+ Pr[S_2 \text{ transmits successfully}/\gamma_2] Pr[\gamma_2] \\ &= \tau_{22}(1 - p_{22}) Pr[\gamma_2] \end{aligned} \quad (30)$$

- $P_{idle}$ : the probability that the channel is idle.

The channel is idle if the  $n_1$  stations of category  $C_1$  don't transmit given that these stations are in one of the states of  $\xi_1$  or if the  $n$  stations (both category  $C_1$  and category  $C_2$  stations) don't transmit given that stations of category  $C_1$  are in one of the states of  $\gamma_1$ . Thus:

$$P_{idle} = (1 - \tau_{11})^{n_1} Pr[\xi_1] + (1 - \tau_{12})^{n_1} (1 - \tau_{22})^{n_2} Pr[\gamma_1] \quad (31)$$

Hence, the expression of the throughput of a category  $C_i$  station is given by:

$$B_i = \frac{P_{i,s} T_p}{P_{Idle} T_e + P_s T_s + \left(1 - P_{Idle} - \sum_{i=1}^2 n_i P_{i,s}\right) T_c} \quad (32)$$

Where  $T_e$  denotes the duration of an empty slot,  $T_s$  and  $T_c$  denote respectively the duration of a successful transmission and a collision.

$\left(1 - P_{Idle} - \sum_{i=1}^2 n_i P_{i,s}\right)$  corresponds to the probability of collision. Finally  $T_p$  denotes the average time required to transmit the packet data payload. We have:

$$T_s = (T_{PHY} + T_{MAC} + T_p + T_D) + SIFS + (T_{PHY} + T_{ACK} + T_D) + DIFS \quad (33)$$

$$T_c = (T_{PHY} + T_{MAC} + T_p + T_D) + EIFS \quad (34)$$

Where  $T_{PHY}$ ,  $T_{MAC}$  and  $T_{ACK}$  are the durations of the *PHY* header, the *MAC* header and the *ACK* packet [1], [13].  $T_D$  is the time required to transmit the two bytes deadline information. Stations hearing a collision wait during EIFS before resuming their backoff.

For numerical results stations transmit 512 bytes data packets using 802.11.b MAC and PHY layers parameters (given in table 1) with a data rate equal to 11Mbps. For simulation scenarios, the propagation model is a two ray ground model. The transmission range of each node is 250m. The distance between two neighbors is 5m. The EIFS parameter is set to ACKTimeout as in ns-2, where:

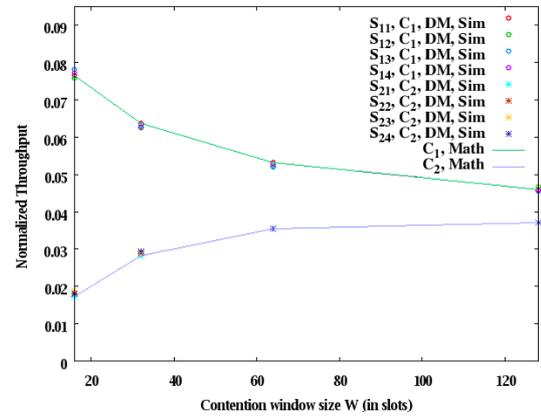
$$ACKTimeout = DIFS + (T_{PHY} + T_{ACK} + T_D) + SIFS \quad (35)$$

**Table 1:** 802.11 b parameters.

<b>Data Rate</b>	11 Mb/s
<b>Slot</b>	20 $\mu$ s
<b>SIFS</b>	10 $\mu$ s
<b>DIFS</b>	50 $\mu$ s
<b>PHY Header</b>	192 $\mu$ s
<b>MAC Header</b>	272 $\mu$ s
<b>ACK</b>	112 $\mu$ s
<b>Short Retry Limit</b>	7

For all the scenarios, we consider that we are in presence of  $n$  contending stations with  $\frac{n}{2}$  stations

for each traffic category. In figure 3,  $n$  is fixed to 8 and we depict the throughput achieved by the different stations present in the network as a function of the contention window size  $W$ , ( $D_{21} = 1$ ). We notice that the throughput achieved by category  $C_1$  stations (stations numbered from  $S_{11}$  to  $S_{14}$ ) is greater than the one achieved by category  $C_2$  stations (stations numbered from  $S_{21}$  to  $S_{24}$ ).



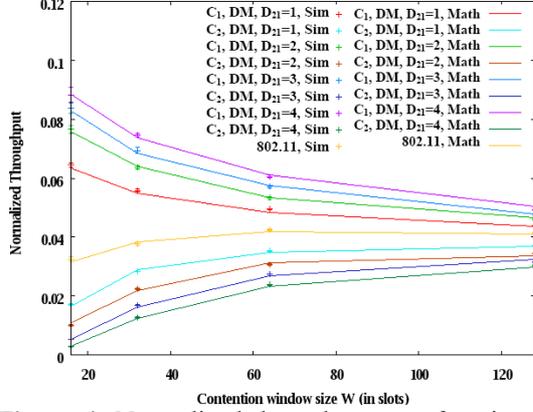
**Figure 3:** Normalized throughput as a function of the contention window size ( $D_{21} = 1, n = 8$ )

Analytically, stations belonging to the same traffic category have the same throughput given by equation (31). Simulation results validate analytical results and show that stations belonging to the same traffic category (either category  $C_1$  or category  $C_2$ ) have nearly the same throughput. Thus, we conclude the fairness of DM between stations of the same category.

For subsequent throughput scenarios, we focus on one representative station of each traffic category. Figure 4, compares category  $C_1$  and category  $C_2$  stations throughputs to the one obtained with 802.11.

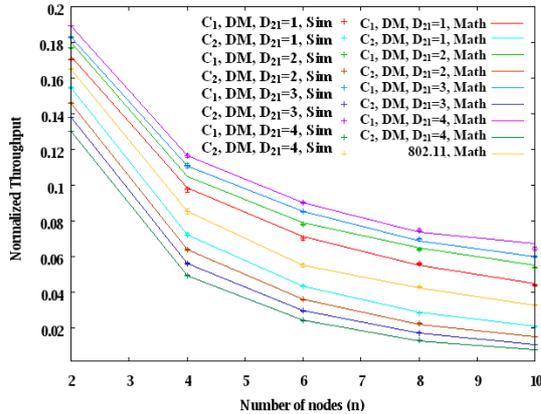
Curves are represented as a function of  $W$  and for different values of  $D_{21}$ . Indeed as  $D_{21}$  increases, the category  $C_1$  station throughput increases, whereas the category  $C_2$  station throughput decreases. Moreover as  $W$  increases, the difference between stations throughputs is reduced. This is due to the fact that the shifting backoff becomes negligible compared to the contention window size.

Finally, we notice that the category  $C_1$  station obtains better throughput with DM than with 802.11, but the opposite scenario happens to the category  $C_2$  station.



**Figure 4:** Normalized throughput as a function of the contention window size (different D21 values)

In figure 5, we generalize the results for different numbers of contending stations and fix the contention window size  $W$  to 32.



**Figure 5:** Normalized throughput as a function of the number of contending stations

All the curves show that DM performs service differentiation over 802.11 and offers better throughput for category  $C_1$  stations independently of the number of contending stations.

## 6 SERVICE TIME ANALYSIS

In this section, we evaluate the average MAC layer service time of category  $C_1$  and category  $C_2$  stations using the DM policy. The service time is the time interval from the time instant that a packet becomes at the head of the queue and starts to contend for transmission to the time instant that either the packet is acknowledged for a successful transmission or dropped.

We propose to evaluate the Z-Transform of the MAC layer service time [3], [14], [15] to derive an expression of the average service time. The service time depends on the duration of an idle slot  $T_e$ , the duration of a successful transmission  $T_s$  and the duration of a collision  $T_c$  [1], [3],[14]. As  $T_e$  is the smallest duration event, the duration of all events will be given by  $\left\lceil \frac{T_{event}}{T_e} \right\rceil$ .

### 6.1 Z-Transform of the MAC layer service time

#### 6.1.1 Service time Z-transform of a category $C_1$ station:

Let  $TS_1(Z)$  be the service time Z-transform of a station  $S_1$  belonging to traffic category  $C_1$ . We define:

$HI_{(R,i,i-j,-D_{21})}(Z)$ : The Z-transform of the time already elapsed from the instant  $S_1$  selects a basic backoff in  $[0, W - 1]$  (i.e. being in one of the states  $(\sim C_2, i, i - D_{21})$ ) to the time it is found in the state  $(R, i, i - j, -D_{21})$ .

Moreover, we define:

- $P_{suc}^{11}$ : the probability that  $S_1$  observes a successful transmission on the channel, while  $S_1$  is in one of the states of  $\xi_1$ .

$$P_{suc}^{11} = (n_1 - 1)\tau_{11}(1 - \tau_{11})^{n_1 - 2} \quad (36)$$

- $P_{suc}^{12}$ : the probability that  $S_1$  observes a successful transmission on the channel, while  $S_1$  is in one of the states of  $\gamma_1$ .

$$P_{suc}^{12} = (n_1 - 1)\tau_{12}(1 - \tau_{12})^{n_1 - 2}(1 - \tau_{22})^{n_2} + n_2\tau_{22}(1 - \tau_{22})^{n_2 - 1}(1 - \tau_{12})^{n_1 - 1} \quad (37)$$

We evaluate  $HI_{(R,i,i-j,-D_{21})}(Z)$  for each state of S1 Markov chain as follows:

$$HI_{(\sim C_2, i, i - D_{21})}(Z) = \frac{1}{W} + \left[ P_{suc}^{11} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + \left( p_{11} - P_{suc}^{11} \right) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right]^{min(i + D_{21} - 1, W - 1)} \sum_{k=i+1}^{min(i + D_{21} - 1, W - 1)} HI_{(\sim C_2, k, i - D_{21})}(Z) + \hat{H}I_{(C_2, i + D_{21}, i - D_{21})}(Z) \left( P_{suc}^{12} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + \left( p_{11} - P_{suc}^{12} \right) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right) \quad (38)$$

Where:

$$\begin{cases} \hat{H}I_{(C_2, i+D_{21}, i, -D_{21})}(Z) = HI_{(C_2, i+D_{21}, i, -D_{21})}(Z) \\ \text{if } (i+D_{21}) \leq W-1 \\ \hat{H}I_{(C_2, i+D_{21}, i, -D_{21})}(Z) = 0 \quad \text{Otherwise} \end{cases} \quad (39)$$

We also have:

$$HI_{(\sim C_2, i, i-j, -D_{21})}(Z) = \frac{((1-p_{11})Z)^j HI_{(\sim C_2, i, i, -D_{21})}(Z)}{1 - P_{suc}^{11} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} - (p_{11} - P_{suc}^{11}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil}} \quad (40)$$

$i = 2..W-1, j = 1..min(i-1, D_{21}-1)$

$$HI_{(C_2, i, i-D_{21}, -D_{21})}(Z) = \frac{((1-p_{11})Z)^{D_{21}} HI_{(\sim C_2, i, i, -D_{21})}(Z)}{1 - P_{suc}^{11} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} - (p_{11} - P_{suc}^{11}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil}} \quad (41)$$

$+ (1-p_{12}) ZHI_{(C_2, i+1, i+1-D_{21}, -D_{21})}(Z), i = D_{21}..W-2$

$$HI_{(C_2, W-1, W-1-D_{21}, -D_{21})}(Z) = \frac{((1-p_{11})Z)^{D_{21}} HI_{(\sim C_2, W-1, W-1, -D_{21})}(Z)}{1 - P_{suc}^{11} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} - (p_{11} - P_{suc}^{11}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil}} \quad (42)$$

$+ (1-p_{12}) ZHI_{(C_2, i+1, i+1-D_{21}, -D_{21})}(Z), i = D_{21}..W-2$

$$HI_{(\sim C_2, 0, 0, -D_{21})}(Z) = \frac{(1-p_{11}) ZHI_{(\sim C_2, 1, 1, -D_{21})}(Z)}{1 - P_{suc}^{11} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} - (p_{11} - P_{suc}^{11}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil}} \quad (43)$$

$+ (1-p_{11}) Z \sum_{i=2}^{min(W-1, D_{21}-1)} HI_{(\sim C_2, i, 1, -D_{21})}(Z) + \frac{1}{W}$

If  $S_1$  transmission state is  $(\sim C_2, 0, 0, -D_{21})$ , the transmission will be successful only if none of the  $(n_1 - 1)$  remaining stations of  $C_1$  transmits. Whereas when the station  $S_1$  transmission state is  $(C_2, D_{21}, 0, -D_{21})$ , the transmission occurs successfully only if none of  $(n-1)$  remaining stations (either a category  $C_1$  or a category  $C_2$  station) transmits.

If the transmission fails,  $S_1$  tries another transmission. After  $m$  retransmissions, if the packet is not acknowledged, it will be dropped.

Thus:

$$TS_1(Z) = Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} \left( (1-p_{11}) HI_{(\sim C_2, 0, 0, -D_{21})}(Z) \right. \quad (44)$$

$+ (1-p_{12}) HI_{(C_2, D_{21}, 0, -D_{21})}(Z) \sum_{i=0}^m \left( Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} (p_{11} HI_{(\sim C_2, 0, 0, -D_{21})}(Z) \right. \right.$

$+ p_{12} HI_{(C_2, D_{21}, 0, -D_{21})}(Z) \left. \left. \right)^{m+1} \right.$

$+ \left( Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} (p_{11} HI_{(\sim C_2, 0, 0, -D_{21})}(Z) + p_{12} HI_{(C_2, D_{21}, 0, -D_{21})}(Z) \right)^{m+1}$

### 6.1.2 Service time Z-transform of a category $C_2$ station:

In the same way, let  $TS_2(Z)$  be the service time Z-transform of a station  $S_2$  of category  $C_2$ . We define:

$H2_{(i, k, D_{21}-j, D_{21})}(Z)$ : The Z-transform of the time already elapsed from the instant  $S_2$  selects a basic backoff in  $[0, W-1]$  (i.e. being in one of the states  $(i, i, D_{21}, D_{21})$ ) to the time it is found in the state  $(i, k, D_{21}-j, D_{21})$ .

Moreover, we define:

- $P_{suc}^{21}$ : the probability that  $S_2$  observes a successful transmission on the channel, while  $S_2$  is in one of the states of  $\xi_2$ .
- $$P_{suc}^{11} = (n_1 - 1) \tau_{12} (1 - \tau_{12})^{n_1 - 1} \quad (45)$$

- $P_{suc}^{22}$ : the probability that  $S_2$  observes a successful transmission on the channel, while  $S_2$  is in one of the states of  $\gamma_2$ .
- $$P_{suc}^{22} = n_1 \tau_{12} (1 - \tau_{12})^{n_1 - 1} (1 - \tau_{22})^{n_2 - 1} \quad (46)$$
- $+ (n_2 - 1) \tau_{22} (1 - \tau_{22})^{n_2 - 2} (1 - \tau_{12})^{n_1}$

We evaluate  $H2_{(i, i, D_{21}-j, D_{21})}(Z)$  for each state of S1 Markov chain as follows:

$$H2_{(i, i, D_{21}-j, D_{21})}(Z) = \frac{1}{W}, i = 0 \text{ and } i = W-1 \quad (47)$$

$$H2_{(i, i, D_{21}, D_{21})}(Z) = \frac{1}{W} + \left( P_{suc}^{22} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + \right. \quad (48)$$

$\left. (p_{22} - P_{suc}^{22}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right) H2_{(i+1, i, 0, D_{21})}(Z), i = 1..W-2$

To compute  $H2_{(i, i, D_{21}-j, D_{21})}(Z)$ , we define  $T_{dec}^j(Z)$ , such as:

$$T_{dec}^0(Z) = 1 \quad (49)$$

$$T_{dec}^j(Z) = \frac{(1 - p_{21})Z}{1 - \left( P_{suc}^{21} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + (p_{21} - P_{suc}^{21}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right) T_{dec}^{j-1}(Z)}$$

for  $j = 1..D_{21}$

$$(50)$$

So:

$$H2_{(i,i,D_{21}-j,D_{21})}(Z) = H2_{(i,i,D_{21}-j+1,D_{21})}(Z) T_{dec}^j(Z),$$

$$i = 0..W-1, j = 1..D_{21}, (i,j) \neq (0,D_{21}) \quad (51)$$

And:

$$H2_{(i,i-1,0,D_{21})}(Z) = (1 - p_{22})ZH2_{(i+1,i,0,D_{21})}(Z)$$

$$+ \frac{(1 - p_{22})ZH2_{(i,i,0,D_{21})}(Z)}{1 - \left( P_{suc}^{22} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + (p_{22} - P_{suc}^{22}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right) T_{dec}^{D_{21}}(Z)}$$

$$i = 2..W-2 \quad (51)$$

$$H2_{(W-1,W-2,0,D_{21})}(Z) = \frac{(1 - p_{22})ZH2_{(W-1,W-1,0,D_{21})}(Z)}{1 - \left( P_{suc}^{22} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + (p_{22} - P_{suc}^{22}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right) T_{dec}^{D_{21}}(Z)} \quad (52)$$

According to figure 2 and using equations (44), we have:

$$H2_{(0,0,0,D_{21})}(Z) = H2_{(0,1,0,D_{21})}(Z) T_{dec}^{D_{21}}(Z)$$

$$+ \frac{(1 - p_{22})ZH2_{(1,1,0,D_{21})}(Z)}{1 - \left( P_{suc}^{22} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + (p_{22} - P_{suc}^{22}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right) T_{dec}^{D_{21}}(Z)} \quad (53)$$

Therefore, we can derive an expression of  $S_2$  Z-transform service time as follows:

$$TS_2(Z) = \left( p_{22} Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} H2_{(0,0,0,D_{21})}(Z) \right)^{m+1} + (1 - p_{22}) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} H2_{(0,0,0,D_{21})}(Z) \sum_{i=0}^m \left( p_{22} Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} H2_{(0,0,0,D_{21})}(Z) \right)^i \quad (54)$$

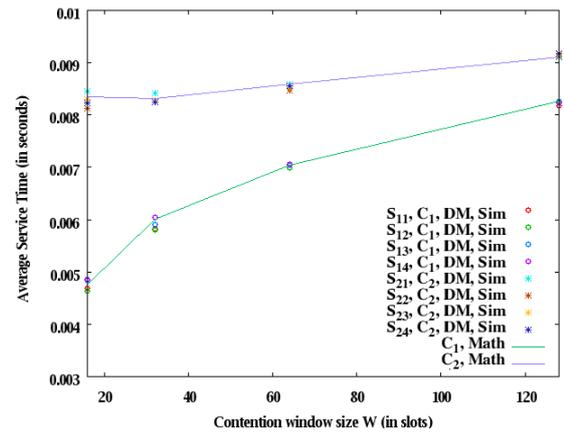
## 6.2 Average Service Time

From equations (43) (respectively equation (54)), we derive the average service time of a category  $C_1$  station ( respectively a category  $C_2$  station). The average service time of a category  $C_i$  station is given by:

$$\overline{X}_i = TS_i^{(1)}(1) \quad (55)$$

Where  $TS_i^{(1)}(Z)$ , is the derivate of the service time Z-transform of station  $S_i$  [11].

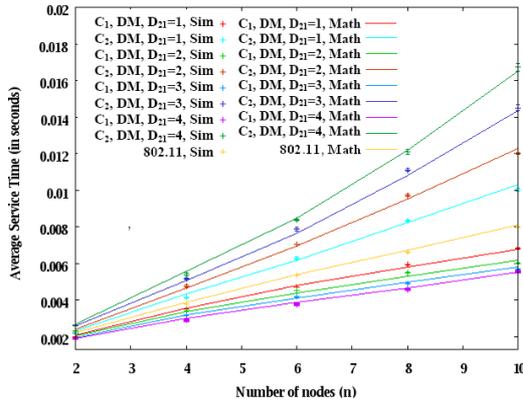
By considering the same configuration as in figure 3, we depict in figure 5, the average service time of category  $C_1$  and category  $C_2$  stations as a function of  $W$ . As for the throughput analysis, stations belonging to the same traffic category have nearly the same average service value. Simulation service time values coincide with analytical values given by equation (55). These results confirm the fairness of DM in serving stations of the same category.



**Figure 6:** Average service time as a function of the contention window size ( $D_{21}=1, n=8$ )

In figure 8, we show that category  $C_1$  stations obtain better average service time than the one obtained with 802.11 protocol. Whereas, the opposite scenario happens for category  $C_2$  stations

independently of  $n$ , the number of contending stations within the network.



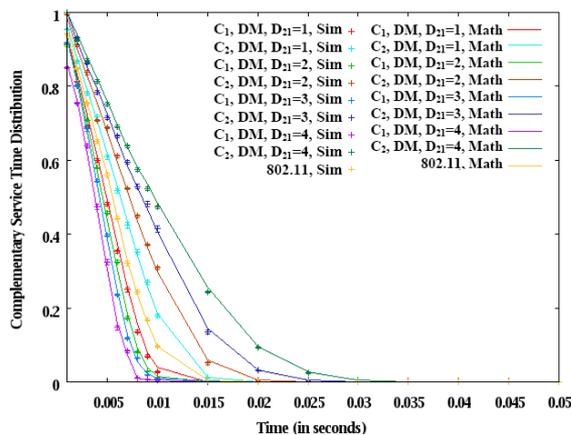
**Figure 7:** Average service time as a function of the number of contending stations

### 6.3 Service Time Distribution

Service time distribution is obtained by inverting the service time  $Z$  transforms given by equations (43) and (54). But we are most interested in probabilistic service time bounds derived by inverting the complementary service time  $Z$  transform given by [11]:

$$\tilde{X}_i(Z) = \frac{1 - TS_i(Z)}{1 - Z} \quad (55)$$

In figure 8, we depict analytical and simulation values of the complementary service time distribution of both category  $C_1$  and category  $C_2$  station ( $W = 32$ ).

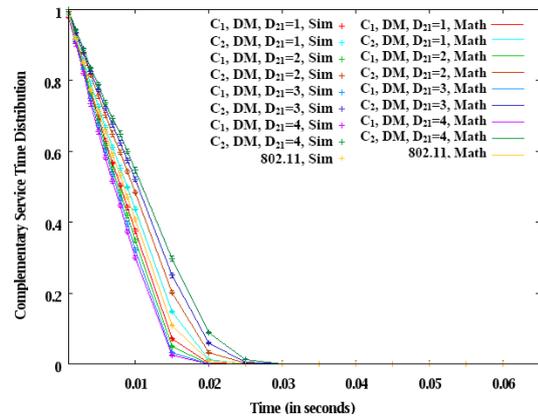


**Figure 8:** Complementary service time distribution for different values of  $D_{21}$ , ( $W = 32$ )

All the curves drop gradually to 0 as the delay increases. Category  $C_1$  stations curves drop to 0 faster than category  $C_2$  curves. Indeed, when

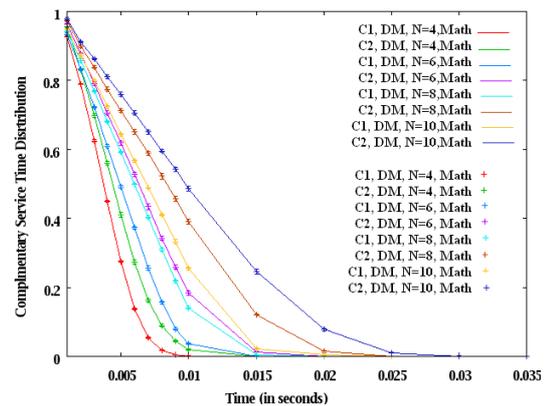
$D_{21} = 4$ , the probability that  $S_1$  service time exceeds 0.005s equals 0.28%. Whereas, station  $S_2$  service time exceeds 0.005s with the probability 5.67%. Thus, DM offers better service time guarantees for the stations with the highest priority.

In figure 9, we double the size of the contention window size and set it to 64. We notice that category  $C_1$  and category  $C_2$  stations service time curves become closer. Indeed, when  $W$  becomes large, the BAB values increase and the (DMSB) becomes negligible compared to the basic backoff. The whole backoff values of  $S_1$  and  $S_2$  become near and their service time accordingly.



**Figure 9:** Complementary service time distribution for different values of  $D_{21}$  ( $W=64$ )

In figure 10, we depict the complementary service time distribution for both category  $C_1$  and category  $C_2$  stations and for values of  $n$ , the number of contending nodes.



**Figure 10:** Complementary service time distribution for different values of the contending stations

Analytical and simulation results show that complementary service time curves drop faster when the number of contending stations is small for both category  $C_1$  and category  $C_2$  stations. This

means that all stations service time increases as the number of contending nodes increases.

## 7 EXTENTIONS OF THE ANAYTICAL RESULTS BY SIMULATION

The mathematical analysis undertaken above show that DM performs service differentiation over 802.11 protocol and offers better QoS guarantees for highest priority stations

Nevertheless, the analysis was restricted to two traffic categories. In this section, we first generalize the results by simulation for different traffic categories. Therefore, we consider a simple multi-hop and evaluate the performance of the DM policy when the stations belong to different broadcast regions.

### 7.1 Extension of the analytical results

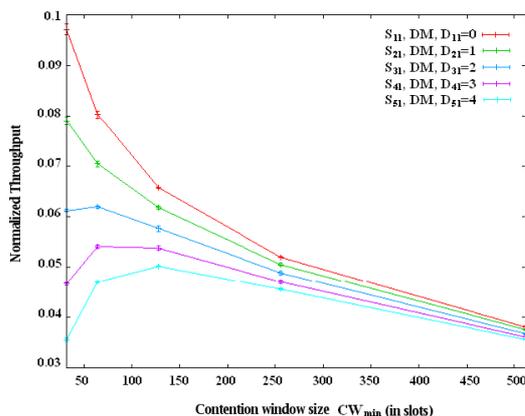
In this section, we consider  $n$  stations contending for the channel in the same broadcast region. The  $n$  stations belong to 5 traffic categories where  $n = 5m$  and  $m$  is the number of stations of the same traffic category. A traffic category  $C_i$  is characterized by a delay bound  $D_i$ , and  $D_{ij} = D_i - D_j$  is the difference between the deadline values of category  $C_i$  and category  $C_j$  stations. We have:

$$D_{ij} = (i - j)K \quad (53)$$

Where  $K$  is the deadline multiplicity factor and is given by:

$$D_{i+1,i} = D_{i+1} - D_i = K \quad (53)$$

Indeed, when  $K$  varies, the deadline values of all other stations also vary. Stations belonging to the traffic category  $C_i$  are numbered from  $S_{i1}$  to  $S_{im}$ .



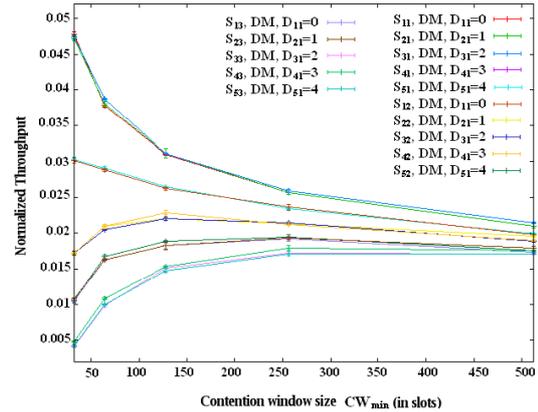
**Figure 11:** Normalized throughput for different traffic category stations

In figure 11, we depict the throughput achieved by different traffic categories stations as a function of the minimum contention window size  $CW_{min}$  such as  $CW_{min}$  is always smaller than  $CW_{max}$ ,

$CW_{max} < 1024$  and  $K = 1$ .

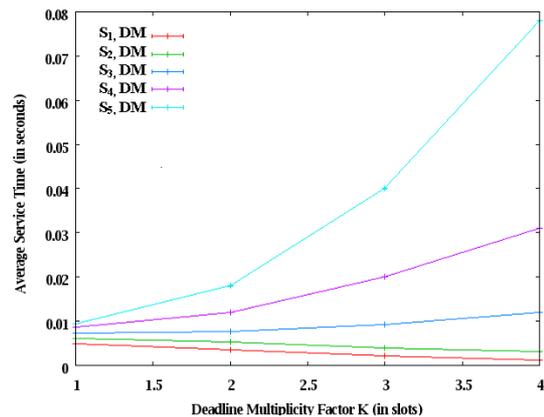
Analytical and simulation results show that throughput values increase with stations priority. Indeed, the station with the lowest delay bound has the maximum throughput.

Moreover, figure 12 shows that stations belonging to the same traffic category have the same throughput. For instance, when  $n$  is set to 15 (i.e.  $m = 3$ ), the three stations of the same traffic category have almost the same throughput.



**Figure 12:** Normalized throughput: different stations belonging to the same traffic category

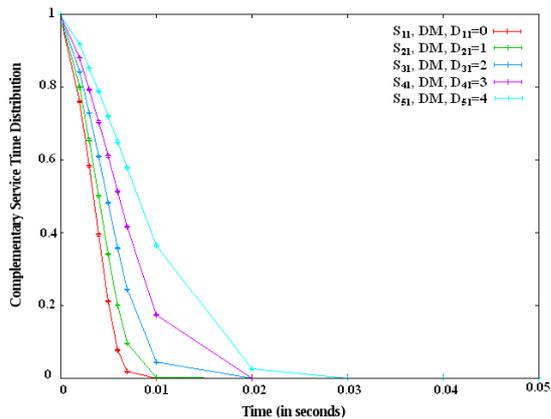
In figure 13, we depict the average service time of the different traffic category stations as a function of  $K$ , the deadline multiplicity factor. We notice that the highest priority station average service time decreases as the deadline multiplicity factor increases. Whereas, the lowest priority station average service time increases with  $K$ .



**Figure 13:** Average service time as a function of the deadline multiplicity factor  $K$

In the same way, the probabilistic service time bounds offered to  $S_{11}$  (the highest priority station) are better than those offered to station  $S_{51}$  (the lowest priority station). Indeed, the probability that  $S_{11}$  service time exceeds  $0.01s = 0.3\%$ . But, station

$S_{51}$  service time exceeds 0.01s with the probability of 36%.



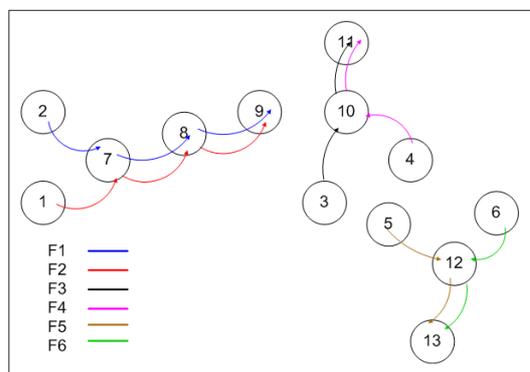
**Figure 14:** Complementary service time distribution ( $W=32$ ,  $n=8$ )

The above results generalize the analytical model results and show once again that DM performs service differentiation over 802.11 and offer better guarantees in terms of throughput, average service time and probabilistic service time bounds for flows with short deadlines.

## 7.2 Simple Multi hop scenario

In the above study, we considered that contending stations belong to the same broadcast region. In reality, stations may not be within one hop from each other. Thus a packet can go through several hops before reaching its destination. Hence, factors like routing protocols or interferences may preclude the DM policy from working correctly.

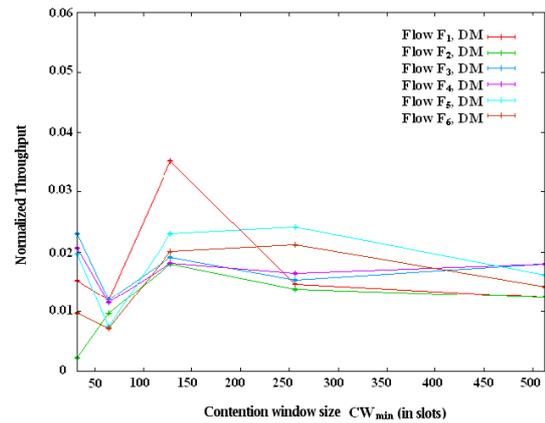
In the following paragraph, we evaluate the performance of the DM policy in a multi-hop environment. Hence, we consider a 13 node simple multi-hop scenario described in figure 15.



**Figure 15:** Simple multi hop scenario  
Six flows are transmitted over the network. Flow packets are routed using the AODV protocol. Flows  $F_1$  and  $F_2$  are respectively transmitted by stations  $S_1$  and  $S_2$  with delay bounds  $D_1$  and  $D_2$

and  $D_{21} = D_2 - D_1 = 5$  slots. Flows  $F_3$  and  $F_4$  are transmitted respectively by  $S_{12}$  and  $S_4$  and have the same delay bound. Finally,  $F_5$  and  $F_6$  are transmitted respectively by  $S_5$  and  $S_6$  with delay bounds  $D_1$  and  $D_2$  and  $D_{2,1} = D_2 - D_1 = 5$  slots.

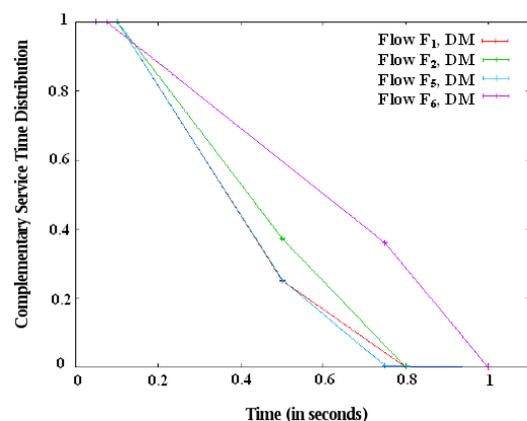
Figure 16 shows that the throughput achieved by  $F_1$  is smaller than the one achieved by  $F_2$ .



**Figure 16:** Normalized throughput using DM policy

Indeed, both flows cross nodes 6 and 7, where  $F_1$  got a higher priority to access the medium than  $F_2$  when the DM policy is used. We obtain the same results for flows  $F_5$  and  $F_6$ . Flows  $F_3$  and  $F_4$  have almost the same throughput since they have equal deadlines.

Figure 17 show that the complementary service time distribution curves drop to 0 faster for flow  $F_1$  than for flow  $F_2$ .



**Figure 17:** End to end complementary service time distribution

The same behavior is obtained for flow  $F_5$  and  $F_6$ , where  $F_5$  has the shortest delay bound.

Hence, we conclude that even in a multi-hop

environment, the DM policy performs service differentiation over 802.11 and provides better QoS guarantees for flows with short deadlines.

## 8 CONCLUSION

In this paper we first proposed to support the DM policy over 802.11 protocol. Therefore, we used a distributed backoff scheduling algorithm and introduced a new medium access backoff policy. Then we proposed a mathematical model to evaluate the performance of the DM policy. Indeed, we considered  $n$  contending stations belonging to two traffic categories characterized by different delay bounds. Analytical and simulation results show that DM performs service differentiation over 802.11 and offers better guarantees in terms of throughput, average service time and probabilistic service time bounds for the flows having small deadlines. Moreover, DM achieves fairness between stations belonging to the same traffic category.

Then, we extended by simulation the analytical results obtained for two traffic categories to different traffic categories. Simulation results showed that even if contending stations belong to  $K$  traffic categories,  $K > 2$ , the DM policy offers better QoS guarantees for highest priority stations. Finally, we considered a simple multi-hop scenario and concluded that factors like routing messages or interferences don't impact the behavior of the DM policy and DM still provides better QoS guarantees for stations with short deadlines.

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