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Younes Bouchaala, Paul Mühlethaler, Nadjib Achir. Analysis of the IEEE 802.11 EDCF scheme for broadcast traffic: Application for VANETs. 2017 Wireless Days, Mar 2017, Porto, Portugal. pp.252 - 257, 10.1109/WD.2017.7918156 . hal-01617895

HAL Id: hal-01617895

<https://hal.science/hal-01617895v1>

Submitted on 17 Oct 2017

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Analysis of the IEEE 802.11 EDCF scheme for broadcast traffic: Application for VANETs

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Abstract—In this paper we propose a model of the IEEE 802.11 Enhanced Distributed Coordination Function (EDCF) which can build different access priorities for different classes of traffic. These priorities are obtained using different inter frame spacings called Arbitration Inter Frame Spacings (AIFSs) to differentiate the access of different classes of traffic. When a node has a pending packet it must first wait for the channel to become idle for a given number A of mini-slots σ before starting to decrement its back-off; this interval of A mini-slots σ is called the AIFS. If the channel becomes busy before this back-off expires, then the node will have to wait for another A mini-slots before starting to decrement its back-off again. The nodes can also use different back-off windows to further differentiate between different classes of traffic. The model we propose is much simpler than previous models [1], [2], [3] and handles the more general case of a Poisson arrival for the traffic. Moreover, the model presented here is designed for broadcast traffic whereas most models handle point-to-point IEEE 802.11 transmission.

When we have two classes of traffic, the model leads to two coupled non-linear equations involving the transmission rates in each class of traffics. These equations can be easily solved using simple numerical methods. The model then allows the successful rate or the throughput for each class of traffic to be computed in a straightforward manner. Numerical examples derived from VANET scenarios show the direct and positive influence of the Arbitration Inter Frame Spacings on the performance of each class of traffic.

Keywords—CSMA, EDCF, Markov Chains, Steady states .

I. INTRODUCTION

Wireless Access in Vehicular Environments (WAVE) [4]. uses the IEEE 802.11p as an access scheme to share the radio medium dedicated to Vehicular Ad Hoc Networks (VANETs). IEEE802.11p is designed to provide communication between vehicles (V2V), and between vehicles and roadside infrastructure (V2I) in new Intelligent Transportation Systems (ITS). One of the prominent applications in V2V communication concerns safety applications; these applications relies on the periodic transmission of packets. There are two main types of applications Car Awareness Messages (CAM) [5] and Decentralized Environmental Notification Messages (DENM) [6]. Car Awareness Messages are used to periodically send information about the vehicles' velocities and positions while DENMs are sent when a hazardous event occurs on the road.

Since IEEE 802.11 is inherently a random access protocol the medium is shared by all the vehicles which compete to transmit their packets. This can create a problem since safety messages may carry traffic of vital information with stringent deadline for their actual delivery. For instance, CAMs or DENMs sent just after a hazardous event carry very urgent information whose delivery might be vital for neighboring vehicles. In the amendment IEEE 802.11e, the IEEE 802.11 group has defined a special mechanism to create different type of access. This mechanism, called the Enhanced Distributed Coordination Function (EDCF) mainly relies on different inter frame spacing called AIFSs for Arbitration Inter Frame Spacings. In this paper we propose a simple model to analyze EDCF for broadcast packets i.e. without acknowledgment and potential retransmission and with a Poisson packet arrival model. We show that the influence of different AIFSs is huge on performance for different classes of traffic.

The remainder of this paper is organized as follows: Section II briefly reviews related work; Section III describes the model proposed to study EDCF. This model is based on coupled and simultaneous Markov chains for which we compute the steady state. We obtain the steady-state transmission rate of each class of traffic. The computation of the throughput of each class of traffic also requires studying the evolution of the position of in Section IV we compute the percentage of successful transmissions and the throughput for each class of traffic. Finally, Section V concludes the paper.

II. RELATED WORK

The seminal paper by Kleinrock [7] gave rise to early studies of CSMA, all of which highlighted the improvement carrier sensing made to Aloha, which was the standard protocol at the time. None of these studies, however, provided a satisfactory model of the back-off techniques that CSMA systems used.

Such a model was, however, provided by Bianchi [8], which led to a breakthrough in the analysis of the backoff techniques used in protocols such as IEEE 802.11.

In recent studies, the Enhanced Distributed Coordination Function was analyzed with techniques stemming from those employed by Bianchi. However these studies [1], [2], [3] focus on point-to-point transmission with a saturated network. Moreover, they use complex Markov chains with a large number

of states. In contrast our study deals with the more general Poisson packet arrival model and also exhibits a Markov chain with a reasonable number of states. We obtain a simple and closed formula for the busy rate ratio.

It must be noted that in this paper we consider that all the nodes are within carriers sense range and thus we do not study the spatial effect of EDCF; the spatial effect of CSMA has been studied in [9] [10] [11].

III. SYSTEM MODEL

The model uses the following assumption for the IEEE 802.11 protocol: the packet length is T and the length of the mini-slot for sensing is denoted by σ . Rather than studying point-to-point transmissions we focus on transmission of broadcast packets thus without acknowledgment. Moreover, the model for the arrival is a Poisson model with a single buffer with loss and an arrival rate λ . We assume that the number of stations M sharing the same radio spectrum is known.

The IEEE 802.11p protocol with priority uses different inter frame spacings called AIFSs for Arbitration Inter Frame Spacings to differentiate various classes of traffic. When a node has a pending packet it must first wait for the channel to become idle for a given number A of mini-slots σ before starting to decrement its back-off; this interval of A mini-slots σ is called the AIFS, see Figure III.1. If the channel becomes busy before this back-off expires, then the node will have to wait for another A mini-slots before starting to decrement its back-off again.

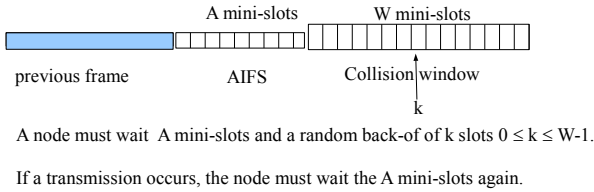


Fig. III.1. Back-off procedure with IEEE 802.11 EDCF scheme.

We first study the steady state of an IEEE 802.11p network which includes the AIFS mechanism.

A. Steady-state of an IEEE 802.11p with AIFS

The state diagram of IEEE 802.11p with priorities is shown in Figure III.2.

The state at the top of the diagram represents the probability that the node is idle i.e. without any packet waiting for transmission and we call c_I the probability of the node being in this state at equilibrium.

The A states just below represent the states when the node starts waiting for the AIFS. We denote by c_i for $1 \leq i \leq A$ the probability that the node has waited for i idle slots in the AIFS part of the waiting time before beginning its transmission.

The W states represented horizontally correspond to the back-off states of the node. The state k with $0 \leq k \leq W-1$ represents the state that the node, having already waited for the entire AIFS interval is now in back-off and still has i mini-slots of back-off to wait. We call b_i for $0 \leq k \leq W-1$

probability that the node still has k mini-slots to wait before it can access the channel. The states (j, i) $0 \leq j \leq W-1$ $0 \leq i \leq A$ illustrated vertically correspond to the case when a back-off procedure (at stage j) has been interrupted by a transmission and the node has to wait A mini-slots again.

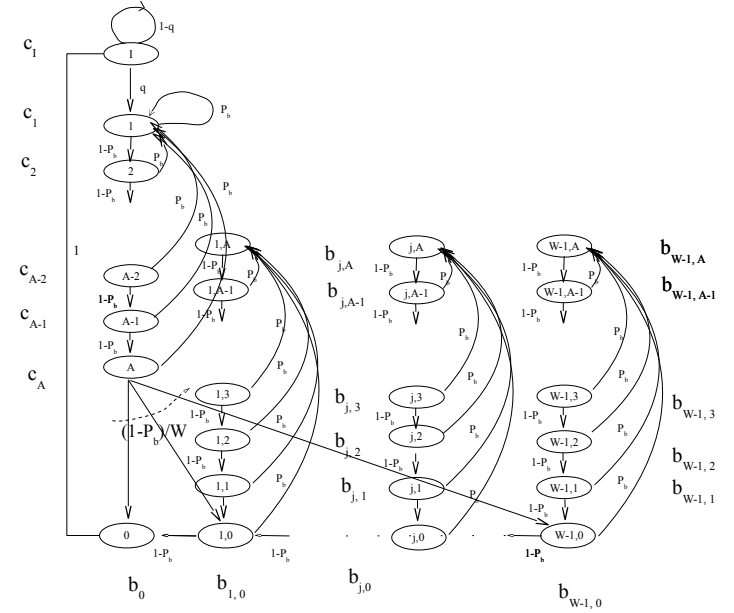


Fig. III.2. State diagram of the back-off scheme with retransmission with AIFS. A contiguous mini-slots must be idle before a transmission can be made and a transmission in one these mini-slots re-start the whole process.

The transitions are

- when a packet arrives at an idle node, the node starts to wait for the AIFS,
- in the AIFS states, the number of idle slots already sensed increases when the current mini-slot on the channel is idle (with probability $1 - P_b$) and the AIFS count down must begin again if the transmission of a packet starts in the current mini-slot (with probability P_b),
- in the back-off states, the remaining number of mini-slots that a node must still wait decreases when the current mini-slot on the channel is idle (with probability $1 - P_b$) and the AIFS count down begins again if the transmission of a packet starts in the current mini-slot (with probability P_b),
- when the back-off reaches 0, the pending packet is transmitted and the state of the node becomes the idle state.

We can see all these transitions in Figure III.2. $c_I, c_1, c_2, \dots, c_A, b_0, b_{i,j}$ $1 \leq i \leq A, 1 \leq j \leq W-1$ are the steady-state probabilities of the corresponding state. The transitions are shown by arrows and the transition probabilities are indicated, see Figure III.2.

We analyze the probability flow between state I (probability c_I) and state $(0, 0)$ (probability b_0). The equation of the steady state is :

$$(1 - q)c_I + b_0 = c_I$$

which is equivalent to

$$qc_I = b_0$$

where q denotes the probability that at least one packet arrives at a node during the mean duration during two observation instants of the Markov chain. The instants at which we observe our Markov chain are at the end of the sensing slots (slots of duration σ) if the channel is empty or after the transmission of a packet (of duration T) if there is a transmission. Thus the mean duration between two instants of observation is $(1 - P_b)\sigma + P_bT$ and

$$q = 1 - e^{-\lambda((1-P_b)\sigma + P_bT)}.$$

Writing the equation for the states i for $1 \leq i \leq A$, we obtain:

$$c_i = (1 - P_b)^{i-1} c_1 \text{ for } 1 \leq i \leq A.$$

Concerning the states $(W - 1, A), (W - 1, A - 1), \dots, (W - 1, 1), (W - 1, 0)$ we have the following equations :

$$b_{W-1, A-i} = (1 - P_b)^i b_{W-1, A} \quad 1 \leq i \leq A,$$

and

$$b_{W-1, A} = P_b(b_{W-1, A} + b_{W-1, A-1} \dots b_{W-1, 0}),$$

$$b_{W-1, 0} = (1 - P_b)b_{W-1, 1} + \frac{c_A(1 - P_b)}{W}.$$

Solving these equations, we find:

$$b_{W-1, i} = \frac{P_b}{(1 - P_b)^i} \frac{c_A}{W} \quad 1 \leq i \leq A,$$

and

$$b_{W-1, 0} = \frac{c_A}{W}.$$

Similarly for states $(j, A), (j, A - 1), \dots, (j, 1), (j, 0)$ we obtain:

$$b_{W-j, i} = \frac{P_b}{(1 - P_b)^i} \frac{j c_A}{W} \quad 1 \leq i \leq A, \quad 1 \leq j \leq W - 1,$$

$$b_{W-j, 0} = \frac{j c_A}{W} \quad 1 \leq j \leq W - 1.$$

We can now compute

$$\sum_{i=0}^A b_{j, i} = \frac{1}{(1 - P_b)^A} \frac{j c_A}{W} \quad 1 \leq j \leq W - 1$$

and thus:

$$\sum_{j=1}^{W-1} \sum_{i=0}^A b_{j, i} = \frac{c_A}{(1 - P_b)^A} \frac{W - 1}{2}.$$

$$b_0 = \frac{W - 1}{W} c_A (1 - P_b) + (1 - P_b) \frac{c_A}{W} = (1 - P_b) c_A$$

$$b_0 = (1 - P_b)^A c_1$$

The normalization condition is :

$$\sum_{j=1}^{W-1} \sum_{i=0}^A b_{j, i} + b_0 + \sum_{i=1}^A c_i + c_I = 1$$

We obtain :

$$c_1 \left(\frac{W - 1}{2(1 - P_b)} + (1 - P_b)^A \left(1 + \frac{1}{q}\right) + \frac{1 - (1 - P_b)^A}{P_b} \right) = 1$$

and thus :

$$b_0 = \frac{(1 - P_b)^A}{\left(\frac{W-1}{2(1-P_b)} + (1 - P_b)^A \left(1 + \frac{1}{q}\right) + \frac{1 - (1 - P_b)^A}{P_b} \right)} \quad (\text{III.1})$$

This equation is a fixed-point equation in b_0 because $P_b = 1 - (1 - b_0)^{M-1}$ when there is only one type of node i.e. the same A and W . To check this equation, we observe that when $A = 0$ we obtain the formula which is in [12].

In the next section, we will study two interdependent Markov chains corresponding to coexisting nodes which have different values of A . We now focus on the analysis of a network containing two kinds of nodes that have different AIFSs and operate with different values of A .

B. Steady-state of the mini-slots observed after the AIFS

We propose to combine nodes using different AIFSs. Although it is possible to build a model with more than two AIFSs, we will present the computation for only two different AIFSs. We consider the traffic with the highest priority with an AIFS A_1 and a collision window W_1 and the low priority traffic with an AIFS $A_2 > A_1$ and a collision window W_2 . We set $L_1 = A_2 - A_1$ and $L_2 = \min(W_1, W_2) - L_1$.

In Figure III.3 we show the state producing i idle mini-slots after an AIFS of A_1 mini-slots. We have a transition rate of $1 - p_b$ from state i to state $i + 1$ for $i \leq L_1$ and a transition rate of $1 - p'_b$ from state i to state $i + 1$ for $0 \leq L_1 \leq i \leq L_1 + L_2$. p_b corresponds to the probability of a busy slot when only the high priority traffic can be sent and p'_b (with $p'_b > p_b$) corresponds to the probability of the current mini-slot being busy when both high and low priority traffic can be sent.

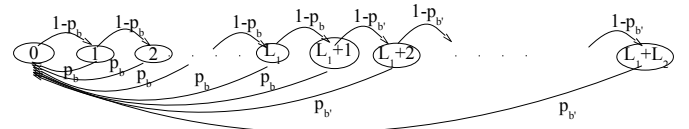


Fig. III.3. State diagram of the state of the channel after the end of a transmission and A_1 mini-slots.

Let d_i with $0 \leq i \leq L_1 + L_2$ be the steady-state probability of state i . We have:

$$d_i = (1 - p_b)^i d_0 \text{ with } 0 \leq i \leq L_1 + 1,$$

$$d_i = (1-p_b)^{L_1+1}(1-p'_b)^{i-L_1+1}d_0, \quad L_1+2 \leq i \leq L_1+L_2+1,$$

and we complete the computation using the normalization rule. Thus the probability of being in the first part of the back-off window (L_1 first mini-slots) is:

$$p_1 = \frac{1 - (1 - p_b)^{L_1+1}}{p_b} \left(\frac{1 - (1 - p_b)^{L_1+1}}{p_b} + (1 - p_b)^{L_1+1} \frac{1 - (1 - p'_b)^{L_2+1}}{p'_b} \right)^{-1}.$$

The probability of being in the second part of the back-off windows (L_2 last mini-slots) is:

$$p_2 = (1 - p_b)^{L_1+1} \frac{1 - (1 - p'_b)^{L_2+1}}{p'_b} \left(\frac{1 - (1 - p_b)^{L_1+1}}{p_b} + (1 - p_b)^{L_1+1} \frac{1 - (1 - p'_b)^{L_2+1}}{p'_b} \right)^{-1}$$

p_1 and p_2 can be used to weight the probabilities of the different back-off situations as shown in the next section.

C. Performance of the system with two classes of traffic using different AIFSs

We assume that we have two IEEE 802.11p networks sharing the radio spectrum and using different value of A (respectively A_1, A_2) with M_1 nodes in the first network and M_2 nodes in the second network.

For the first type of nodes we call τ_1 the transmission rate in the steady state. For the second type of nodes we call τ_2 the transmission rate in the steady state. Thus we have Equation III.1 with $b_0 = \tau_1$, $P_b = 1 - (1 - \tau_1)^{M_1-1}(1 - \tau_2)^{M_2-1}$, with $A = A_1$ for the first type of nodes. We have Equation III.1 with $b_0 = \tau_2$, $P_b = 1 - (1 - \tau_1)^{M_1-1}(1 - \tau_2)^{M_2-1}$ and $A = A_2$ for the second type of nodes. Thus we have two non-linear and coupled equations in τ_1 and τ_2 that must be solved numerically. We can use Maple to perform this task.

We now use the analysis developed in Subsection III-B. The first part of the back-off window with only the high traffic contains $L_1 = A_2 - A_1$ mini-slots and we still have $L_2 = W - (A_2 - A_1)$ mini-slots to complete the back-off window. We are not taking into account the last mini-slots of the back-off window where there are only arrivals of low priority traffic.

We also have:

$$p_b = 1 - (1 - \tau_1)^{M_1-1}, \quad p'_b = 1 - (1 - \tau_1)^{M_1-1}(1 - \tau_2)^{M_2-1} = P_b.$$

We can compute the success rate for a node belonging to the first kind of nodes. In the first part of the back-off window the transmission is successful when exactly one high priority node transmits. In the second part of the back-off the transmission is successful when exactly one high priority node transmits and no low priority node transmits. Thus the success rate for the high priority nodes can be written as

$$succ_1 = p_1 M_1 \tau_1 (1 - \tau_1)^{M_1-1} + p_2 M_1 \tau_1 (1 - \tau_1)^{M_1-1} (1 - \tau_2)^{M_2-1}$$

For the low priority nodes the success rate is simply:

$$succ_2 = M_2 \tau_2 (1 - \tau_2)^{M_2-1} (1 - \tau_1)^{M_1}$$

The normalized throughput for the high priority nodes is :

$$thr_1 = \frac{succ_1 T}{P_b T + \sigma(1 - P_b)}$$

The normalized throughput for the low priority nodes is :

$$thr_2 = \frac{succ_2 T}{P_b T + \sigma(1 - P_b)}$$

The formulas obtained here can be generalized with more than two classes of traffic.

D. Performance of the system with two classes of traffic using different collision windows

If we study two classes of coexisting nodes using EDCA with the same value of A but different values for the W (e.g W_1 and W_2) we will obtain two coupled equations of type III.1 in τ_1 and τ_2 with W_1 and W_2 . These equations can be easily solved numerically. Since the value of A is the same in the two kinds of nodes the formulas derived in Subsection III-B are no longer useful and a direct computation of the successful probability and the normalized throughput can be computed for both kinds of traffic.

IV. RESULTS OF THE MODEL FOR THE IEEE 802.11 WITH PRIORITIES

We use the previous model to compute the effect of the AIFS with two populations of M vehicles and we use the same figures i.e. packet inter-arrival in a node: 100 ms, $\sigma = 77$ bits. The packet size, including the overhead, is $T = 3998$ bits and the data rate is 6 Mbps thus $\lambda = 1/600000$. We use (if not otherwise specified) $l = 25$ m for the mean distance between two vehicles in a lane and we vary the carrier sense range (C_{cs} in meter) to modify the number M of contending vehicles. We assume that all the vehicles within the carrier sense range share the same medium and can collide. Thus $M = \frac{2nb \times C_{cs}}{l}$ where nb is the number of lanes, here we assume $nb = 2$.

The first type of the M_1 vehicles uses an IEEE 802.11 access with an AIFS with $A_1 = 1$ slots and $W = 32$. The second type of the M_2 vehicles uses an IEEE 802.11 access with an AIFS with $A_2 = 6$ slots and $W = 32$. We have $M_1 + M_2$ vehicles contending for access. We thus have $L_1 = 5$ and $L_2 = 27$.

In Figure IV.1, we show the probability of success for the two classes of traffic which, is the probability that a transmitted packet is actually received. When the carrier sense range increases, more vehicles are in the same contention area and thus the probability of success tends to decrease. We observe that the EDCF scheme with $A = 1$ and $A = 6$ creates two classes of traffic which have different probabilities of success. However, even when the carrier sense range is large,

the difference in success probabilities remains modest: around 15%.

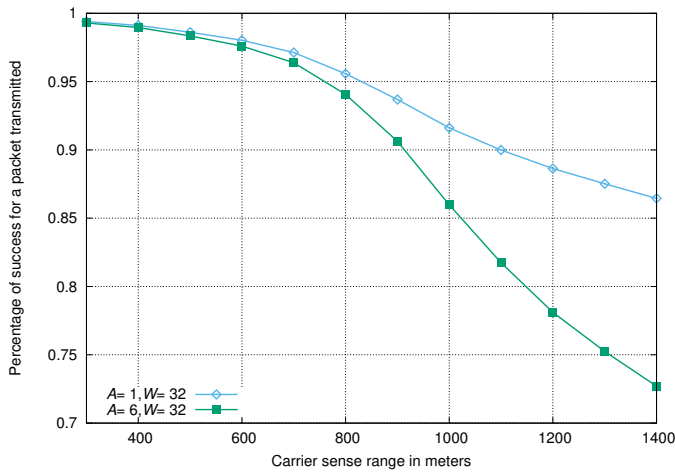


Fig. IV.1. Percentage of successful transmissions for both kinds of traffic with different AIFS values.

In Figure IV.2, we show the actual throughput for the two classes of traffic with the EDCF scheme with $A = 1$ and $A = 6$. In contrast to what we note for the probability of success, the EDCF scheme creates two very different classes of traffic. When the carrier sense range increases above 900 m the class of traffic with $A = 1$ continues to increase its throughput whereas the class of traffic with $A = 6$ starts to decrease its throughput. The scheme operates as if the low priority traffic vanishes in order to leave room for the high priority traffic.

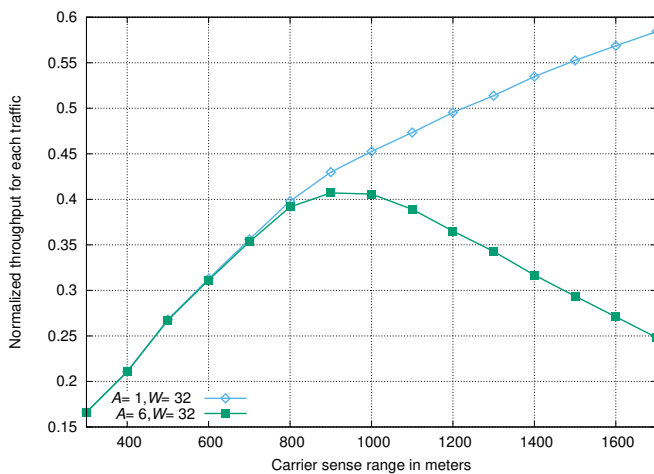


Fig. IV.2. Throughput for both kinds of traffic with different AIFS values.

In Figure IV.3, we study the effect of varying the values of A on the performance. We study three cases: two classes of traffic with $A = 1$ and $A = 6$, two classes of traffic with $A = 1$ and $A = 8$ and finally two classes of traffic with $A = 1$ and $A = 10$. Surprisingly, we observe that increasing the difference between the two values of A actually reduces the difference between the success rates. Moreover the average success rate

is larger when the difference between the two values of A increases.

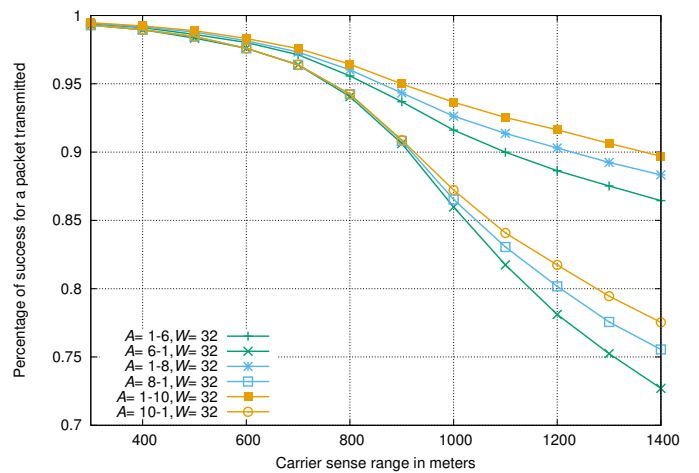


Fig. IV.3. Percentage of successful transmissions for both kinds of traffic with different AIFS values. Effect of different values for A

In Figure IV.4, we study the effect of varying the values of A on the throughput. We study three cases: two classes of traffic with $A = 1$ and $A = 6$, two classes of traffic with $A = 1$ and $A = 8$ and finally two classes of traffic with $A = 1$ and $A = 10$. This time, the result can be predicted, when the difference between the two values of A increases, the difference between the throughput of the two traffics also tends to increase.

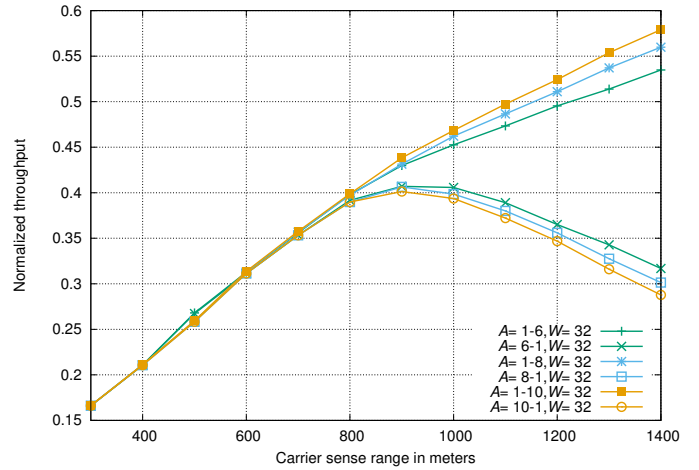


Fig. IV.4. Throughput for both kinds of traffic with different AIFS values. Effect of different values for A

In Figure IV.5, we compare the effect of varying the values of A and varying the values of W on the percentage of successful transmission. We set up a network with two types of vehicles, one using $A = 1$ and the other $A = 6$, both with $W = 32$ and another network with two types of vehicles, one using $W = 8$ and the other $W = 64$, both with $A = 1$. We observe that the differentiation obtained by varying the values of A is much greater than that obtained by varying the values of W .

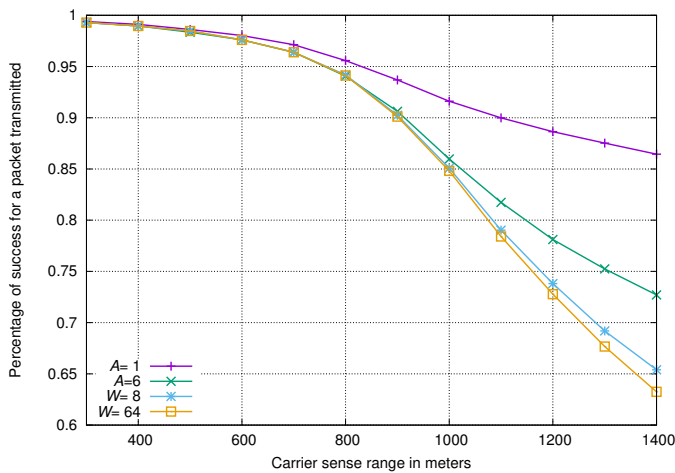


Fig. IV.5. Percentage of successful transmissions for both kinds of traffic. Comparison between varying A and varying W

In Figure IV.6, we compare the effect of varying the values of A and varying the values of W on normalized throughput. We compare a network with two types of vehicles, one using $A = 1$ and the other $A = 6$, both with $W = 32$ and another network with two types of vehicles, one using $W = 8$ and the other $W = 64$, both with $A = 1$. We observe that the differentiation obtained by varying the values of A is much greater than that obtained by varying the values of W .

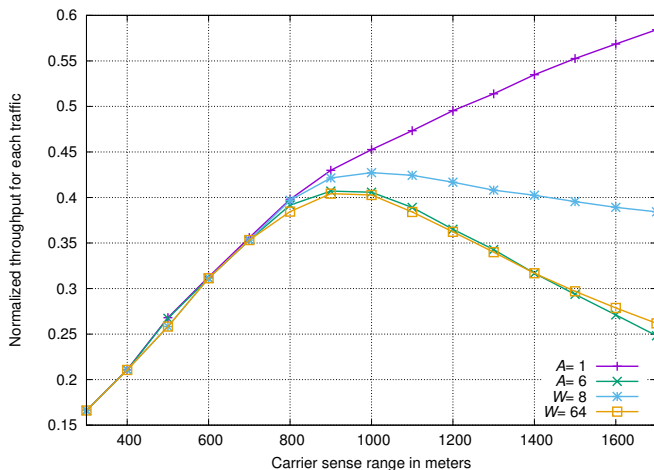


Fig. IV.6. Throughput for both kinds of traffic with different AIFS values. Comparison between varying A and varying W

V. CONCLUSION

In this paper, we present a simple probabilistic model for the IEEE 802.11 Enhanced Distributed Coordination Function (EDCF) which can build different access priorities for different classes of traffic. These priorities are obtained using different inter frame spacings called Arbitration Inter Frame Spacings (AIFSs) to differentiate the access of different classes of traffic. The model is composed of Markov chains (node Markov chains) which, for each class of traffic, provide the back-off timer and possibly the position in the inter frame spacing and a Markov chain (the back-off Markov chain) which provides the

current value of the back-off timer during the back-off process. To assess the performance of the network, one must solve the coupled Markov chains in order to obtain the busy rate ratio in each class of traffic. These solutions must be used in the steady-state of the back-off Markov chain to be able to derive the success probability and the throughput rate of each traffic class.

The results provided by the analytical model show that using different value of A to differentiate two traffic classes actually has a very significant impact on the throughput when the input load increases, whereas the impact on the probability of successful transmission remains moderate. The model shows that a small difference (e.g. $A = 1$ and $A = 6$) between the two values of A is enough to obtain a very significant effect on the throughput.

When we compare the effect obtained by varying A and the effect obtained by varying W we note that varying A is much more efficient to differentiate the performance of traffics sharing the same radio spectrum.

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