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 distrbution. To evaluate the performance of the DM policy, we develop a Markov chain based analytical model and derive expressions of the throughput, the average MAC layer service time and the service time distribution. Therefore, we validate the mathematical model and extend analytial results to a multi-hop network by simulation using the ns-2 network simulator.

Keywords: Deadline Monotonic, 802.11, Performance evaluation, Average 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 the 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 80.211e 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 the paper 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 stations 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 such 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, the 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 proposed a model that takes into consideration all the differentiation parameters of the EDCA 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 introduced 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, authors of [18] proposed a generic backoff policy that can be used by a class of 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 (DM) policy over 802.11 to schedule delay sensitive flows. For instance, we use a priority broadcast mechanism similar to [18] and introduce 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 $\left(S_j, D_j\right)$ 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 HOL packets deadlines, we propose to use the two way handshake DATA/ACK access mode.

When a node S_i transmits a DATA packet, it piggybacks the deadline of its HOL packet. 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 $D_{21} = \left(D_2 - D_1\right)$.

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 revaluated 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 WHole Backoff (*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 revaluates 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_1 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.
- i: the value of the BAB selected by S_1 in $[0, W-1]$.

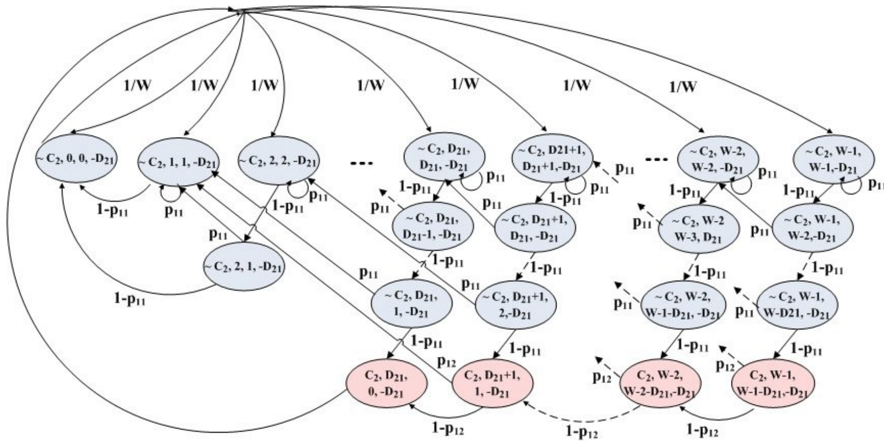

Figure 1: Markov chain modeling a category C_1 Station

- $(i-j)$: 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 $(\sim C_2, i, i-j, -D_{21})$, for $i = 1..W-1$, $j = 0..min(D_{21}-1, i-1)$ 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.

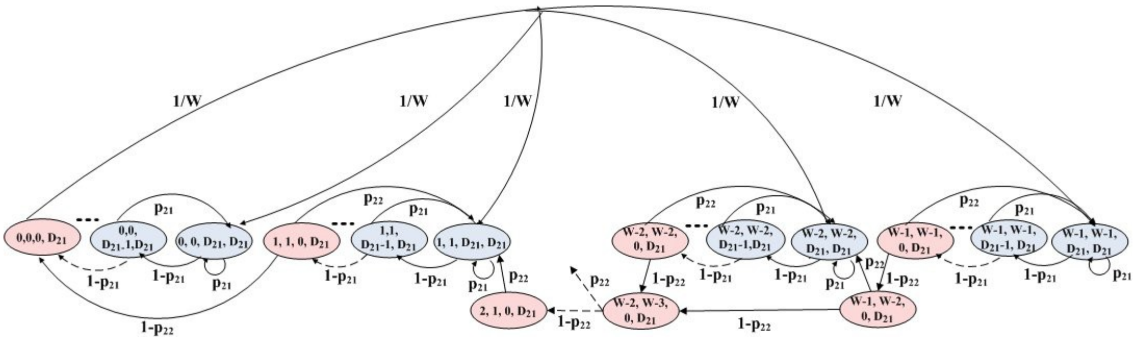

Figure 2: Markov chain modeling a category C_2 Station

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 the $(n-1)$ 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 $(i-1,i-1,D_{21},D_{21})$, $i=2..W-1$.

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:

- ξ_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).
  $\xi_1=\{(\sim C_2,i,i-j,-D_{21}),i=0..W-1,$
  $j=0..min(max(0,i-1),D_{21}-1)\}$

- γ_1 : the set of states of S_1 where stations of category C_2 can contend for the channel (pink states in figure 1).
  $\gamma_1=\{(C_2,i,i-D_{21},-D_{21}),i=D_{21}..W-1\}$

- ξ_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).
  $\xi_2=\{(i,i,D_{21}-j,D_{21}),i=0..W-1,$
  $j=0..(D_{21}-1)\}$

- γ_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 the states of ξ_1, stations of category C_2 are in one of the states of ξ_2. Similarly, when stations of category C_1 are is in one of the states of γ_1, stations of category C_2 are in one of the states of γ_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 ξ_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 ξ_1.

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

where τ_{11} is the probability that a station $S_1^{'}$ of C_1 transmits given that $S_1^{'}$ is in one of the states of ξ_1:

$$\tau_{11}=Pr\left[S_1^{'}\ transmits\ /\xi_1\right]$$
$$=\frac{\pi_1^{(\sim C_2,0,0,-D_{21})}}{\sum_{i=0}^{W-1}\left(\sum_{j=0}^{min(max(0,i-1),D_{21}-1)}\pi_1^{(\sim C_2,i,i-j,-D_{21})}\right)} \qquad (4)$$

$\pi_1^{(R,i,i-j,-D_{21})}$ 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 γ_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 γ_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 γ_2.

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

where τ_{12} is the probability that a station $S_1^{'}$ of C_1 transmits given that $S_1^{'}$ is in one of the states of γ_1.

$$\tau_{12} = Pr\left[S_1^{'}\ transmits\ /\gamma_1\right] = \frac{\pi_1^{(C_2,D_{21},0,-D_{21})}}{\sum_{i=D_{21}}^{W-1}\pi_1^{(C_2,i,i-D_{21},-D_{21})}} \quad (6)$$

and τ_{22} the probability that a station $S_2^{'}$ of C_2 transmits given that $S_2^{'}$ is in one of the states of γ_2.

$$\tau_{12} = Pr\left[S_2^{'}\ transmits\ /\gamma_2\right] = \frac{\pi_2^{(0,0,0,D_{21})}}{\sum_{i=0}^{W-1}\pi_2^{(i,i,0,D_{21})}+\sum_{i=2}^{W-1}\pi_2^{(i,i-1,0,D_{21})}} \quad (7)$$

$\pi_2^{(i,k,D_{21}-j,D_{21})}$ 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 shown in figure 2:

– p_{21}: the probability that S_2 is blocked given that S_2 is in one of the states of ξ_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 γ_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:

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

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

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

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

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

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

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

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

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

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

By replacing p_{11} and p_{12} by their values in equations (3) and (5) and by replacing P_1 and Π_1 in (10) and solving the resulting system, we can express $\pi_1^{(R,i,i-j,-D_{21})}$ as a function of τ_{11}, τ_{12} and τ_{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:

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

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

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

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

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

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

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

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

By replacing p_{21} and p_{22} by their values in equations (8) and (9) and by replacing P_2 and Π_2 in (10) and solving the resulting system, we can express $\pi_2^{(i,k,D_{21}-j,D_{21})}$ as a function of τ_{11}, τ_{12} and τ_{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:

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

Solving the above system (28), allows deducing the expressions of τ_{11}, τ_{12} and τ_{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 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:

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

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

- 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 ξ_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 γ_1. Thus:

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

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

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

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 packets.

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.

Data Rate	11 Mb/s
Slot	20 µs
SIFS	10 µs
DIFS	50 µs
PHY Header	192 µs
MAC Header	272 µs
ACK	112 µs
Short Retry Limit	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 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}).

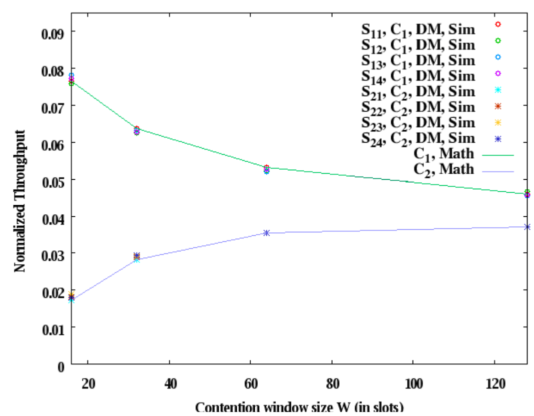

Figure 3: Normalized throughput as a function of the contention window size $(D_{21} = 1, n = 8)$

Analytically, stations belonging to the same traffic category have the same throughput given by equation (32). 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 category C_2 station.

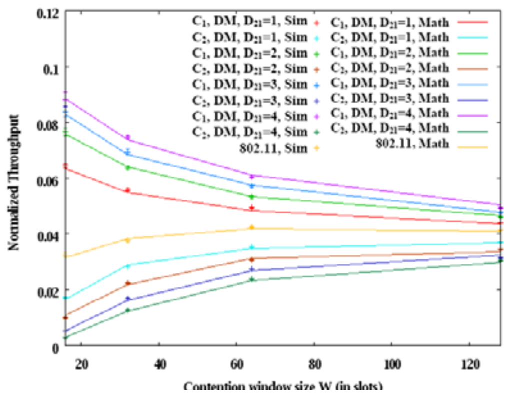

Figure 4: Normalized throughput as a function of the contention window size (different D_{21} values)

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

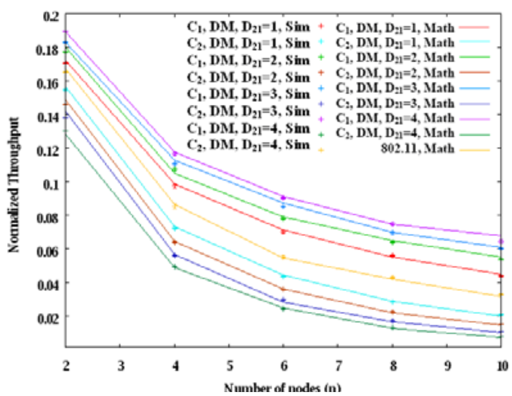

Figure 5: Normalized throughput as a function of the number of contending stations

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 [3].

We propose to evaluate the Z-Transform of the MAC layer service time [3], [14], [15] to derive the service time distribution. 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:

$H1_{(R,i,i-j,-D_{21})}(Z)$: 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 ξ_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 γ_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 $H1_{(R,i,i-j,-D_{21})}(Z)$ for each state of S_1 Markov chain as follows:

$$H1_{(\sim C_2,i,i,-D_{21})}(Z) = \frac{1}{W} + \left[P_{suc}^{11} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + \left(p_{11} - P_{suc}^{11}\right) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right] \sum_{k=i+1}^{\min(i+D_{21}-1,W-1)} H1_{(\sim C_2,k,i,-D_{21})}(Z)$$

$$+ \hat{H}1_{(C_2,i+D_{21},i,-D_{21})}(Z) \left(P_{suc}^{12} Z^{\left\lceil \frac{T_s}{T_e} \right\rceil} + \left(p_{11} - P_{suc}^{12}\right) Z^{\left\lceil \frac{T_c}{T_e} \right\rceil} \right)$$

an

2 21 21

(38)

Where:

$$\begin{cases} \hat{H}1_{(C_2,i+D_{21},i,-D_{21})}(Z) = H1_{(C_2,i+D_{21},i,-D_{21})}(Z) & \text{if } (i+D_{21}) \le W-1 \\ \hat{H}1_{(C_2,i+D_{21},i,-D_{21})}(Z) = 0 & \text{Otherwise} \end{cases} \quad (39)$$

We also have:

$$H1_{(\sim C_2,i,i-j,-D_{21})}(Z) = \frac{((1-p_{11})Z)^j \, H1_{(\sim C_2,i,i,-D_{21})}(Z)}{1-P_{suc}^{11}Z^{\lceil \frac{T_s}{T_e} \rceil} - (p_{11}-P_{suc}^{11})Z^{\lceil \frac{T_c}{T_e} \rceil}}$$

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

(40)

$$H1_{(C_2,i,i-D_{21},-D_{21})}(Z) = \frac{((1-p_{11})Z)^{D_{21}} H1_{(\sim C_2,i,i,-D_{21})}(Z)}{1-P_{suc}^{11}Z^{\lceil \frac{T_s}{T_e} \rceil} - (p_{11}-P_{suc}^{11})Z^{\lceil \frac{T_c}{T_e} \rceil}} + (1-p_{12})ZH1_{(C_2,i+1,i+1-D_{21},-D_{21})}(Z), i = D_{21}..W-2$$

(41)

$$H1_{(C_2,W-1,W-1-D_{21},-D_{21})}(Z) = \frac{((1-p_{11})Z)^{D_{21}} H1_{(\sim C_2,W-1,W-1,-D_{21})}(Z)}{1-P_{suc}^{11}Z^{\lceil \frac{T_s}{T_e} \rceil} - (p_{11}-P_{suc}^{11})Z^{\lceil \frac{T_c}{T_e} \rceil}} \quad (42)$$

$$H1_{(\sim C_2,0,0,-D_{21})}(Z) = \frac{(1-p_{11})ZH1_{(\sim C_2,1,1,-D_{21})}(Z)}{1-P_{suc}^{11}Z^{\lceil \frac{T_s}{T_e} \rceil} - (p_{11}-P_{suc}^{11})Z^{\lceil \frac{T_c}{T_e} \rceil}} + (1-p_{11})Z\sum_{i=2}^{min(W-1,D_{21}-1)} H1_{(\sim C_2,i,1,-D_{21})}(Z) + \frac{1}{W}$$

(43)

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, the Z-transform of station S_1 service time is:

$$TS_1(Z) = Z^{\lceil \frac{T_s}{T_e} \rceil}\left((1-p_{11})H1_{(\sim C_2,0,0,-D_{21})}(Z) + (1-p_{12})H1_{(C_2,D_{21},0,-D_{21})}(Z)\right)\sum_{i=0}^{m}\left(Z^{\lceil \frac{T_c}{T_e} \rceil}\left(p_{11}H1_{(\sim C_2,0,0,-D_{21})}(Z) + p_{12}H1_{(C_2,D_{21},0,-D_{21})}(Z)\right)\right)^i + \left(Z^{\lceil \frac{T_c}{T_e} \rceil}\left(p_{11}H1_{(\sim C_2,0,0,-D_{21})}(Z) + p_{12}H1_{(C_2,D_{21},0,-D_{21})}(Z)\right)\right)^{m+1}$$

(44)

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 ξ_2.
$$P_{suc}^{21} = n_1\tau_{11}(1-\tau_{11})^{n_1-1} \quad (45)$$
- 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 γ_2.
$$P_{suc}^{22} = n_1\tau_{12}(1-\tau_{12})^{n_1-1}(1-\tau_{22})^{n_2-1} + (n_2-1)\tau_{22}(1-\tau_{22})^{n_2-2}(1-\tau_{12})^{n_1} \quad (46)$$

We evaluate $H2_{(i,i,D_{21}-j,D_{21})}(Z)$ for each state of S_2 Markov chain as follows:

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

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

$\lceil T_c \rceil)$

$_{22} \quad | _T | \, |$

$$\left(p_{22} - P_{suc}\right) Z^{| \; e \; |} \left| H2_{\left(i+1, i, 0, D_{21}\right)}(Z), i = 1..W - 2 \right. \quad (48)$$

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

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

$$T_{dec}^{j}(Z)=\frac{(1-p_{21})Z}{1-\left(P_{suc}^{21}Z^{\left\lceil \frac{T_s}{T_e}\right\rceil}+\left(p_{21}-P_{suc}^{21}\right)Z^{\left\lceil \frac{T_c}{T_e}\right\rceil}\right)T_{dec}^{j-1}(Z)}$$
$$for\ j=1..D_{21} \qquad (50)$$

So:

$$H2_{(i,i,D_{21}-j,D_{21})}(Z)=H2_{(i,i,D_{21}-j+1,D_{21})}(Z)T_{dec}^{j}(Z),$$
$$i=0..W-1,\ j=1..D_{21},(i,j)\neq(0,D_{21}) \qquad (51)$$

And:

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

$$H2_{(W-1,W-2,0,D_{21})}(Z)=\frac{(1-p_{22})ZH2_{(W-1,W-1,0,D_{21})}(Z)}{1-\left(P_{suc}^{22}Z^{\left\lceil \frac{T_s}{T_e}\right\rceil}+\left(p_{22}-P_{suc}^{22}\right)Z^{\left\lceil \frac{T_c}{T_e}\right\rceil}\right)T_{dec}^{D_{21}}(Z)} \qquad (53)$$

According to figure 2 and using equation (51), we have:

$$H2_{(0,0,0,D_{21})}(Z)=H2_{(0,1,0,D_{21})}(Z)T_{dec}^{D_{21}}(Z)+\frac{(1-p_{22})ZH2_{(1,1,0,D_{21})}(Z)}{1-\left(P_{suc}^{22}Z^{\left\lceil \frac{T_s}{T_e}\right\rceil}+\left(p_{22}-P_{suc}^{22}\right)Z^{\left\lceil \frac{T_c}{T_e}\right\rceil}\right)T_{dec}^{D_{21}}(Z)} \qquad (54)$$

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

$$TS_2(Z)=\left(p_{22}Z^{\left\lceil \frac{T_c}{T_e}\right\rceil}H2_{(0,0,0,D_{21})}(Z)\right)^{m+1}+$$
$$(1-p_{22})Z^{\left\lceil \frac{T_s}{T_e}\right\rceil}H2_{(0,0,0,D_{21})}(Z)\sum_{i=0}^{m}\left(p_{22}Z^{\left\lceil \frac{T_c}{T_e}\right\rceil}H2_{(0,0,0,D_{21})}(Z)\right)^{i} \qquad (55)$$

6.2 Average Service Time

From equations (44) (respectively equation (55)), 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:

$$\overline{X_i}=TS_i^{(1)}(1) \qquad (56)$$

Where $TS_i^{(1)}(Z)$, is the derivate of the service time Z-transform of a category C_i station [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 (56). These results confirm the fairness of DM in serving stations of the same category.

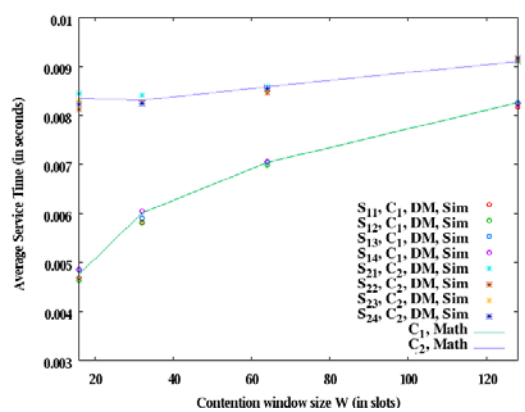

Figure 6: Average service time as a function of the contention window size $(D_{21}=1,n=8)$

In figure 7, 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 in the network.

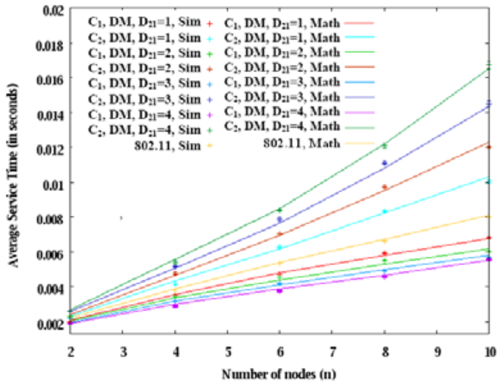

Figure 7: Average service time as a function of the number of contending stations

6.3 Service Time Distribution

Service time distribution is obtained by inverting the service time Z transforms given by equations (44) and (55). But we are most interested in probabilistic service time bounds derived by inverting the complementary service time Z transform given by [11]:

$$\tilde{X}_i(Z) = \frac{1 - TS_i(Z)}{1 - Z} \qquad (56)$$

In figure 8, we depict analytical and simulation values of the complementary service time distribution of a category C_1 and a category C_2 stations for different values of D_{21} and $(W = 32)$.

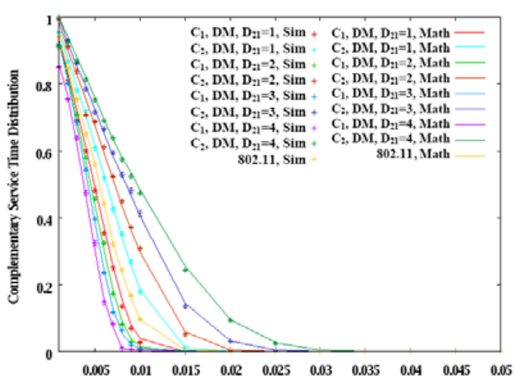

Figure 8: Complementary service time distribution for different values of D_{21}, $(W = 32)$

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 $D_{21} = 4$ slots, the probability that S_1 service time exceeds 0.01s equals 0.2%. Whereas, station S_2 service time exceeds 0.01s with the probability 57,6%. 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 closer and their service time accordingly.

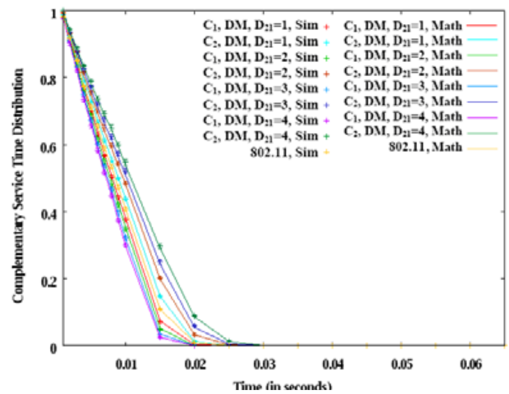

Figure 9: Complementary service time distribution for different values of D_{21} $(W = 64)$

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

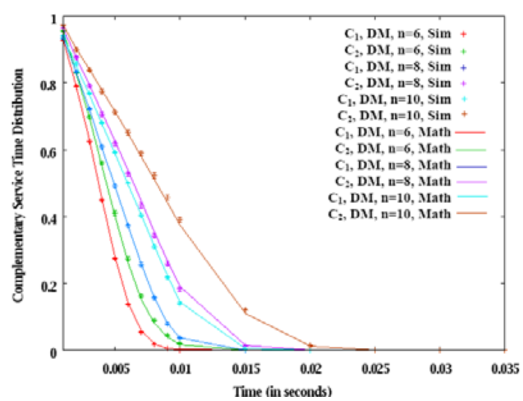

Figure 10: Complementary service time distribution for different values of the contending stations

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 showed 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. Then, 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:

$$D_{ij} = (i - j)K \qquad (57)$$

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

$$D_{i+1,i} = D_{i+1} - D_i = K \qquad (58)$$

Indeed, when K varies, the D_{ij} the difference between deadline values of category C_i and category C_j stations also varies. Stations belonging to the traffic category C_i are numbered from S_{i1} to S_{im}.

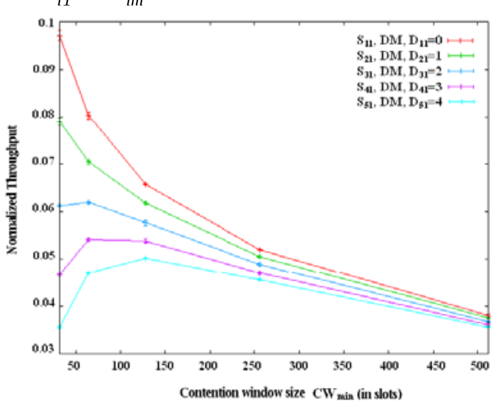

Figure 11: Normalized throughput for different traffic category stations

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 priorities. 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 each traffic category have almost the same throughput.

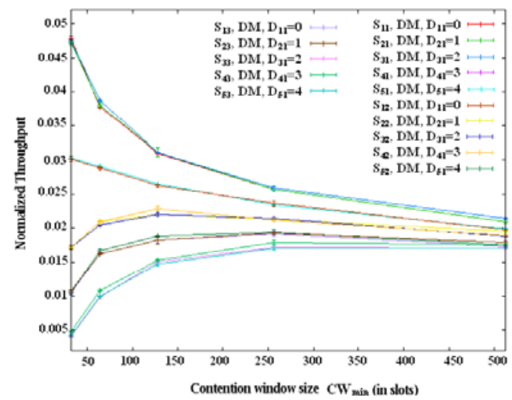

Figure 12: Normalized throughput: different stations belonging to the same traffic category

In figure 13, we depict the average service time of the different traffic categories 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.

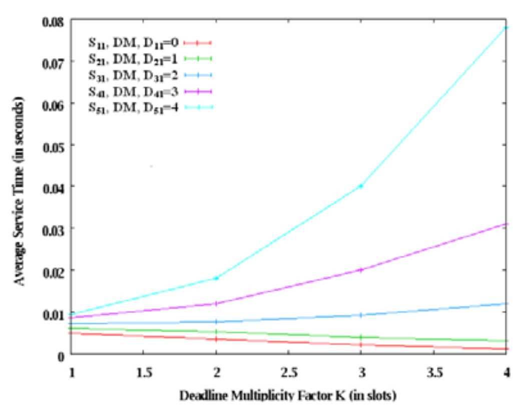

Figure 13: Average service time as a function of the deadline multiplicity factor K

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%.

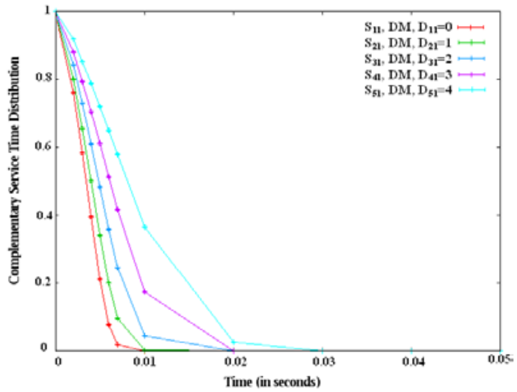

Figure 14: Complementary service time distribution $(CW_{min} = 32, n = 8)$

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 mtlti-hop scenario described in figure 15. Six flows are transmitted over the network.

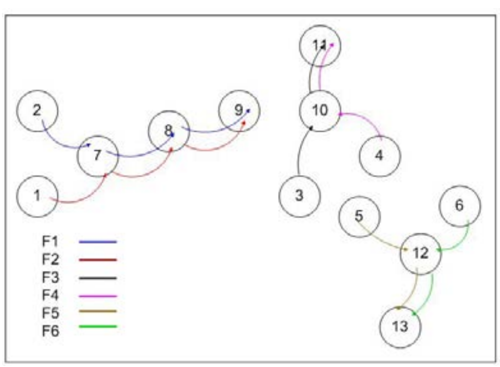

Figure 15: Simple multi hop scenario

Flows packets are routed using the Ad-hoc On Demand (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_3 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_5 and D_6 and $D_{65} = D_6 - D_5 = 4$ slots.

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

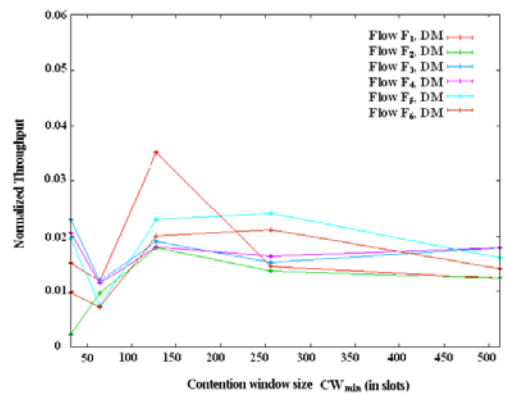

Figure 16: Normalized throughput using DM policy

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

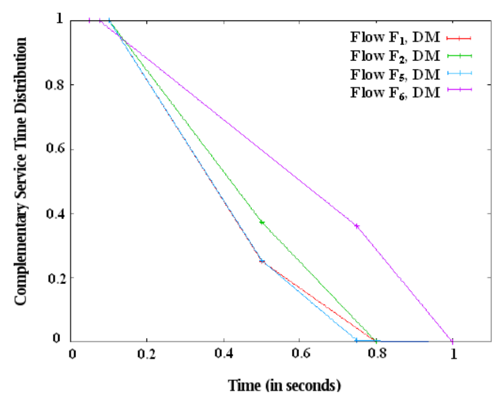

Figure 17: End to end complementary service time distribution

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 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 Markov Chain based mathematical model to evaluate the performance of the DM policy in terms of throughput , average medium access delay and medium access delay distribution. Analytical and simulation results showed 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 flows with 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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