# Performance Comparison of IEEE 802.11 DCF and EDCA for Beaconing in Vehicular Networks

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**Abstract.** For use in vehicular networks, IEEE 802.11p has been standardized as the underlying wireless system. The 802.11 standard distinguishes two main methods of operation with respect to channel access, the Distributed Coordination Function (DCF) and the Enhanced Distributed Channel Access (EDCA), where the latter is the mandated method to be used in vehicular networks (in 802.11p). We present validated analytical models for both DCF and EDCA, and compare both methods in the context of beaconing. We will show that, surprisingly, DCF outperforms EDCA under assumptions that are realistic for beaconing in vehicular networks.

## 1 Introduction

Vehicular networks are expected to enable increased traffic safety and efficiency, and reduced environmental impact of road traffic. Many traffic safety and efficiency applications rely on vehicles wirelessly broadcasting, e.g., their position and speed, to vehicles in their surroundings. The rate at which this beaconing occurs, may vary from once per few seconds until up to 25 times per second, depending on the application.

For use in vehicular networks, a dedicated variant of the IEEE 802.11 family of wireless communication protocols [1] has been specified. The most important adaptations made in this IEEE 802.11p standard are the increased symbol time and reduced data rate, in order to deal with the vehicular environment, and the possibility to communicate with other stations in an ad-hoc manner, without preestablishing an association. The typical communication range for IEEE 802.11p ranges between a few hundred to thousand meters.

In a vehicular environment communication is taking place directly between vehicles, and not via an access point. Hence, it is important to perform medium access control in a fully distributed way. In the traditional IEEE 802.11 standard, access to the medium is governed using the so-called Distributed Coordination Function (DCF), which applies a form of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The DCF uses carier sensing to avoid interference and collisions between different nodes. The start of a new transmission after a busy period is randomized by decrementing a backoff counter ($bc$). To

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allow for prioritized access for traffic flows, the so-called EDCA has been defined, which treats packets from different Access Categorys (ACs) differently. To make this prioritization possible, the rules for decrementing the *bc* have been slightly changed. IEEE 802.11p prescribes the use of EDCA in vehicular networks.

Beaconing in vehicular networks is fundamentally different from communication in traditional wireless LANs, where most traffic consists of series of unicast messages to or from an access point. In case of beaconing, nodes broadcast a single packet periodically. Broadcast implies that transmitted packets are not acknowledged by the receiver. As a consequence, packets are never retransmitted, and nodes do not adapt their load on the network, based on the success or failure of previous transmissions. Because nodes are typically dispersed of a large geographical area, and the use of Request-To-Send Clear-To-Send (RTS/CTS) is not possible in a broadcast environment, vehicular networks suffer a lot from hidden terminal problems. Beaconing in vehicular networks is characterized by a large number of nodes, each with a relatively low load. Vehicles may receive beacons from many other vehicles in their surroundings, which poses a scalability challenge to such networks.

This paper evaluates the scalability of beaconing in vehicular networks using the IEEE 802.11p DCF and EDCA. More specifically, we investigate the impact of the modified *bc* decrement rules on the probability of successful transmission and throughput. We present analytical performance models for the DCF and EDCA. We focus on the *bc* decrement behaviour, hence, we do not model the effect of hidden terminals. Solving the analytical models, and comparing numerical results reveals remarkable differences in the system performance for both access methods, which we will explain.

In [2], we already introduced the DCF model described in Sec. 3. The contributions of this paper are as follows. (1) We present an analytical model for beaconing in vehicular networks using EDCA. (2) We compare the beaconing performance of EDCA and DCF, and (3) we present a detailed analysis of the effect of the *bc* decrement rules on the system performance.

In the following, we first describe DCF and EDCA and their differences, in Sec. 2. Models of these mechanisms are described and analysed in Sec. 3. In Sec. 4, we compare and explain numerical results for both mechanisms. For ease of understanding, related work on modeling IEEE 802.11(p) is only reviewed in Sec. 5. Finally, we give conclusions and future work in Sec. 6.

## 2 Operation of IEEE 802.11DCF and EDCA

### 2.1 Distributed Coordination Function (DCF)

The mandatory Distributed Coordination Function (DCF) specifies basic rules for medium access and contention resolution in all IEEE 802.11 stations [1]. It coordinates transmission attempts by multiple stations contending for access to the same wireless channel, and prevents collisions. To reduce the probability of collision, the DCF specifies the use of CSMA/CA. The Carrier Sense (CS) part prevents a node from transmitting when an other node is already transmitting.

The medium is idle when the detected signal level is below the carrier sense threshold. In this case, a node may proceed to access the channel. If the channel is busy, the access attempt is deferred until the medium turns idle again.

The Collision Avoidance (CA) part prevents collisions where they are most likely to occur: just after a transmission by an other node. As described above, CS mandates to defer access until the channel turns idle again. If multiple contending nodes are waiting for the channel to become idle, they are somehow synchronised and could cause a collision if they were to transmit immediately. To alleviate this, CA mandates use of a so-called backoff. When the medium turns idle, a node does not immediately begin transmission, but will wait a mandatory gap, called Interframe Space (IFS), and some random extra time by means of a backoff counter (*bc*). The *bc* is randomly drawn from the a range $[0, \texttt{CWmin}]$, the contention window. More precisely, the DCF performs the following operations once the network layer submits a packet to the MAC's transmission queue, assuming the station starts in the idle state:

1. Upon reception of a packet in the transmission queue, the MAC performs CS.
   (a) If the channel is **idle** for at least one IFS, the transmission may commence immediately.
   (b) If the channel is **busy**, the node enters contention, which is divided into a countdown and freeze state.
2. The node draws a *bc* from the contention window, according to the discrete uniform distribution $[0,\texttt{CWmin}]$.
3. When the channel turns **idle**, the node waits one IFS.
4. After every idle timeslot $\sigma$, the *bc* is decremented.
5. If the channel turns **busy** during Countdown, *bc* is frozen and the process continues from step 3.
6. When *bc* reaches 0, the node transmits the frame. This may also happen if a node chooses 0 as *bc* in step 2.

The operation of the DCF is illustrated in Fig. 1, where the actions relating to decrementing or transmitting are illustrated on top of the blocks. In this example, node A finds the medium busy and chooses a *bc* of 1. Another node B has choosen $bc = 0$ during the same medium busy period, and transmits immediately after the IFS. Node A then has to wait for an IFS, and an empty slot $\sigma$ to decrement its *bc* to 0, after which it can transmit. These two transmissions follow each other without intermediate $\sigma$. However, all nodes that have a non-zero *bc* freeze until an empty slot is observed on the medium. This consecutive series of transmissions without intermediate empty slots is called a *streak*.

### 2.2 Extended Interframe Spacing and Post-Backoff

The Extended Interframe Space (EIFS) is used to respond to a frame which failed its CRC check. This implies that the station was also not able to determine the nature of the (badly) received packet, i.e., whether it was a broadcast or

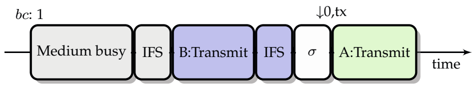


**Fig. 1.** DCF operation (empty slot needed for counter decrement)

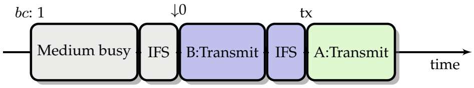


**Fig. 2.** EDCA operation (no empty slot needed for counter decrement)

unicast transmission. To prevent this station from interfering with an ongoing transaction, it has to wait until the intended recipient had an opportunity to return an acknowledgement frame, which is done after leaving the medium idle for a Short IFS (SIFS). So the EIFS extends the DIFS with a SIFS and the time to transmit a full acknowledgement frame. Nodes that notice a collision on the medium will also refrain from accessing the medium for this prolonged time.

Post-backoff (PBO) prevents unfair advantage of nodes that have just finished a transmission and still have packets to send. Since other nodes in the system are still counting down their *bc* values, such a node may find the medium idle, and can immediately transmit without performing backoff. The mechanism of PBO prevents the starvation of other nodes, which could be caused by a node with a very high traffic load. PBO is similar to the backoff prior to performing a transmission: (i) After completion of a transmission, the node draws a *bc* from the contention window. (ii) After an IFS during which the channel remains idle, for every timeslot $\sigma$ in which the channel remains idle, the *bc* is decremented. (iii) If the channel turns busy the *bc* is frozen and the process may only continue after the channel has turned idle, and remained idle for at least an IFS. (iv) When *bc* reaches 0, the node transmits the frame if there was a frame to transmit. If the transmission queue is empty, the node remains idle.

## 2.3 Enhanced Distributed Channel Access (EDCA)

To enable service differentiation for packets of different flows, Enhanced Distributed Channel Access has been introduced in IEEE 802.11. In EDCA, packets are classified based on an Access Category (AC), and each AC has its own transmission queue within a station. The service differentiation is defined among traffic from different stations, but also among traffic from different ACs within a single node.

Instead of the standard IFS used in the DCF (DIFS), EDCA uses a different Arbitration Interframe Space (AIFS) for each AC. Stations with a longer Arbitration Interframe Space (AIFS) have less chance of accessing the medium than stations with a shorter AIFS. Another way of differentiation is using different

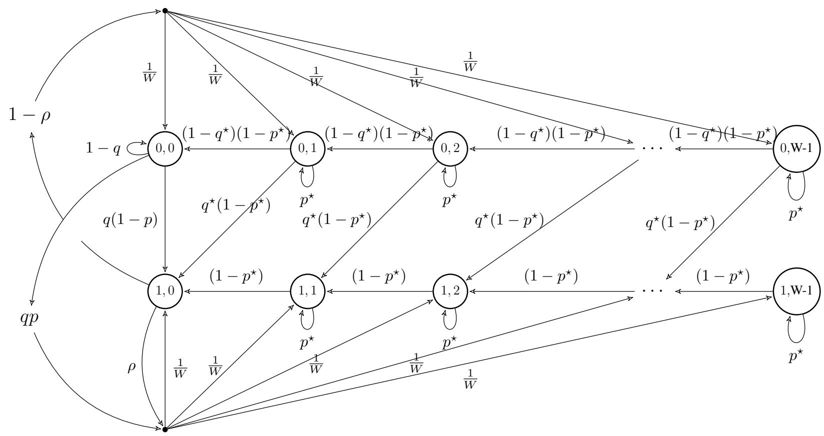


**Fig. 3.** Markov chain of the DCF model

contention window sizes for different ACs. This applies both to the initial contention window (`CWmin`) and to the maximum contention window (`CWmax`). The latter is however not used in broadcast transmissions. Stations with a smaller `CWmin` value can on average acquire the medium faster than stations with a larger value. The Transmission Opportunity (TXOP) value is defined for use with unicast transmissions. A station with a non-zero TXOP is allowed to send frames in rapid succession for a certain duration, separated by a Short IFS (SIFS) in stead of a DIFS or AIFS.

Another difference between DCF and EDCA, which is less widely understood, is the way the backoff counter is decremented. Whereas DCF decrements the *bc* after an empty slot $\sigma$ and is allowed to transmit at the moment the *bc* reaches 0, EDCA decrements the *bc* at slot boundaries. In this case, a station decrements the *bc* at the beginning of a timeslot immediately following the IFS (either AIFS or EIFS), irrespective of the channel status in that slot [3]. However, it is not allowed to decrement the *bc and* start transmission simultaneously at the same slot boundary. At a slot boundary, a station shall perform only one of the following actions [1]: start a transmission, decrement the *bc*, invoke the backoff procedures for an internal collision (a virtual collision with a packet from another AC in the same station), or do nothing. Hence, an EDCA node has to wait for the next slot boundary to transmit, once its *bc* reaches zero.

Fig. 2 illustrates the operation of EDCA for the same scenario as discussed for DCF in Fig. 1. Note the difference when *bc* decrement takes place. Station A can decrement its *bc* at the slot boundary following the first IFS. Immediately after the second IFS, after B's transmission, A can start transmission. This provides EDCA a *bc* decrement advantage over DCF [3]. However, as we will see this decrement advantage is not always beneficial for the system performance.

# 3 Modelling and Analysis

## 3.1 General Model Structure and Assumptions

Along the lines of [4], we model a single station as an $M/G/1$ queueing station with successive beacon arrivals according to a Poisson process, i.e., exponentially distributed inter-arrival times with mean $1/\lambda_g$. A station is assumed to have and infinite queue. This is not a strong simplification, as it turns out that queueing is very limited. The server of the $M/G/1$ queueing station has a general service time distribution, where the service time of a packet includes the time the station contents for medium access before a packet is transmitted. A packet is considered serviced regardless of the success or failure of the transmission, i.e., also if a collision takes place. The mean of this service time $\mathbb{E}[S]$ is derived from an embedded Discrete Time Markov Chain (DTMC), which models the behaviour of the DCF or EDCA in detail. The DTMC model in turn, needs the utilization $\rho$ ($\rho = \lambda_g \mathbb{E}[S]$) from the $M/G/1$ queue.

In the DTMC, which models a single station, time is discretised into generic slots. A slot is either idle or busy; a busy slot is either successful or a collision. When deriving the probability of packet arrivals in a generic slot, the exact duration of a slot, e.g., the deterministic time to transmit a beacon, is taken into account. Using the DTMC, we can determine the probability $\tau$ that the station is transmitting in a generic slot. It is assumed that $n$ stations are sharing the medium, and are able to receive each other. No hidden terminals are assumed. Using a mean-field approximation technique [5], a station is assumed to experience the average behaviour for each of the $n-1$ other stations, and will assume that each of them is also accessing the medium in a generic slot with probability $\tau$. This way, we can obtain results for the overall model using a fixed point iteration.

## 3.2 DCF Model

We have presented and analysed the DTMC model of DCF used in this paper in [2]. For comparison purposes, we recall the model here, without deriving all variables and solving the steady-state equations. Instead, we refer to the original paper.

Fig. 3 shows the DTMC model for a DCF node that is only broadcasting. The state space $S$ of the DTMC consists of a finite set of states $\mathcal{S} = \{s_{j,k} | j \in \{0,1\} \wedge k \in \{0,\ldots,W-1\}\}$, where $j=0$ holds for a node that is currently not accessing the medium (it is either in PBO or idle) and $j=1$ means that the node is contending for medium access (BO), or actually transmitting. Parameter $k$ denotes the current *bc* value, when (1) a station takes a packet from the queue and starts its medium access attempt and finds the medium busy, or (2) when a station starts PBO. Each *bc* value between 0 and $W-1$ is chosen with probability $1/W$, where $W-1$ equals the initial contention window, `CWmin`.

When the *bc* reaches zero ($s_{1,0}$), the node transmits the current frame. After transmission, with probability $\rho$ the station finds another packet in its queue and performs a new BO for medium access. With probability $1-\rho$ the queue is empty and the node will enter PBO. While in BO or in PBO, the *bc* is decremented for every idle slot. If a transmission by an other node is overheard (with probability $p^\star$) the *bc* is frozen. Countdown resumes when the channel turns idle again, with probability $1-p^\star$.

During PBO, with probability $q^\star$ a frame enters the transmission queue. The *bc* countdown will continue, in order to access the medium. This is modelled by the "diagonal transitions" in Fig. 3. When a node reaches $s_{0,0}$, which represents an idle node, it receives a packet in its transmission queue with probability $q$ or remains idle with probability $1-q$. A node perceives the channel busy with probability $p$, hence, will perform a BO with probability $qp$, or a direct transmission with $q(1-p)$, if it perceives the channel idle. Both the direct transmissions and those mediated by BO will transition into $s_{1,0}$: the transmission state. The probability that the DTMC is in this state, i.e., that a station is transmitting in a generic slot, is denoted as $\tau$, which is used in the mean field approximation.

### 3.3 EDCA Model

As the behaviour of a station operating according to EDCA is different from a station using DCF operation, also the DTMC model for EDCA is different. Since we assume that all beaconing stations are using the same Access Category (AC), we do not model the service differentiation features of the EDCA, although we do take the modified IFS and `CWmin` into account. The most important difference sbetween the DCF and EDCA model come from the modified *bc* decrement rules. Fig. 4 shows the DTMC model for EDCA. Because an EDCA station always decrements at slot boundaries, *bc* countdown occurs in generic slots, irrespective of the medium condition. Thus, the *bc* is not frozen with probability $p^\star$, as in DCF, but is decremented at every generic slot. This behaviour was already taken into account in the original Bianchi model [4] where DCF *bc* freezing was modelled incorrectly. While in the DCF model, the probability of a packet arrival during PBO ("the diagonal transition") was denoted as $q^\star$, the probability of an arrival during a freezing period or streak, in the EDCA model, it is equal to $q$, the probability of an arrival in a generic slot. Because a generic slot can be empty, contain a successful transmission, or a collision, an arrival occurs in one of these slots with different probability depending on the type of slot. The mix of these types depends on the probability of occurence of such slots. Therefore, the probability $q$ that a packet arrival occurs in a generic slot, is given by a weighted Poisson arrival process with parameter $\lambda_g$:

$$q = 1 - \left( (1-p_b^\star)e^{-\lambda_g T_e} + p_s^\star e^{-\lambda_g T_s} + (p_b^\star - p_s^\star)e^{-\lambda_g T_c} \right), \tag{1}$$

where $p_s^\star$ is the probability that the node under consideration observes a slot containing a successful transmission from one of the $n-1$ others. This means that out of these other nodes, one does transmit and $n-2$ do not transmit:

$$p_s^\star = (n-1)\tau(1-\tau)^{n-2}. \tag{2}$$

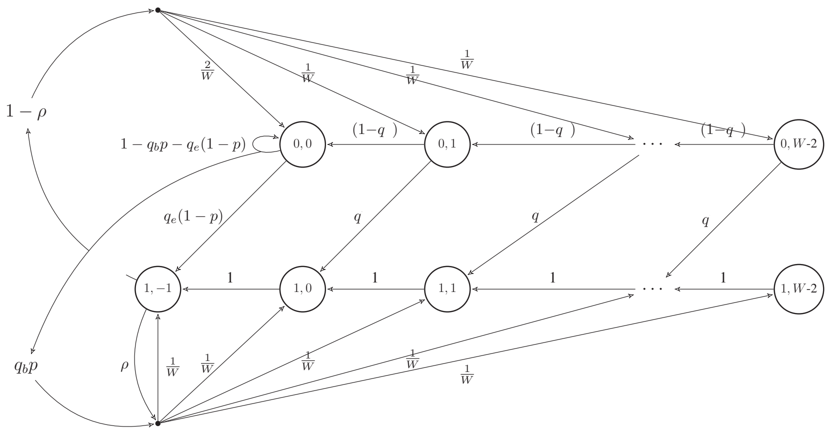


**Fig. 4.** Markov chain of the EDCA model

The probability of observing a busy slot is obtained as:

$$p_b^{\star} = 1 - (1 - \tau)^{n-1}. \tag{3}$$

Finally, $T_e$, $T_s$, and $T_c$ denote the duration of an empty, successful, or collision slot, respectively. A successful slot lasts the time for transmission of the entire packet, including preamble and headers, plus the AIFS period following the transmission. Similarly, a collision slot lasts the time for packet transmission plus the EIFS period following the transmission.

To account for the fact that an EDCA station may not decrement its $bc$ to 0 and transmit in the same slot, an extra state ($s_{1,-1}$) is added to the model, which represents a station transmitting in a generic slot. Upon completion of a transmission, a station goes into BO with probability $\rho$ and into PBO with probability $1 - \rho$. In both cases, the randomly chosen $bc$ can be decremented directly after the IFS following the transmission. This means that if a $bc$ of $W - 1$ is chosen, it is already decremented before the next generic slot. As a result, states $s_{j,W-1}$ are not present in the EDCA model. If the station choses $bc = 0$ while going into BO, it immediately transmits the frame in the next slot, and returns to state $s_{1,-1}$. If the station choses $bc = 0$ while going into PBO, it will go to the same idle state ($s_{0,0}$) as when it choses $bc = 1$. This is why the probability of going from transmission to idle is 2 times higher than the probability of going into another PBO state ($2/W$ versus $1/W$).

When a station is idle ($s_{0,0}$), what happens during the next generic slot depends on the type of of the current slot. The current generic slot is a busy slot with probability, $p$, that at least one of the other $n - 1$ stations is transmitting:

$$p = 1 - (1 - \tau)^{n-1}. \tag{4}$$

With probability $q_e(1-p)$, the current slot is idle and a packet arrival occurs within the slot, so that the station can transmit in the next slot, i.e., go to $s_{1,-1}$. Here, $q_e$ denotes the probability of a packet arrival during an empty slot;

$$q_e = 1 - e^{-\lambda_g T_e}. \tag{5}$$

With probability $q_b p$, the current slot is busy, and a packet arrival occurs within the slot, so that the station will draw a new $bc$ and go into BO. Similarly, $q_b$ denotes the probability of a packet arrival during a busy slot;

$$q_b = 1 - \left( \frac{p_s}{p_b} e^{-\lambda_g T_s} + \left(1 - \frac{p_s}{p_b}\right) e^{-\lambda_g T_c} \right). \tag{6}$$

If no packet arrival occurs while in $s_{0,0}$, with probability $1 - q_b p - q_e(1-p)$, the station will remain in the same state. (6) is again a weighted Poisson arrival process, where $p_b$ denotes the probability that a slot is busy, i.e., at least one of the $n$ nodes is transmitting,

$$p_b = 1 - (1-\tau)^n. \tag{7}$$

Furthermore, $p_s$ denotes the probability that a generic slot contains a successful transmission, i.e., one of the $n$ stations transmits, and the other $n-1$ do not transmit,

$$p_s = n\tau(1-\tau)^{n-1}. \tag{8}$$

### 3.4 Steady State Distribution of the EDCA Model

Let $b_{0,k}$, $b_{1,k}$, and $b_{1,-1}$ denote the stationary probability of being in states $s_{0,k}$, $s_{1,k}$, and $s_{1,-1}$ for $k \in \{0, \ldots, W-2\}$. By working recursively from right to left (see Fig. 4), the following expressions for the steady state probabilities can be derived. Complete derivations can be found in [6].

The steady-state probability for a node in PBO is given by:

$$b_{0,k} = \frac{1-\rho}{W} b_{1,-1} \frac{1-(1-q)^{W-k-1}}{q}, \text{ for } k = 1, \ldots, W-2. \tag{9}$$

A node is idle with steady-state probability:

$$b_{0,0} = \frac{(1-\rho)}{W(q_b p + q_e(1-p))} b_{1,-1} \left(1 + \frac{1-(1-q)^{W-1}}{q}\right). \tag{10}$$

The steady-state probability for a node in BO is given by:

$$\begin{aligned} b_{1,k} = \tfrac{b_{1,-1}}{W} \Big( &(W-k-1)\left(\rho + \tfrac{q_b p(1-\rho)}{W(q_b p + q_e(1-p))}\left(1 + \tfrac{1-(1-q)^{W-1}}{q}\right)\right) \\ &+ (1-\rho)\left((W-k-1) - \tfrac{1-(1-q)^{W-k-1}}{q}\right)\Big), \text{ for } k = 0, \ldots, W-2. \end{aligned} \tag{11}$$

The probability that a node transmits in a generic slot, $\tau$, equals the probability of being in the state in which transmission is performed, which is obtained by normalisation:

$$\tau = b_{1,-1} = \left(1 + \frac{(W-1)}{2} + \left(\frac{1-\rho}{W(q_b p + q_e(1-p))}\right.\right.$$
$$\left.\left.\left(1 - \frac{1-(1-q)^{W-1}}{q}\right)\right)\left(1 + \frac{q_b p(W-1)}{2}\right)\right)^{-1}. \quad (12)$$

## 3.5 Service Time

We can now derive an expression for the service time of the EDCA. This is the sum of the time it takes to transmit a frame (including the IFS), and the time spent in contention. Recall that whether or not to perform contention depends on the state of the channel upon arrival of a packet. The probability that a slot is observed busy is expressed as $p$, see (4). However, arrivals can happen at random moments in time (and not only on slot boundaries), so following the PASTA property, these Poisson arrivals see time averages. In this line, we need to find the observed real-time channel utilisation ($\mu$) by multiplying the probability of encountering a busy slot with the duration of such a slot, and divide by the duration of a generic slot:

$$\mu = \frac{p\mathbb{E}[T_b]}{\mathbb{E}[T]}, \quad (13)$$

where the average duration of a generic slot is:

$$\mathbb{E}[T] = (1-p_b)T_e + p_s T_s + (p_b - p_s)T_c, \quad (14)$$

and the average duration of a busy slot:

$$\mathbb{E}[T_b] = \frac{p_s}{p_b}T_s + \left(1 - \frac{p_s}{p_b}\right)T_c. \quad (15)$$

The expected service time $\mathbb{E}[S]$ is obtained as follows. Transmission of a message, including the IFS, has a duration of $\mathbb{E}[T_b]$. A station observes the medium busy and has to perform BO with probability $\mu$. In this case, the event which caused it to back off has a mean remaining duration of $\frac{\mathbb{E}[T_b]}{2}$, after which BO starts. On average, the station has to count down $\frac{(W-1)}{2}$ empty slots of average slot length $\mathbb{E}[T]$. The expected service time of the EDCA, including contention, then becomes:

$$\mathbb{E}[S] = \mathbb{E}[T_b] + \mu\left(\frac{\mathbb{E}[T_b]}{2} + \frac{(W-1)}{2}\mathbb{E}[T]\right). \quad (16)$$

Then, Little's Law can be used to obtain $\rho = \lambda_g \mathbb{E}[S]$.

## 4 Performance Comparison

We will now use the models presented in Sec. 3 to compare the performance of the DCF and EDCA. The analytical results from the DTMC models are obtained by solving the system of equations using a fixed-point iteration approach in Matlab. The iterations terminate once $\tau - \tau_{new} < \varepsilon$, with $\varepsilon = 1 \cdot 10^{-6}$.

The parameters values used in the experiments are as follows. The number of nodes is varied from $n = 1, \ldots, 200$, to analyze the scalability of DCF and EDCA. The generation rate $\lambda_g$ is either kept constant at 10 beacons per second, or varied between 0 and 25 beacons per second. The data rate of beacons is assumed to be 3 Mbps (for highly robust beacon broadcasting), and a beacon is assumed to have 3200 bits of data. For EDCA, Access Class 0 is assumed, leading to a duration of a successful packet of $T_s = 1.336 \cdot 10^{-3}$s, and, because of the longer EIFS, a duration of a collision of $T_c = 1.480 \cdot 10^{-3}$s. For the DCF, these durations are slightly shorter, because of the use of a DIFS instead of AIFS: $T_s = 1.224 \cdot 10^{-3}$s; $T_c = 1.368 \cdot 10^{-3}$s. For both EDCA and DCF, the duration of an empty backoff slot is $T_e = 16 \cdot 10^{-6}$s. Finally, W=16, i.e., the (initial) contention window, `CWmin`, is 15 for both DCF and EDCA (AC0).

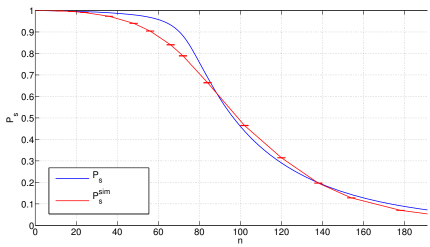


**Fig. 5.** Success probability EDCA, analysis and simulation

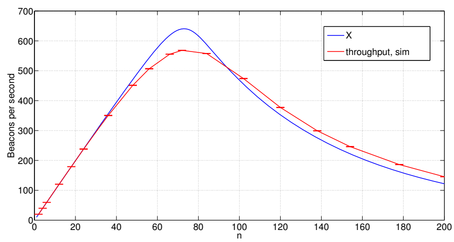


**Fig. 6.** Throughput EDCA, analysis and simulation

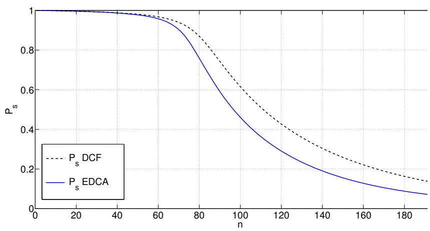


**Fig. 7.** Success probability, DCF vs. EDCA

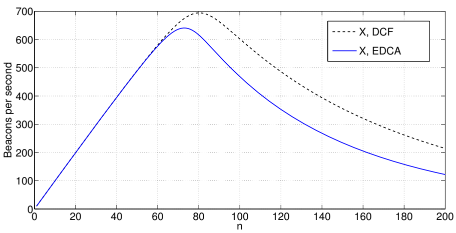


**Fig. 8.** Throughput, DCF vs. EDCA

We compare DCF and EDCA with respect to the success probability and throughput. The success probability of a transmitted beacon is the probabability that none of the other stations transmits in the same slot and given by $P_s = (1 - \tau)^{n-1}$. The throughput, $X = \frac{p_s}{\mathbb{E}[T]}$, is defined as the mean number of successful beacon transmissions per second, can be found by multiplying the expected number of slots per second, $\frac{1}{\mathbb{E}[T]}$, with the probability that these slots contain successful transmission, $p_s$.

Both models have been validated against simulation experiments performed using OMNeT++ and MiXiM with extensions to simulate vehicular networking [6]. The validation results for the DCF model have been published in [2] and the validation for the EDCF model is presented in Fig. 5 and Fig. 6. As is the case for the DCF model, the EDCA model also retains inaccuracies in the semi-saturated areas for $n$ between 60 and 80.

Fig. 7 shows the beacon success probability, $P_s$, for both DCF and EDCA. The general trend is that with increasing number of nodes, $n$, $P_s$ first decreases slowly, and after a critical point drops sharply. DCF is able to achieve a significantly larger $P_s$ than EDCA with increasing $n$. For DCF, the sharp decrease in $P_s$ occurs also at a larger $n$, and for $n > 150$, it is nearly double the $P_s$ for EDCA. Note that these values of $n$ correspond to a saturated network. In general, one would like to avoid these highly congestion situations. However, beaconing in vehicular networks will have to deal with a wide range of vehicle densities, and from time to time, the network will experience situations with high overload, e.g., around a highway junction with (road traffic) congestion a vehicle may find hundreds of cars within transmission distance. It is therefore of paramount importance to have a reasonably smooth performance degradation with increasing load.

The difference between DCF and EDCA is even more visible in Fig. 8, which shows the throughput, $X$, for both mechanisms. The DCF is able to achieve a significantly larger throughput and its saturation point occurs at larger $n$.

The performance difference between the two mechanisms can partially be attributed to the smaller IFS of the DCF, which leaves more channel resources for effective use. However, the dominant factor determining the better performance of the DCF is the difference in *bc* decrement rules. The explanation of the performance difference between DCF and EDCA, given below, has been confirmed by other model variables (streak length and collision multiplicity) and by simulation experiments in [6].

As the medium gets more heavily loaded, more and more of the generic slots on the medium are busy slots. Since the EDCA does not need empty slots to decrement its *bc*, stations typically do a transmission in a randomly chosen slot within `CWmin` slots after the beacon generation. With the parameter setting used in the experiments, beacons are mostly transmitted before the next beacon arrives. As a result, the EDCA tends to spread its transmissions randomly and evenly over all generic slots, and the system behaviour resembles slotted Aloha behaviour at high load.

For the DCF, the behaviour at high load is different. Since the DCF is freezing its *bc* in case of busy slots, it needs empty slots to move from backoff to transmission. As a result, transmissions are done in streaks, where a streaks is an empty slot followed by a number of busy slots (See Fig. 1). During the empty

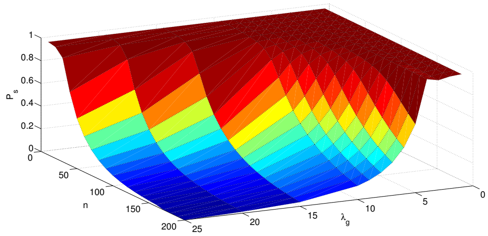


**Fig. 9.** Influence of $\lambda_g$ and $n$ on $P_s$ for the DCF

slot, all stations in backoff will decrement their counter. A significant fraction of those (on average 1/`CWmin`) will decrement to 0, and start transmission in the first slot of a streak. Only a small subset of the stations is allowed to transmit in the second slot of a streak. Those are the stations that were idle and generated a new packet for transmission during the first slot, and have chosen 0 as the *bc* value. Furthermore, stations that transmitted in the first slot of the streak, found another packet in their queue, and have chosen 0 as *bc* value are also allowed in the second slot. Similarly, even fewer stations are allowed to transmit in the third slot of a streak, if any. As a result, in case of DCF, we can observe streaks on a highly loaded medium, where on average many stations do a transmission in the first slot of a streak, and relatively few do a transmission in successive slots of the streak. Therefore, the first slot will most often yield a collision, whereas subsequent slots have a much higher probability of success. This uneven distribution of transmissions over time increases the probability that in an average slot exactly one station transmits, and hence the success probability.

We now explore the joint effect of increasing the beacon generation rate, $\lambda_g$, and the number of stations, $n$, on the success probability, $P_s$, for DCF (Fig. 9) and EDCA (Fig. 10). We can observe that also if either $\lambda_g$ or $n$ is high, the DCF gives a somewhat higher beacon success probability than the EDCA. However, as can also be observed, for a large range of parameter values, the beaconing performance of DCF and EDCA is very poor. It can be concluded that the scalability of the IEEE 802.11 multiple access mechanisms towards high rate beaconing and high node density is limited. Adapting the beaconing rate and/or the number of stations in range (by reducing transmission power) as the medium becomes heavily loaded, as for instance described in [7], is essential.

## 5 Related Work

IEEE 802.11 standards have been widely studied over the past fifteen years. Bianchi introduced a foundational model of the IEEE 802.11 DFC [4], [8], [9] which focuses on saturation throughput for the Basic Access mechanism and RTS/CTS in the DCF under ideal channel conditions for the 802.11b Medium Access Control (MAC). This sparked a whole family of models, each adding protocol features or extracting different metrics. For example, [10] models the

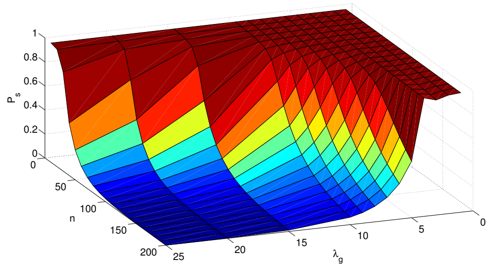


**Fig. 10.** Influence of $\lambda_g$ and $n$ on $P_s$ for the EDCA

IEEE 802.11e EDCA based on [8], [9] and [11] and adds priority differentiation with respect to contention window size and a finite retransmission limit.

In [12] the impact of the CA feature of the IEEE 802.11 DCF is evaluated using a 2-dimensional Markov Chain, focusing on the state the MAC is in. The IEEE 802.11 MAC is modelled as a gated system with no buffer; arrivals after the beginning of the current contention period will not be served until the next contention period. [13] adds *bc* freezing behaviour to Bianchi's model by using a separate DTMC to model the channel state. [14] explicitly models the queue size in the third dimension of the Markov chain. As a consequence, all 802.11 DCF system characteristics can be obtained directly from the Markov model.

[15] extends the EDCA model by adding AIFS differentiation and modifying for use in the whole saturation range, from non-saturated to fully saturated. In addition, post-backoff behaviour is added, which finally ends up in an idle state. Whether or not to exhibit saturation behaviour is governed by a probability $\rho$ that the queue contains another packet after transmission completes.

Yang *et al.* [16] identify that the EDCA brings difficulties and complexities to the per-slot based Markov chain modelling techniques widely used for analysis of the DCF. One problem is that, due to AIFS differentiation, it is no longer possible to accurately define a common time scale across all nodes. This common time scale is a fundamental property of many Markov-chain based models. To cope with these problems, [16] uses a channel access cycle-based modelling approach and adapt this for use in non-saturated conditions.

As opposed to IEEE 802.11 as used in WLAN situations where unicast dominates, the large scale use of broadcast as envisioned in vehicular networks has received little attention in the early modelling work. Chen *et al.* [17] analyse IEEE 802.11 broadcast performance using a one-dimensional Markov chain, modelling the *bc* decrementing behaviour of the DCF under saturation conditions. Ma and Chen [18] provide a model for broadcast in VANETs, including the presence of hidden terminals. Their model always performs backoff, exhibiting saturation behaviour without *bc* blocking. In [19], Vinel *et al.* address the trade-off between generation rate and network performance using deterministic arrivals, assuming backoff prior to transmission–also saturated behaviour. To the best of our knowledge, there is no existing work that analytically models and compares the performance of the DCF and EDCA for beaconing in vehicular networks.

## 6 Conclusions and Future Work

In this article, we have identified differences in the backoff counter (*bc*) decrement rules for the IEEE 802.11 DCF and EDCA. We have described analytical performance models for both mechanisms and compared their performance. The surprising result of our analysis is that the original DCF exhibits better scalability than the EDCA, which is mandated for use in the IEEE 802.11p standard. The explanation for this difference is the fact that DCF nodes need empty timeslots in order to proceed with decrementing their *bc*, whereas EDCA nodes do not. As a result, DCF transmissions occur in streaks, where towards the end of the streak very few nodes are contending for the medium, yielding a relatively high success probability. In EDCA, transmission attempts are spread out evenly, leading to a relatively low success probability if many nodes are contending. It can be concluded that in vehicular networks based on IEEE 802.11p, the service differentiation probabilities of the EDCA come at the cost of a reduced beaconing performance.

In future work, the interaction of hidden terminals with the described behaviour of both mechanisms needs to be taken studied. It is also important to derive other performance metrics, e.g., related to delay and the freshness of beacons from the presented models. Finally, the presented models can also be used to make simulation models at the traffic (safety) application level more accurate, yet computationally efficient. Incorporating approaches for congestion control by means of reducing transmit power or beaconing rate in our models is another important topic for future work.

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