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Performance analysis of the EDCA medium access mechanism over the control channel of an IEEE 802.11p WAVE vehicular network

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***Abstract* — The FCC has set apart a frequency band with the specific goal of improving safety and efficiency of the transportation system. Its purpose is to provide wireless communications between stations on the roadside and mobile radio units located on board of vehicles. The resulting technology is known as WAVE and is currently under development as draft standard IEEE 802.11p. The most time-critical messages, carrying urgent safety-related information, are transmitted over the so-called control channel (CCH). WAVE devices use the EDCA MAC protocol, defined in the 2007 version of the IEEE 802.11 standard, to compete for the transmission medium. This work analyzes the performance of EDCA under the specific conditions of the CCH of a WAVE environment. The protocol is modeled using Markov chains and results related to throughput, frame-error rate, buffer occupancy and delay are obtained under different traffic-load conditions.**

***Keywords* — WAVE, vehicular networks, IEEE 802.11p, EDCA MAC protocol, performance analysis, Markov processes.**

I. Introduction

THE FCC has allocated a frequency band in the 5.9 GHz range for Intelligent Transportation Systems (ITS) communications. This set of frequencies is known as DSRC (Dedicated Short-Range Communications) band, and its purpose is to provide vehicle-to-roadside as well as vehicle-to-vehicle wireless communications, so that stations on the roadside (RSU) and mobile radio units located on board of vehicles (OBU) can share information related to road and traffic conditions and use it to improve the safety and efficiency of the transportation system. The resulting technology is known as WAVE (Wireless Access in Vehicular Environments), and its overall architecture is defined in IEEE standards 1609.1, 1609.2, 1609.3, 1609.4, and P802.11p. The latter is not yet in its final form, but is currently under development. The WAVE concept includes several channels within the DSRC band, one of them is known as the Control Channel (CCH) and the remaining six are known as Service Channels (SCH). Time is subdivided into synchronization intervals of 100 ms each. During the first half of each interval (50 ms) it is mandatory for all stations (OBUs and RSUs) to listen to the CCH, unless they are transmitting on it. Therefore, really urgent messages have to be broadcast over the CCH during the mandatory periods, so that they can be received by as many devices as possible. Thus, if we are interested in the performance of WAVE networks as a way to improve safety and efficiency of the transportation system, we have no choice but to analyze the CCH.

There are different priorities for the messages sent over the CCH, depending on how critical they are for vehicle safety. For that reason, WAVE devices use the Enhanced Distributed Channel Access (EDCA) MAC protocol, defined in the 2007 version of the IEEE 802.11 standard [1], to orderly gain access to the transmission medium. The highest priority is given to safety-related urgent information, which could be present at the RSU (e.g. accidents, obstacles, slippery or damaged roads, broken or missing traffic signs, etc.), or it could be information generated by cars (emergency vehicle approaching, vehicle with malfunctioning brakes, speeding over a certain limit, or posing any type of hazard to other vehicles). The second highest priority may be given for vehicles to advertise their presence to other vehicles, which is useful when visual detection is not possible (e.g. due to obstacles, uneven terrain, haze, heavy rain, sunshine right in front of eyes, etc.). A lower priority may be given to non-urgent messages (e.g. informing that a vehicle needs help because it broke down, ran out of gas, or collided with an obstacle, but poses no risk to other vehicles) and, finally, the lowest priority may be given to messages aimed at establishing new non-safety-related connections over the service channels (e.g. to look for nearby hotels or to download a map).

Messages are then classified into different access categories (AC), where the lowest priority corresponds to AC0 and the highest to AC3. Table I shows the parameters to be used by each access category to compete for the CCH.

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TABLE I
EDCA PARAMETERS TO BE USED IN THE CCH OF WAVE NETWORKS

Access category	CWmin	AIFSN
AC0	15	9
AC1	7	6
AC2	3	3
AC3	3	2

Recall that, if we use σ to denote a slot time, then:

$$\mathrm{AIFS}[\mathrm{AC}i] = \mathrm{SIFS} + \mathrm{AIFSN}[\mathrm{AC}i]\cdot\sigma \quad (1)$$

Since AIFSN is smaller for higher priorities, as shown in Table I, so will the corresponding AIFS.

II. RELATED WORK

This is a relatively new technology, therefore there are not many publications dealing with its performance. In [2], the author proposes formulas to evaluate the throughput and the collision probability in a WAVE environment assuming that nodes always have frames to send (saturation condition) and that backoff intervals are of constant length, equal to what would be the average value in a real environment. He also assumes that nodes select contention-window periods to attempt a transmission with the same probability, regardless of their access category. These assumptions give results that, in general, will not be very accurate.

There are other pieces of work analyzing the performance of EDCA in general (e.g. [3]–[6]). The results in [3]–[5] are only applicable to the saturated case (nodes always having frames to transmit), which are not very relevant in a WAVE environment in which fast delivery of messages is vital, hence working in saturation is not an option. Reference [6] in turn assumes that the probability of collisions among nodes corresponding to different priorities is negligible. Even though in general this is a reasonable assumption for low-traffic conditions, in WAVE it is essential to obtain results as accurate as possible since, again, we need to make sure that the time taken to successfully deliver a safety-related critical message does not exceed the little time vehicles have to react in the presence of danger. This work does not make any of those assumptions but, on the contrary, models very explicitly the way EDCA differentiates among nodes corresponding to the different access categories.

III. PROPOSED MODELS

We propose a different model for each access category. Each of the models shown in figures 1-3 is a discrete-time Markov chain representing a single node competing for the medium through the EDCA MAC protocol. In figure 1, which represents a highest-priority node (AC3), the number $k \in \{0, 1, 2, 3\}$ in the lower states corresponds to the current value of the backoff counter. The node is only allowed to change state at very specific time instants. To be more precise, the node cannot change its state when the channel is detected busy. It will be allowed to change its state when a busy period ends and the channel remains idle for a period of length AIFS[AC3], as described in the IEEE 802.11 standard. If the channel continues being idle, the node can keep changing its state every slot, which is defined as a period of length σ. When the channel is detected busy again, the Markov chain will freeze once more until the next idle period. The time elapsed between instants at which the Markov chain is allowed to change state will be referred to as a *cycle*.

In figure 2, which represents a second-highest-priority node (AC2), state (k, ℓ) is such that the number $k \in \{0, 1, 2, 3\}$ corresponds to the current value of the backoff counter and $\ell \in \{0, 1\}$ tells how many times a highest-priority node may have decreased its backoff counter since the most recent busy period. In other words, a transition from state $(k, 0)$ to state $(k, 1)$ means that the medium has been idle for AIFS[AC3], which is enough for a highest-priority station to decide that the medium is idle and decrease its backoff counter once. If the node is in state $(k, 1)$ and the medium remains idle for one more slot, then the station can start decreasing its own counter by moving into state $(k-1, 0)$ or $(k-1, 1)$, depending on whether the medium becomes busy again or remains idle.

The meaning of state (k, ℓ) in figure 3, which represents a lowest-priority node (AC1), is similar to that in figure 2. The value of ℓ goes now all the way up to 4 since, due to the difference in the respective AIFSN values, a highest-priority node may have counted down 4 times by the time a lowest-priority station decides that the medium is idle.

All three models include three states that represent those periods of time during which the node has no traffic to transmit. There are three different *empty* states because, depending on the length of the period during which the Markov chain freezes (because the channel was idle during σ, because an attempted transmission failed, or because a frame was successfully transmitted), the probability of new frames being generated is different, since we are assuming that traffic is generated in bursts according to a Poisson process and the size of each burst has an exponential distribution. To be more specific, E_{idle} represents a state in which the relevant node's transmission buffer is empty and none of the other nodes in the network attempts a transmission, E_{coll} represents a state in which the relevant node's transmission buffer is again empty and two or more of the other nodes attempt a transmission and collide, and finally E_{succ} represents a state in which the relevant node's transmission buffer is empty and exactly one of the other nodes successfully transmits a frame.

Notice that one important difference between the models proposed here and all models previously proposed in the literature is that these models only have one backoff stage. That is due to the fact that all transmissions over the CCH are broadcast, hence there is no way to know if a frame transmission is successful or not since nobody will send back an acknowledgment.

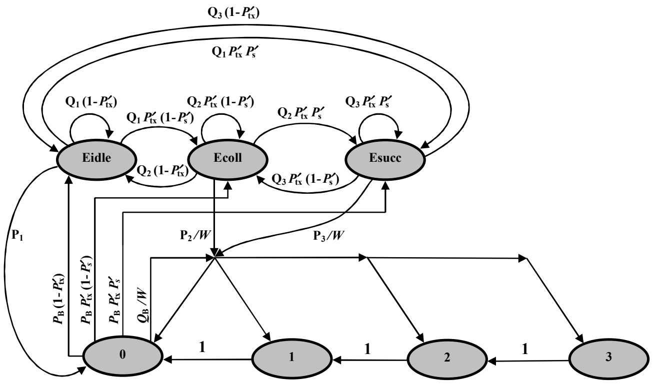


Figure 1. Markov model of a node corresponding to access category 3, thus having the highest priority.

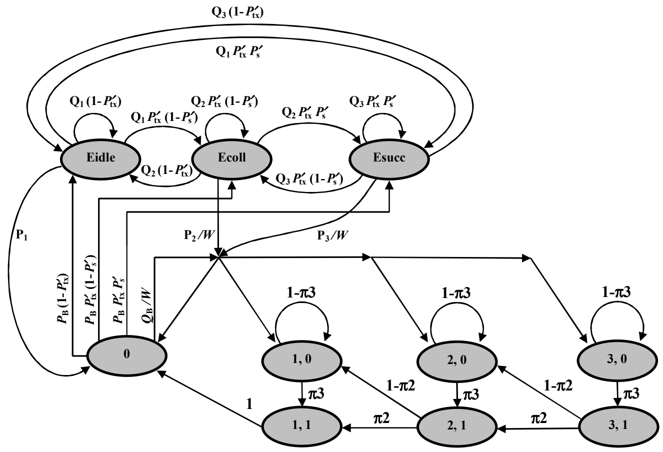
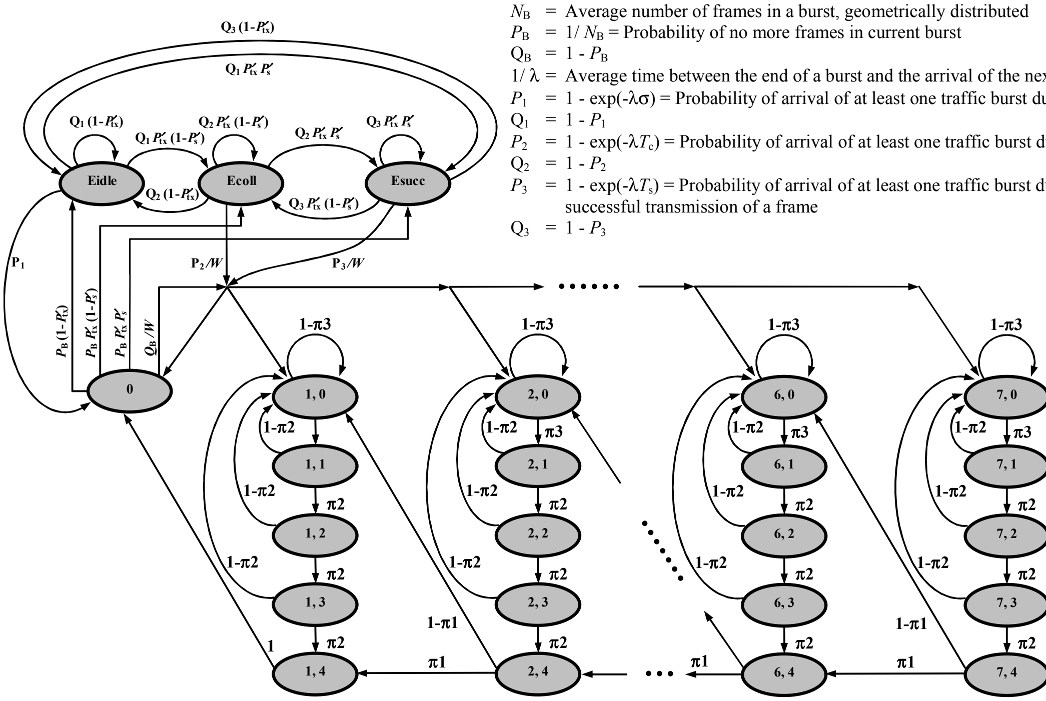


Figure 2. Markov model of a node corresponding to access category 2, thus having the second-highest priority.



N_B = Average number of frames in a burst, geometrically distributed
P_B = $1/N_B$ = Probability of no more frames in current burst
Q_B = $1 - P_B$
$1/\lambda$ = Average time between the end of a burst and the arrival of the next one, exponentially distributed
P_1 = $1 - \exp(-\lambda\sigma)$ = Probability of arrival of at least one traffic burst during an idle period
Q_1 = $1 - P_1$
P_2 = $1 - \exp(-\lambda T_c)$ = Probability of arrival of at least one traffic burst during a busy period ending in a collision
Q_2 = $1 - P_2$
P_3 = $1 - \exp(-\lambda T_s)$ = Probability of arrival of at least one traffic burst during a busy period ending in the successful transmission of a frame
Q_3 = $1 - P_3$

Figure 3. Markov model of a node corresponding to access category 1, thus having the lowest priority.

Another big difference is the great level of detail in which priorities are explicitly modeled.

Each model includes the influence of other competing terminals through the following probabilities: π_j, $j \in \{1, 2, 3\}$, which is the probability that no node of priority j or higher will transmit during the current cycle; P'_{tx}, which is the probability that at least one of the *other* competing terminals transmits; and P'_s, which is the probability that there is a successful transmission given that at least one of the *other* competing terminals transmits. All of these probabilities depend on the access category $i \in \{1, 2, 3\}$ that the relevant node belongs to. This dependence is not explicitly shown in figures 1-3 for the sake of simplicity, but it will be shown in the equations included below. If we denote by τ_j the probability that a node of priority j transmits during a cycle, and by N_j the number of priority-j nodes present in the system, then the following equations hold:

$$\pi_3 = (1 - \tau_3)^{N_3} \quad . \tag{2}$$

As seen by a node of AC2:

$$\pi_2 = (1 - \tau_3)^{N_3} (1 - \tau_2)^{N_2 - 1} \quad . \tag{3}$$

As seen by a node of AC1:

$$\pi_2 = (1-\tau_3)^{N_3}(1-\tau_2)^{N_2}, \quad (4)$$

$$\pi_1 = (1-\tau_3)^{N_3}(1-\tau_2)^{N_2}(1-\tau_1)^{N_1-1}. \quad (5)$$

Now, as seen by a node of access category i:

$$P'_{tx,i} = 1-(1-\tau_i)^{N_i-1}\prod_{\substack{j=1\\ j\neq i}}^{3}(1-\tau_j)^{N_j} \quad (6)$$

$$P'_{s,i} = \frac{1}{P'_{tx,i}}\left[(N_i-1)\tau_i(1-\tau_i)^{N_i-2}\prod_{\substack{m=1\\ m\neq i}}^{3}(1-\tau_m)^{N_m} + \sum_{\substack{j=1\\ j\neq i}}^{3}N_j\,\tau_j(1-\tau_j)^{N_j-1}(1-\tau_i)^{N_i-1}\prod_{\substack{m=1\\ m\neq i,j}}^{3}(1-\tau_m)^{N_m}\right] \quad (7)$$

In equation (7), the first term represents a successful transmission of a node of AC i and the second term represents a successful transmission of a node of an AC different from i. The presence of $P'_{tx,i}$ in the denominator comes from the fact that $P'_{s,i}$ is a conditional probability.

Let b_0 denote the steady-state probability that the Markov chain is in state 0. Let us also define $A = Q_1\cdot(1-P'_{tx,i})$, $B = Q_2\cdot P'_{tx,i}\cdot(1-P'_{s,i})$, and $C = Q_3\cdot P'_{tx,i}\cdot P'_{s,i}$. Solving the equations obtained from figure 1, we find that, for a highest-priority station, we have:

$$\frac{1}{b_0} = \frac{\text{CWmin}+2}{2} + \frac{P_B}{1-(A+B+C)} \quad (8)$$

When we solve the equations obtained from figure 2, we find that, for a second-highest-priority station, we have:

$$\frac{1}{b_0} = 1 + \frac{P_B}{1-(A+B+C)} + \left[\frac{\text{CWmin}}{2}\left(\frac{1+\pi_3}{\pi_3}\right) - \frac{\text{CWmin}\,(\text{CWmin}-1)}{2(\text{CWmin}+1)}\left(\frac{\pi_2}{\pi_3}\right)\right]\cdot \left[\frac{P_B\cdot P'_{tx,2}\cdot\left[P_2(1-P'_{s,2})+P_3\cdot P'_{s,2}\right]}{1-(A+B+C)} + Q_B\right] \quad (9)$$

Finally, from the equations obtained from figure 3, we find for a lowest-priority station:

$$\frac{1}{b_0} = 1 + \frac{P_B}{1-(A+B+C)} + \left\{\left[\frac{\text{CWmin}}{2} - \frac{\text{CWmin}\,(\text{CWmin}-1)}{2(\text{CWmin}+1)}\cdot\pi_1\right]\cdot\left(\frac{1+\pi_3+\pi_2\cdot\pi_3+\pi_2^2\cdot\pi_3}{\pi_2^3\cdot\pi_3}\right) + \frac{\text{CWmin}}{2}\right\}\cdot \left[\frac{P_B\cdot P'_{tx,1}\cdot\left[P_2(1-P'_{s,1})+P_3\cdot P'_{s,1}\right]}{1-(A+B+C)} + Q_B\right] \quad (10)$$

Note that, at the same time, the probability τ_i that a priority-i node transmits during a given cycle is equal to the corresponding b_0. This fact plus each one of equations (8)-(10) allow us to numerically calculate the values of τ_i, $i \in \{1, 2, 3\}$. Notice, however, that in order to be able to use equations (6) and (7) it is necessary to know the values of τ_j for all priorities j different from i. When we start performing our calculations we clearly do not know any of those values. To solve this problem, we propose to use initially the following approximation to estimate the τ_j that have not yet been calculated:

$$\tau_j \approx \min\left\{\frac{\rho_j}{\rho_i}\cdot\tau_i,\ 0.5\right\} = \min\left\{\frac{\lambda_j\cdot N_{B,j}}{\lambda_i\cdot N_{B,i}}\cdot\tau_i,\ 0.5\right\} \quad (11)$$

In equation (11), ρ_j is the traffic load generated by a priority-j terminal, λ_j is the burst generation rate and $N_{B,j}$ is the average number of frames per burst. When all values of τ_j have been calculated, the process is restarted but this time the most recently calculated values are used instead of equation (11). This process is recursively repeated until the new values and the previous ones are sufficiently close. In our case, the relative difference has to be smaller than 0.1%.

A. Throughput calculation

When the values of τ_i, $i \in \{1, 2, 3\}$, have been calculated, we can compute $P_{tx,i}$ and $P_{s,i}$, which are respectively the probability that at least one priority-i terminal transmits, and the probability that there is a successful transmission given that at least one priority-i terminal transmits. Namely:

$$P_{tx,i} = 1-(1-\tau_i)^{N_i} \quad (12)$$

$$P_{s,i} = \frac{1}{P_{tx,i}}N_i\cdot\tau_i\cdot(1-\tau_i)^{N_i-1}\prod_{\substack{j=1\\ j\neq i}}^{3}(1-\tau_j)^{N_j} \quad (13)$$

This will in turn allow us to compute the throughput achievable by priority-i terminals as follows:

$$S_i = \frac{P_{tx,i}\cdot P_{s,i}\cdot E[P_i]}{E[cycle]} \quad (14)$$

In the previous equation, $E[P_i]$ is the average frame payload size and $E[cycle]$ is the average duration of each cycle, which is given by:

$$E[cycle] = \sum_{j=1}^{3}P_{tx,j}\cdot P_{s,j}\cdot T_s + P_{notx}\cdot\sigma + \left(1-P_{notx}-\sum_{j=1}^{3}P_{tx,j}\cdot P_{s,j}\right)\cdot T_c \quad (15)$$

In turn, σ represents the duration of an empty cycle in which no node transmits, T_c is the average duration of a cycle in which there is a collision because two or more nodes attempt a transmission, and T_s is the average duration of a cycle in which a node successfully transmits a frame. P_{notx} denotes the probability that no station transmits, regardless of priority, and is given by:

$$P_{notx} = \prod_{j=1}^{3}(1-\tau_j)^{N_j} \quad (16)$$

TABLE II
PHYSICAL LAYER PARAMETERS

Parameter	Value
PHY header	
- PLCP Preamble	32 µs
- PLCP Signal	8 µs
- PLCP Service	16 bits
- PLCP Tail	6 bits
MAC header	288 bits
Frame payload E[P]	4096 bits
Channel bit rate	6 Mbps
Propagation delay (δ)	1 µs
Slot (σ)	13 µs
SIFS	32 µs

The parameters σ, T_c and T_s depend on the physical layer. We are assuming a scenario compatible with the IEEE 802.11a standard, with 10 MHz channel spacing, and running at 6 Mbps. Table II summarizes the parameter values assumed. With them we can calculate:

$$T_s = T_c = \text{PHY\_header} + \text{MAC\_header} + E[P] + AIFS[j] + \delta \quad (17)$$

B. Frame-error-rate calculation

The frame error rate (FER) is defined as the probability that a frame transmission attempt fails at the MAC level due to collisions. The expression to calculate FER for a priority-*i* node is as follows:

$$\text{FER}_i = 1 - (1 - \tau_i)^{N_i - 1} \prod_{\substack{j=1 \\ j \neq i}}^{3} (1 - \tau_j)^{N_j} \quad (18)$$

C. Service time, buffer occupancy and delay calculations

The service time for a priority-*i* node, defined as the time elapsed from the moment a frame arrives at the head of its queue until it is finally transmitted, is given by:

$$E[X_i] = E[n_{x,i}] \cdot E[cycle] + T_s \quad (19)$$

where $n_{x,i}$ is the number of cycles the frame has to back off, waiting in the buffer for its turn to be transmitted.

The following equations apply to AC3 and AC2, respectively:

$$E[n_{x,3}] = \frac{\text{CWmin}}{2} = 1.5 \quad (20)$$

$$E[n_{x,2}] = \frac{3}{4}\left(2 + \frac{2}{\pi_3} - \frac{\pi_2}{\pi_3}\right) \quad (21)$$

Now, the total delay is defined as the time elapsed from the moment a frame is generated by the application layer until it is finally transmitted. We also calculated the average total delay that will be experienced by highest-priority frames, which are the most critical for vehicle safety, as mentioned before. To do that, we used the G/G/1 queuing model for which the following equation holds:

$$E[N_{buff}] = \frac{E[Y^2] + E[Y] - 2 \cdot E^2[Y]}{2 \cdot (1 - E[Y])} \quad (22)$$

In the previous equation, N_{buff} is the buffer occupancy, including the frame in service, and Y is the number of frames that arrive during a service time. From here, we can calculate the total frame delay using Little's theorem as follows:

$$E[D] = \frac{E[N_{buff}]}{\lambda_{eff}} \quad (23)$$

where $\lambda_{eff} = \lambda \cdot N_B$ is the effective frame arrival rate.

IV. NUMERICAL ANALYSIS

Different scenarios were analyzed.

- A single high-priority station generating different traffic loads, from 5% to 90%.
- A varying number of high-priority stations, from 1 to 24, each generating a constant amount of traffic (5%).
- A fixed number of high-priority stations (4) and a varying number of lower-priority stations, from 1 to 24, each generating a constant amount of traffic (5%).

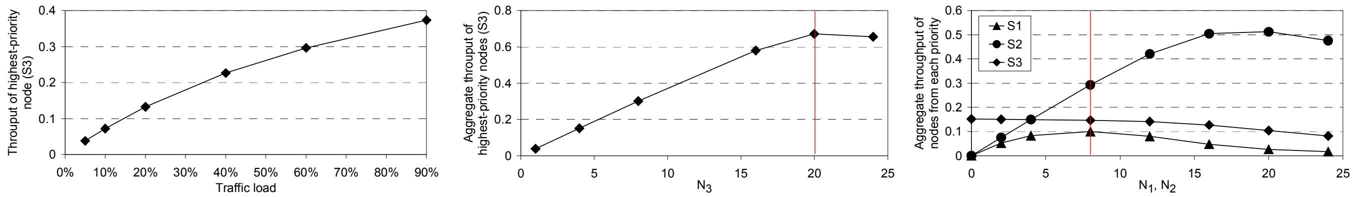
We estimate the load that each node puts into the system as $\lambda \cdot N_B \cdot T_S$, which is the average number of frames per time interval of length T_S. In all cases N_B is equal to 5 and λ is varied to achieve the desired load.

We present results related to throughput and losses for all three access categories, and total delay for highest-priority frames only.

We can see from figure 4(a) that, in the case of a single high-priority station using the network, the throughput keeps increasing even for offered loads of 90%, but at the price of experiencing increasingly higher frame delays, as shown in figure 6(a). In this case there are no frame losses since there are no other stations to collide with.

When there are only high-priority nodes, the system can work relatively well for loads of up to 40% (8 competing nodes), in the sense that the throughput increases linearly and the delay and losses do not increase noticeably, as displayed in figures 4(b), 5(b) and 6(b). After that point, the throughput keeps increasing linearly for load values of up to 80%, but the FER goes above 4% and increases very sharply for loads above the saturation point (marked by a vertical line in the figures).

When we have all types of nodes, on the other hand, the highest-priority throughput is not affected noticeably even when the system reaches saturation, as shown in figure 4(c). The throughput of AC2 nodes keeps increasing until the load offered by AC3 and AC2 nodes reaches 100%, meaning that the load offered by AC1 nodes does not have a perceptible impact on it. When we compare the FER corresponding to AC3 nodes in figures 5(a) and 5(b), we can see that the load introduced by lower-priority nodes does not have as bad an impact as compared to the case in which competition is among AC3 nodes only, but still performance is degraded beyond acceptable levels for loads of 60% and above.

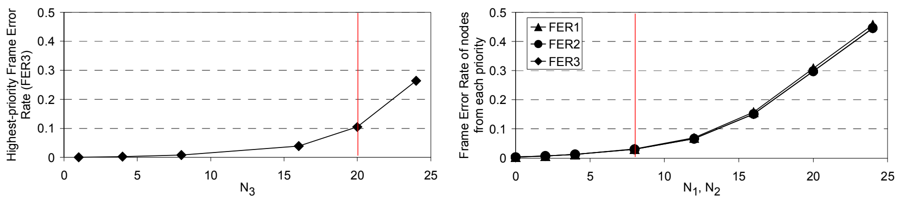


(a) High-priority throughput with one station generating different traffic loads

(b) High-priority throughput with a varying number of high-priority stations

(c) Throughput with a varying number of lower-priority stations

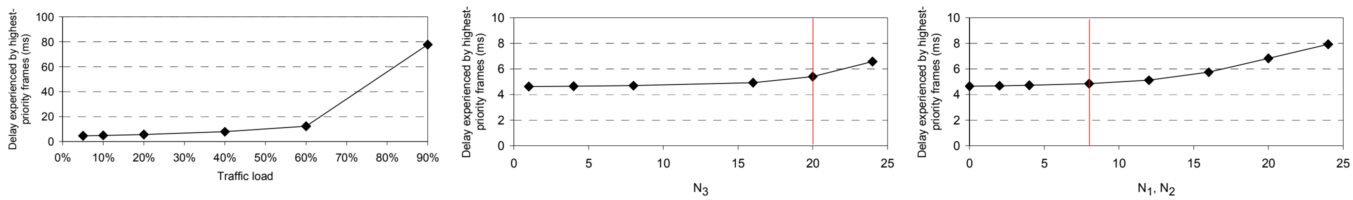
Figure 4. Throughput results



(a) High-priority FER with a varying number of high-priority stations

(b) FER with a varying number of lower-priority stations

Figure 5. Frame-error rate results



(a) Total high-priority delay with one station generating different traffic loads

(b) Total high-priority delay with a varying number of high-priority stations

(c) Total high-priority delay with a varying number of lower-priority stations

Figure 6. Total delay results

As we can se from figures 6(b) and 6(c), the delay is not increased dramatically even when the offered load goes far beyond saturation. The reason for this is the fact that, even though there is a great level of competition among stations, the feedback usually provided by acknowledgments (or the lack thereof) to detect congestion is inexistent in this case since all frames are broadcast.

V. CONCLUSION

We have proposed a model for the EDCA MAC protocol, taking into consideration the specific conditions of the control channel of a WAVE environment. The model is based on discrete-time Markov chains and captures the fact that EDCA can establish priorities among stations.

We present results related to throughput, losses, buffer occupancy and delays, all of which are very important QoS metrics, especially in a vehicular environment in which a short time can make a great difference when there are dangerous situations.

The main differences between this work and what is already available in the literature are: *i*) that in our case there are no unreasonable simplifying assumptions, *ii*) that the protocol priorities are very explicitly modeled, *iii*) that traffic load can be varied, and *iv*) that the total frame delay is calculated, and not only the service time when the frame is already at the head of the queue.

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