Evaluation of MAC Contention Techniques for Efficient Geo-Routing in Vehicular Networks

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Abstract

In this paper we provide a novel performance evaluation methodology and fair comparison of the most relevant MAC-network cross-layer proposals for efficient geo-routing in the context of vehicular networks. In particular, GeoNetworking, the standard European network layer protocol for vehicle-to-vehicle (V2V) communications, proposes Contention-Based Forwarding (CBF) as basic forwarding mechanism, which can be also implemented at MAC layer in order to optimize its operation. A categorization and unified formal description of different proposals for such contention-based mechanisms is provided. We not only qualitatively discuss them, but also derive a more precise mathematical description of the operation of the proposals. Then we put forward a common framework for the analysis of their performance in the critical scenario of emergency warning delivery. Interestingly, with this model the performance metrics can be computed even when each vehicle selects its contention slot in a different way, unlike other models. This approach is validated by a thorough evaluation of the selected proposals in single-hop and multi-hop scenarios under ideal propagation conditions with both the proposed model and simulations. Finally, these techniques are also evaluated under more realistic fading conditions and compared with the purely network-layer implementation of CBF.

Keywords: GeoNetworking Protocol, MAC, VANET, contention mechanisms, cross-layer, multihop

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1. Introduction

Intervehicle communications based on wireless technologies pave the way for innovative applications in traffic safety, driver-assistance, traffic control and other advanced services which will make up future Intelligent Transportation Systems (ITS) [1]. Communications for Vehicular Ad-Hoc Networks (VANETs) have been developed and standardized over the last years. At the moment, a dedicated short range communication (DSRC) bandwidth has been allocated to vehicular communications at 5.9 GHz and both American and European standards [2] have adopted IEEE 802.11p as the physical and medium access control (MAC) layers, based on carrier-sense multiple access with collision avoidance (CSMA/CA) [3].

At the network layer, European standards [4] specify the GeoNetworking protocol as the default network layer protocol for vehicle-to-vehicle (V2V) communications. It is a geo-routing protocol, that is, packet forwarding is based on the geographical positions of the nodes. GeoNetworking supports the communication among individual ITS stations as well as the distribution of packets in geographical areas. As basic forwarding algorithms, the standard proposes *Greedy Forwarding* and *Contention-Based Forwarding (CBF)* [5]. With the former the source selects the most distant known neighbor as the next forwarder. With the latter, the packet is broadcast and each receiver station decides whether it becomes the next hop (forwarding router) according to its position: Upon receiving a packet, all receivers start a timer whose timeout depends on the specific position of the receiver, usually inversely proportional to the distance to the source. The major advantage of CBF is that it provides an implicit reliability mechanism in case the most suitable forwarder does not receive the packet, which in highly dynamic environments, such as those of vehicular networks, is quite likely.

As defined by the standard, CBF is completely implemented at the network layer. However, CBF might be also implemented directly at the MAC layer, in order to optimize its operation. For instance, implementing CBF at MAC layer should result in lower latency, since forwarding delay is removed and only access delay counts. This is an example of *cross-layer* design, which is widely used in vehicular networks [6]. Cross-layer design allows information to be exchanged and shared across layer boundaries in order to enable more efficient and robust protocols. Over the last years there have been a number of such cross-layer proposals aimed at optimizing the operation of geo-routing [7, 8] as well as general purpose MAC approaches which could also be used quite effectively in this framework [9, 10].

In this paper we provide a comparative evaluation of the most relevant

MAC-network cross-layer proposals for efficient CBF geo-routing in the context of vehicular networks. We focus on contention-based MAC mechanisms for wireless nodes. The majority of them are based on the CSMA/CA mechanism, whose operation and performance can be controlled by several parameters, namely: contention window size, random and deterministic carrier sense intervals as well as the probability distribution for the contention slots selection. Overall, it results in multiple degrees of freedom to optimize the medium access operation according to the most critical functionality offered by the network. In particular, for vehicular networks, the most important functionality is the delivery of geographically-addressed messages, which as mentioned before is performed by the GeoNetworking protocol. In some cases, this delivery might be critical, for instance, in safety-related applications which rely and are built on top of the functionality of the geo-routing protocol. In that case, optimizing the operation of the MAC layer may be a design requirement even independently of the network layer protocol. Not only emergency messages benefit from optimized operation of the MAC layer, but also more general-purpose applications, since all of them[1] work on top of GeoNetworking. Therefore, the goal of the evaluated proposals is to optimize the operation of the GeoNetworking protocol (in the network layer) by selecting appropriate MAC operation parameters. The increased complexity due to cross-layer interaction is traded off with some benefit in performance, such as an increase in the speed of packet advance, which could not be achieved in a layer-independent approach. In summary, GeoNetworking isolated at the network layer provides very limited room for optimization, apart from the adjustment of the timer parameters. On the contrary, the cross-layer design opens a variety of alternatives for the optimization of its performance, which should result in the improvement of the service/applications which operate on top of it.

We first briefly review and discuss both techniques specifically addressing vehicular networks and general-purpose proposals, which can be adapted to VANETs. Later we evaluate them, focusing on the most critical functionality, that is, the delivery of emergency messages to a particular location in multi-hop scenarios. This way we define a baseline scenario in order to provide a comparison as fair as possible of the performance of different proposals regarding the critical functionality.

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[1] At least most of the Vehicle-to-Vehicle (V2V) applications, since the standard specifies GeoNetworking as "a network layer protocol that provides packet routing in an ad hoc network". Vehicle-to-Infrastructure (V2I) applications might use different network layers.

The main contributions of this paper are thus the following:

- We provide a unified formal description of the discussed techniques in terms of the form that takes both the random and/or deterministic delays of the contention mechanism. Unlike previous works [11, 12, 13], we do not only qualitatively describe the operation of the contention mechanism, but also extract a more precise mathematical description of it, which is later used in a common evaluation framework.
- We provide a common framework for the performance analysis of the different techniques in the baseline scenario and define several metrics of interest. That is, we perform a simplified stochastic analysis of the proposals. The results are exact for one-hop scenarios and approximated, yet accurate enough, for multi-hop scenarios, as we shall show. It makes it a useful numerical tool for a quick evaluation of new proposals and mechanism variations, as we also illustrate with examples. Moreover, it is specifically aimed at the case in which vehicles select their contention slots in different ways, unlike other available models [14, 15, 16, 17].
- The evaluated proposals have been also simulated to validate our results. We provide a thorough evaluation of the different proposals for both ideal and realistic scenarios and compare them with the basic CBF mechanism specified by the standard. Our results show that there is little difference between them under realistic channel conditions, which should be taken into account in the design of new proposals.

The remainder of this paper is structured as follows. Related work is reviewed in Section 2. Section 3 provides a categorization and formal description of the selected mechanisms. In Section 4, after the description of the reference scenario, an analytical model for the performance evaluation of the selected protocols is developed, which is then used to provide a comparative evaluation of the different techniques for the single-hop and multi-hop cases. In Section 6 we exemplify the use of our model as a quick evaluation tool for different combinations of the techniques. Realistic scenarios are investigated and discussed next in Section 7, including the evaluation of the basic CBF protocol proposed by the standard. Concluding remarks are given in Section 8.

2. Related Work

We can find in the literature a number of surveys categorizing different routing protocols for VANETs [11, 12, 13]. Beyond that, in addition to the categorization of routing protocols, in [18] and [19] the authors provide a classification of intervehicle communication applications and examine the suitability of different routing protocols to each application class. In general, it is concluded that position-based routing and geo-casting are more effective than other routing protocols for VANETs. Several works [20, 21, 22] survey this specific type of protocols. In particular, in [22] geo-routing protocols are grouped into sender-based and receiver-based, being this last category in which our evaluated proposals would fall.

On the other hand, a thorough survey and general overview of cross-layer design for VANETs can be found in [6]. In this paper we focus on the most relevant MAC-network cross-layer proposals in the context of vehicular networks. To the best of our knowledge, there is no work specifically categorizing cross-layer techniques based on the contention stage of the MAC layer for efficient geo-routing in VANETs. And in addition to the protocol classification, we develop a common framework for the performance analysis of the different protocols, which is also validated through simulation. The majority of existing surveys merely describe qualitatively the different protocols and only a few of them perform simulations for comparative purposes. However, unlike our work, formal descriptions and analytical models for quick numerical evaluation of the different proposals are rarely provided. In this latter regard, different analytical models can be found in [14, 15, 16, 17], but none of them can be applied when each vehicle selects its contention time slot in a different way.

3. Description of Proposals

In this section we categorize and describe MAC proposals which either have been specifically proposed to be used to improve the operation of a geo-routing protocol, such as GeoNetworking, or are general-purpose but can be adapted conveniently for this context. The proposals are briefly described qualitatively but their operation is also formally expressed in terms of random and deterministic delays in a unified way. In the next subsection we discuss common operational aspects which we assume that hold for all the proposals, establish the main assumptions and the basic notation and compare them to the usual operation of the IEEE 802.11 *Distributed*

Coordination Function (DCF) [3]. We briefly describe the most representative at each category, which are the ones selected for comparison, and later summarize all the mentioned proposals in Table 1.

3.1. Common Description of the Contention Mechanisms

From now on we assume that all vehicles use a basic carrier sense multiple access with collision avoidance (CSMA/CA). A station with a new packet to transmit first monitors the channel activity. If the channel is idle for a given *deterministic time interval*, t_D, the station transmits. Otherwise, if the channel is sensed busy (either immediately or during t_D), the station keeps on listening to the channel until it is measured idle for t_D. At this point, the station generates a *random backoff time interval*, t_R, before transmitting. If the channel has been idle for the duration of the random interval, the station transmits the packet. This basic operation coincides with IEEE 802.11 DCF. In that case, t_D equals one of the defined interframe spaces, usually the DCF Interframe Space (DIFS). In our description of the proposals, in order to facilitate a common analysis, we assume that both t_D and t_R times are discretized, that is, that their values are an integer multiple of some arbitrarily small time slot σ, as is in fact defined in the standard [3].

In DCF, the duration of the slotted backoff time t_R is uniformly chosen in the range $[0, CW]$, called the contention window (CW). The value of CW for unicast packets is doubled every time an unsuccessful transmission occurs. For broadcast packets, there is no acknowledgment or error recovery procedure and so CW remains constant all the time. In fact, vehicular communications are mainly broadcast in nature and all the proposals considered here do not modify the window size as a result of an error. Moreover, unlike DCF, we assume that the slots of t_R can be chosen from arbitrary probability distributions. Additionally, to achieve fairness and avoid channel capture with DCF, the backoff time counter is decremented only when the channel is sensed idle, and “frozen” when a transmission is detected on the channel. In vehicular networks, the main goal of a CBF mechanism is to select the next forwarder and, once a node has retransmitted a packet, the remaining nodes cancel the pending packet. As as consequence, the backoff timer is reset, and there is no timer suspension in practice. All the previous arguments allows us to assume that a memoryless backoff procedure is in use.

To summarize, in the next subsections we categorize the collected protocols according to the way they modify the standard backoff selection method described above and select the channel sensing (contention) delay. To this purpose, let us define the total contention delay t_L, which is an integer multiple of a σ time slot and determines the exact time a node has to wait before it is allowed to transmit a frame, that is, the time it founds the medium idle. Then, $t_L = t_D + t_R$ is the sum of two terms: a deterministic term, t_D, and a random one, t_R, any of which can be zero in general. Therefore, the protocols are classified according to the way t_D and t_R are selected.

Throughout the rest of the paper we use also the following notation: an index v is used to identify a vehicle, the function $dist(x, y)$ is the Euclidean distance between two points, R_{tx} is the transmission range of a vehicle and x_s, x_d and x_v define the position of the source, the destination and the node v, respectively. Let us also remark that the time slot σ duration is not shown in the equations to simplify notation, that is, t_L, t_D and t_R are dimensionless integers, even though sometimes are referred to as time intervals in the discussions. To regain time, they should be multiplied by σ.

3.2. Deterministic Strategies

First, we consider the approaches that use a pure deterministic delay. This approach works well when the delay is selected according to some criterion which makes it unique among the contending nodes. This technique is usually implemented at the network layer, and, in a typical non cross-layer design, it would operate on top of a standard MAC, such as 802.11, which would add a random delay. Hence, it should be considered the baseline to which compare the advantages of a cross-layer MAC-network design. Thus, t_D takes a deterministic value between t_{min} and a maximum forwarding delay, t_{max}, as a function of selected parameters. For each vehicle v within the transmission range this waiting time is given by:

$$t_D(v) = t_{max} \cdot (1 - F(v)) + t_{min}, \tag{1}$$

where F is a function that quantifies the advantage obtained from a node being the next forwarder. The selection of this function depends on the particular application or the target objective of the broadcast process. $F(v)$ is usually a continuous function and therefore t_D takes a continuous value. In a real implementation, it cannot actually take a continuous value, and so nodes providing a similar advantage (near values of the function F) may select an identical backoff value. As a consequence, a finer discretization (in our notation, a shorter time slot) increases the efficiency of this method. An advantage of implementing these techniques at the MAC layer is that the delays might be potentially much shorter, but at the cost of a much higher implementation complexity. Though several of these schemes have been proposed in other contexts [23], we describe the main representative examples for vehicular networks.

- **CBF** [5] and **Role-Based** [24]. CBF is one of the mechanisms specified for the GeoNetworking protocol [4]. Basically, in vehicular networks the delay is selected according to the distance from the source, as originally described in [5], and may be refined with other vehicle parameters [24], resulting in a typical advantage function

  $$F(v) = \max\left\{0, \frac{dist(x_s, x_d) - dist(x_v, x_d)}{R_{tx}}\right\}. \tag{2}$$

  A clear disadvantage of this function is that it depends on the selected value for the transmission range R_{tx}, which is unknown and random in real scenarios, and may result in performance degradation.

3.3. Random Strategies: Contention Window Modification

We now turn to purely MAC approaches. First, we describe approaches that only employ the contention window range to adapt the channel access mechanism to the intended goal. Vehicles dynamically establish a contention range according to some classification criterion. Two main approaches can be found, which differ essentially in whether the selected contention window ranges can overlap.

3.3.1. Overlapped Contention Windows Assignment

In this case, each vehicle v computes its individual value $CW(v)$ as a function of some given criterion. In fact, most of the proposals are variations of the basic CBF scheme with more refined utility functions, based on multiple parameters. So, for each vehicle v the value of t_R is selected from a uniform distribution as:

$$t_R(v) \sim U(0, CW(v)). \tag{3}$$

In all cases under consideration, the deterministic term t_D is also used and given a constant value, usually a DIFS, except for the EDCA* proposal, as we discuss later.

- **Fast Broadcast** [7]. This protocol was designed to reduce the time required by a message to propagate from the source to the farthest node in a certain strip-shaped area-of-interest, and it is based on a distributed mechanism for the estimation of the communication range of mobile nodes, $\hat{R}_{tx}$. The contention window for each vehicle is computed based on its position in the estimated communication range using the next formula:

$$\begin{aligned} CW(v) = & \lfloor CW_{min} + \\ & + \frac{\hat{R}_{tx} - dist(x_s, x_v)}{\hat{R}_{tx}} (CW_{max} - CW_{min}) \rfloor, \end{aligned} \tag{4}$$

where CW_{max} and CW_{min} are the maximum and minimum contention window sizes. This is a variation of the basic CBF scheme discussed earlier, but implemented at the MAC layer and refined with the estimation procedure for the transmission range. This latter refinement makes it suitable for a real deployment, but at the cost of increased protocol overhead and complexity.

- **EDCA*** [3]. Within this category of protocols we also include the EDCA mechanism, used by the 802.11p standard [3], by which different classes of frames can be given priority over another in their competition to access the medium. It defines up to four access categories (ACs) of frames, each of which has its own queue. Each frame arriving at the MAC layer with a priority is mapped into one of the four possible ACs. The priority advantage is the result of modifying two parameters of the protocol. The first one is the contention window size; both the minimum and maximum CW values can be configured per AC. The second parameter is the delay after the medium goes idle before a contender either begins a transmission or initiates a backoff. So, for each particular AC the delays t_D and t_R are computed as follows:

$$t_D(AC) = SIFS + AIFSN[AC], \tag{5}$$

$$t_R(AC) \sim U(0, CW[AC]), \tag{6}$$

where SIFS (short interframe space) and AIFSN (arbitration interframe space number) are protocol parameters. Obviously, this scheme can be adapted to optimize the operation of the network layer in different ways. Any of the utility functions discussed so far may be used to map the frame to an AC. For instance, the transmission range can be split into four intervals and mapped to the ACs according to the vehicle position relative to the source. Let us note that in the following evaluation we focus on broadcast communications and so we assume EDCA works also with no window size increase and backoff timer suspension, that is, as a memoryless backoff, and therefore we call it EDCA*.

3.3.2. Disjoint Contention Windows Assignment

This method involves dividing the range $[0, CW]$ into m non-overlapping intervals, $I_1, \dots, I_m$, so that each vehicle, depending on its priority, selects a backoff value randomly from one of the m intervals. Assuming that the length of each interval I_i is W_i, the resulting intervals are:

$$[0,\ W_1 - 1]\,,\ [W_1,\ W_1 + W_2 - 1]\,, \dots, \left[\sum_{i=1}^{m-1} W_i,\ \sum_{i=1}^{m} W_i - 1\right]. \tag{7}$$

We define the function:

$$w_k = \begin{cases} 0, & \text{for } k = 1, \\ w_{k-1} + W_{k-1}, & \text{for } k = 2, \dots, m. \end{cases} \tag{8}$$

Then, the values of t_D and t_R are expressed as follows:

$$t_D(v) \ = \ \mathrm{DIFS} + \sum_{k=1}^{m} w_k \cdot \mu_{I_k}(v), \tag{9}$$

$$t_R(v) \ \sim \ U\left(0, \sum_{k=1}^{m} W_k \cdot \mu_{I_k}(v) - 1\right), \tag{10}$$

where $\mu_{I_k}(v)$ is equal to 1 if vehicle v is associated with interval I_k and 0 otherwise.

- **Smart Broadcast** [8]. A distributed position-aware broadcast protocol for highway inter-vehicular networks, which is able to guarantee high reliability, low propagation latency and redundancy reduction, without requiring perfect knowledge of the network topology. Given the transmission range, R_{tx}, it is partitioned into m adjacent and non-overlapping sectors numbered from S_1 to S_m, starting by the farthest sector from the source node. Each sector S_i is associated to a size of the contention window K_i, and the disjoint intervals are constructed as explained before, so that the highest priority corresponds to the farthest nodes from the source.

3.4. Random Strategies: Probability Distribution Modification

In all the preceding random strategies the backoff counter was selected uniformly within the specified contention window range, which was adjusted in order to prioritize certain contenders. On the contrary, the idea under this category is to carefully choose a nonuniform probability distribution that nodes use to randomly select their backoff counters, but keeping the contention window constant. Depending on the shape and the particular characteristics of the probability distribution used, some contenders will have more priority to access the channel than others.

If we choose a discrete probability distribution g_{CW} over the slots of the contention window, then the random term t_R of the waiting time for each vehicle v is given by the probability mass function:

$$P\left(t_R(v) = j\right) = g_{CW}(j),\ j = 0, \ldots, CW. \tag{11}$$

The deterministic term t_D, if present, can be set to a constant value such as DIFS.

- **Sift** [9]. In many situations, the network operation synchronizes the medium access of all nodes, that is, all receivers of a packet immediately become potential forwarders and contend for the medium. In this particular case, in [9] it is shown that there exists an optimal distribution for the contention slots that maximizes the contention success probability. Although the optimal distribution cannot be implemented in practice, geometric distributions approximate the optimal one. So authors proposed an approximation that uses a truncated geometric distribution. The size of the contention window is constant, and the probability $g_{CW}(j)$ of selecting a certain slot j increases with the slot number. The probability of choosing the slot j is given by:

  $$g_{CW}(j) = \frac{(1-\alpha)\cdot\alpha^{CW+1}}{1-\alpha^{CW+1}}\cdot\alpha^{-(j+1)},\ j = 0, \ldots, CW, \tag{12}$$

  where $\alpha = g_{CW}(j)/g_{CW}(j+1)$ is a characteristic coefficient that determines the shape of the probability distribution, and it is adapted to the estimated number of contenders. The geometric distribution assigns low probability to initial slots, and high probability to the last few slots in the contention window, which greatly reduces the probability of packet collision.

- **COMIC** [10]. In this work a scheme for backoff-based collision resolution is proposed. The contention window is fixed for all the contenders, but the uniform contention slot selection distribution over $[0, CW]$ is replaced by a truncated normal distribution:

  $$g_{CW}(j) = \frac{f(j)}{\int_0^{CW} f(r)dr},\ j = 0, \ldots, CW, \tag{13}$$

where $f(x) = \frac{1}{\rho\sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2\rho^2}}$ is the normal probability distribution function.

This procedure is designed for non-broadcast communication processes and it is based on the standard Binary Exponential Backoff procedure for contention window expansion and contraction upon collision and success. So, for consecutive backoff stages, the shape of the truncated normal distribution is intelligently tuned, adapting the mean $\bar{x}$ and standard deviation ρ, according to the backoff value previously selected, so that the selection likelihood of relatively less collision-probable contention slots is maximized. However, for broadcast communication processes there are no retransmission attempts, and therefore there is no history information available, so in this paper $\bar{x}$ and ρ are assigned $\lfloor \frac{CW}{2} \rfloor$ and $\sqrt{\frac{CW}{2}}$, respectively.

As we shall show, both procedures perform remarkably well in terms of global transmission success, but unlike the previously discussed ones, all the vehicles have equal success probability. Depending on the application, this might not be desirable, for instance, if we want to maximize the packet progress.

3.5. Summary

In Table 1 we summarize the categorization of the described protocols, together with their particular characteristics. Most of the considered procedures, at least those specifically proposed for vehicular networks, have been designed to optimize the packet advance. And most of them are variations of the basic CBF scheme with refined utility functions involving the physical state of the vehicle and communications, such as distance, position or link quality.

Up to this point we have formally described and qualitatively discussed several alternatives, but attending only to their description it is not obvious which are the real advantages and drawbacks of the different proposals. Moreover, in the literature, they have been evaluated in quite different scenarios and with different assumptions and parameters and the results available are not usually directly comparable. Therefore, in the following sections, we provide a common evaluation stochastic model, a set of performance metrics and a baseline scenario in order to provide a fair comparison of the different proposals.

Table 1: Summary of broadcasting techniques based on contention

Classification	**Kernel Function**	**Protocol**	**Particular Characteristics**
Deterministic strategies	$t_D(v) = t_{max} \cdot (1 - F(v)) + t_{min}$ $t_R(v) = 0$ $P(t_L(v) = j) = \begin{cases} 1, & j = t_{max} \cdot (1 - F(v)) + t_{min} \\ 0, & j \neq t_{max} \cdot (1 - F(v)) + t_{min} \end{cases}$	CBF, Role-Based	$F(v) = \max \left\{ 0, \frac{dist(x_s, x_d) - dist(x_v, x_d)}{R_{tx}} \right\}$
Random strategies *Overlapped CW*	$t_D(v) = \text{DIFS}$ $t_R(v) \sim U(0, CW(v))$ $P(t_L(v) = j) = \begin{cases} 0, & j = 0, \ldots, t_D(v) - 1 \\ \frac{1}{CW(v)+1}, & j = t_D(v), \ldots, t_D(v) + CW(v) \end{cases}$	Fast Broadcast	$CW(v) = \left\lfloor CW_{min} + \frac{\hat{R}_{tx} - dist(x_s, x_v)}{\hat{R}_{tx}} (CW_{max} - CW_{min}) \right\rfloor$
		EDCA*	$t_D(AC) = SIFS + AIFSN[AC]$ $t_R(AC) \sim U(0, CW[AC])$
Random strategies *Disjoint CW*	$t_D(v) = \text{DIFS} + \sum_{k=1}^{m} w_k \cdot \mu_{I_k}(v)$ $t_R(v) \sim U \left(0, \sum_{k=1}^{m} W_k \cdot \mu_{I_k}(v) - 1 \right)$ $P(t_L(v) = j) = \begin{cases} 0, & j = 0, \ldots, t_D(v) - 1 \\ \frac{1}{\sum_{k=1}^{m} W_k \cdot \mu_{I_k}(v)}, & j = t_D(v), \ldots, t_D(v) + \sum_{k=1}^{m} W_k \cdot \mu_{I_k}(v) - 1 \end{cases}$	Smart Broadcast	$R_{tx} = S_1 \cup S_2 \cup \ldots \cup S_m$ S_1 is the farthest sector from the node Nodes in S_i select their backoff from I_i.
Random strategies Pdf Modification	$t_D(v) = \text{DIFS}$ $t_R(v) \sim g_{CW}$ $P\left(t_L(v) = j\right) = \begin{cases} 0, & j = 0, \ldots, t_D(v) - 1 \\ g_{CW}(j), & j = t_D(v), \ldots, t_D(v) + CW \end{cases}$	Sift	$g_{CW}(j) = \frac{(1-\alpha) \cdot \alpha^{CW+1}}{1 - \alpha^{CW+1}} \cdot \alpha^{-(j+1)}$
		COMIC	$g_{CW}(j) = \frac{f(j)}{\int_0^{CW} f(r) dr}, \qquad f(x) = \frac{1}{\rho\sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2\rho^2}}$

4. Performance Evaluation Model

In the following sections we present a comparative study to show the performance of the discussed procedures as forwarding algorithms for the GeoNetworking protocol [4]. The current set of ETSI standards [4] requires the implementation of GeoNetworking in all ITS stations[2] as well as its use for communications over the 5.9 GHz band in Europe, including periodic transmission of safety-related messages. Hence, new proposals in this field should take it into account in their design and they should be evaluated under this protocol. Many applications with different requirements can be implemented on top of GeoNetworking, but delivery of emergency messages is usually regarded as the most critical one. In this case, it is typically required that packets advance as much and as quickly as possible. Consequently, we define related performance metrics for the comparison of proposals.

First we develop a common analytical model. It is based on the abstraction of the MAC contention procedure by defining a matrix whose elements are the probabilities of a vehicle selecting a given contention delay, including both the deterministic and the random terms. A major advantage of this approach is that each row of the matrix reflects the contention procedure of a given vehicle and can be different from other rows, that is, vehicles can use completely different contention procedures. All the metrics are defined

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[2] An Intelligent Transportation System (ITS) station is a vehicle equipped with a wireless interface which implements the ITS communications architecture, according to the ETSI definition [2].

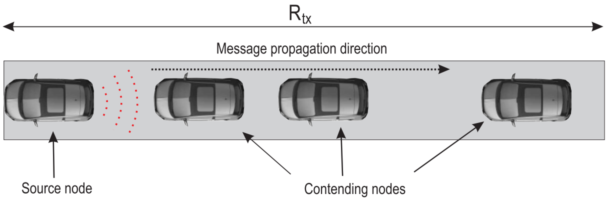

Figure 1: Scenario under consideration.

as a function of this matrix, and therefore we obtain a unified framework to compare the different proposals. These performance metrics provide exact results for single-hop scenarios, but for multi-hop scenarios we provide an approximation algorithm.

4.1. Scenario Description

The vehicular network considered here is a strip-shaped area, where vehicles are randomly distributed according to a one-dimensional Poisson process of intensity λ. The parameter λ represents the density of vehicles on the road, defined as the average number of vehicles per meter. We assume that each vehicle is equipped with a GPS-like device so that each node knows its own geographical position. We also suppose that all the nodes in the considered area have synchronized time scale.

In this scenario, a broadcast message generated by the source node (positioned at the beginning of the area) should be propagated along the strip in the opposite direction of movement, as depicted in Fig. 1. Each broadcast message contains a header field that includes the spatial coordinates of the transmitting node, the message propagation direction and information about the destination (a particular node or a geographical area). We also assume that the broadcast message is correctly received by all vehicles within the transmission range area R_{tx}, that is, we suppose an ideal deterministic radio propagation model with no errors. Upon receiving the message all the nodes try to forward it, contending to access the channel. Therefore, the number of contending nodes is also a random variable following a Poisson distribution with parameter λR_{tx}. Let us finally note that the following analysis can be applied to any other vehicle position distribution.

4.2. Performance Metrics for a single hop scenario

We start with the stochastic analysis of the protocols, taking into account that for the techniques under evaluation the nodes in the network not necessarily select their waiting time with the same probability distribution nor an equal window size. So, we construct a matrix $\mathbf{P}$ where $\mathbf{P}(i, j)$, with $i = 1, \ldots, N$ and $j = 0, \ldots, W$, is the probability of node i selecting j time slots of σ duration for channel sensing before transmitting, that is, $\mathbf{P}(i, j) = P(t_L(v) = j)$. Therefore, the dimension of $\mathbf{P}$ is $N \times W$, where N is the number of contenders and $W = \max_i t_L(v)$ is the maximum possible delay (in slots) that can be chosen by any of the nodes. Let us remark that t_L includes both the deterministic and random number of slots. We call this matrix the *delay probability matrix*.

For the sake of clarity, we illustrate the construction of the matrix $\mathbf{P}$ with a brief example. Suppose that there are three nodes in the network that select their delays as follows:

- For the first node the deterministic delay is 0 and the random one is uniformly selected from $\{0, 1, 2\}$. Therefore, $t_L(1) = t_D(1) + t_R(1) = t_R(1)$, can take the values 0, 1 or 2, each with probability 1/3. $t_L(1)$ cannot be greater than 2 slots, so each element is 0 for $j > 2$.
- For the second node the deterministic delay is 1 and the random one is uniformly selected from $\{0, 1, 2\}$. Therefore, $t_L(2) = t_D(2) + t_R(2) = 1 + t_R(2)$, can take the values 1, 2 or 3, each with probability 1/3.
- For the third node the deterministic delay is 1 and the random one is uniformly selected from $\{0, 1\}$. Therefore, $t_L(3) = t_D(3) + t_R(3) = 1 + t_R(3)$, can take the values 1 or 2, each with probability 1/2.

The resulting matrix is the following:

$$\begin{aligned}\mathbf{P} &= \begin{pmatrix} P(t_L(1)=0) & P(t_L(1)=1) & P(t_L(1)=2) & P(t_L(1)=3) \\ P(t_L(2)=0) & P(t_L(2)=1) & P(t_L(2)=2) & P(t_L(2)=3) \\ P(t_L(3)=0) & P(t_L(3)=1) & P(t_L(3)=2) & P(t_L(3)=3) \end{pmatrix} \\ &= \begin{pmatrix} 1/3 & 1/3 & 1/3 & 0 \\ 0 & 1/3 & 1/3 & 1/3 \\ 0 & 1/2 & 1/2 & 0 \end{pmatrix}. \qquad (14)\end{aligned}$$

Then, by using this delay probability matrix, and assuming that all nodes are in range, we compute the probability of a successful transmission by the vehicle v in the slot r, $S_{v,r}$, which is the probability of vehicle v selecting slot r multiplied by the probability of all the other vehicles selecting later slots:

$$S_{v,r}(\mathbf{P}) = \mathbf{P}(v, r) \prod_{j=1, j\neq v}^{N} \left(1 - \sum_{k=0}^{r} \mathbf{P}(j, k)\right). \qquad (15)$$

Then, by addition of the corresponding probabilities we can obtain the success probability in a specific slot (S_r^S), the probability of a successful transmission by a particular vehicle (S_v^V) and the total success probability (S):

$$S_r^S(\mathbf{P}) = \sum_{v=1}^{N} S_{v,r}(\mathbf{P}), \tag{16}$$

$$S_v^V(\mathbf{P}) = \sum_{r=0}^{W} S_{v,r}(\mathbf{P}), \tag{17}$$

$$S(\mathbf{P}) = \sum_{i=1}^{N} \sum_{r=0}^{W} S_{v,r}(\mathbf{P}), \tag{18}$$

Next, we compute the index (i) of the vehicle that wins the contention (on average), provided that the transmission attempt is successful:

$$veh^*(\mathbf{P}) = \frac{\sum_{i=1}^{N} i \cdot S_v^V(\mathbf{P})}{S(\mathbf{P})}. \tag{19}$$

The randomly-generated position of the vehicles is stored in a vector ve. Then the position of the winner vehicle, denoted by pos^*, is obtained by interpolating the average index to the position of the vehicles in ve with the nearest ones.

Similarly, the mean slot number when the successful transmission starts is given by the following expectation:

$$t_s(\mathbf{P}) = \frac{\sum_{r=0}^{W} r \cdot S_r^S(\mathbf{P})}{S(\mathbf{P})}. \tag{20}$$

On the other hand, in the slot r there is no packet collision if one of the following situations occurs: there is success or collision before slot r; there is success in slot r; or all the nodes choose their slots after slot r. Therefore, the probability of a collision in the slot r is:

$$\begin{aligned} C_r(\mathbf{P}) = 1 - \sum_{k=0}^{r-1} \left(S_k^S(\mathbf{P}) + C_k(\mathbf{P}) \right) - \\ - S_r^S(\mathbf{P}) - \prod_{j=1}^{N} \sum_{k=r+1}^{W} \mathbf{P}(j,k). \end{aligned} \tag{21}$$

And the mean slot number when the collision occurs is given by:

$$t_c(\mathbf{P}) = \frac{\sum_{r=0}^{W} r \cdot C_r(\mathbf{P})}{1 - S(\mathbf{P})}, \tag{22}$$

where t_c is defined for $N \geq 2$ since the collision may only happen if more than one node compete for the channel access.

Now, from the above metrics, we compute the critical performance metrics in the considered emergency-message scenario: the *Mean Channel Access Delay* (T_{acc}) and the *End-to-end Delay* (T_e), which are expressed in seconds. Let σ and L_{Pkt} be the time duration for a slot and a packet transmission, also expressed in seconds. The Mean Access Delay is defined as the average time from the instant the nodes start trying to send a packet until the beginning of a successful transmission. It is computed as follows:

$$T_{acc}(\mathbf{P}) = (E[A(\mathbf{P})] - 1) \cdot (\sigma \cdot t_c(\mathbf{P}) + L_{Pkt}) + \sigma \cdot t_s(\mathbf{P}), \tag{23}$$

where $E[A(\mathbf{P})]$ represents the expected number of attempts until a node wins the contention. Let us note that the probability of succeeding at the i-th attempt equals $(1-S(\mathbf{P}))^{i-1}S(\mathbf{P})$. Thus, the expected number of attempts is computed as follows: $E[A(\mathbf{P})] = \sum_{i=1}^{\infty} i\,(1 - S(\mathbf{P}))^{i-1}\,S(\mathbf{P}) = \frac{1}{S(\mathbf{P})}$, where the last equality is a consequence of the infinity sum of a geometric series. The number of attempts may be restricted by a *hop limit* parameter, in which case, the summation would be truncated to such value.

Finally, the End-to-end Delay is defined as the average delay incurred by the packet to reach the destination area, which in a one-hop scenario is simply: $T_e(\mathbf{P}) = T_{acc}(\mathbf{P}) + L_{Pkt}$.

In order to account for the random vehicle position we have to generate several replications of the vehicle positions, according to a given probability distribution, compute the metrics, and average them over all the replications. That is, the model is evaluated with a Monte Carlo simulation over the vehicle distributions.

The above metrics are exact (under the assumptions we made) for a single-hop network, where all the nodes are in range of each other, which makes them suitable for fair comparisons in a number of ideal situations. However, we are interested in the performance of the different proposals in a more realistic scenario, where the emergency message has to advance multiple hops, until it reaches an intended destination point, *Dest*.

4.3. Performance Metrics for multi-hop scenarios

In this scenario, the number and positions of the new contenders in a contention round depend on what happened in all the previous contention rounds, that is, which exactly are the nodes that won or collided in these rounds. We cannot take advantage of a memoryless model and the analysis becomes more complex. In order to keep it simple, we provide the algorithm in Fig. 3 to approximate the metrics of interest in a multi-hop scenario. The rationale for this algorithm is explained next.

We declare a function `ComputeMetrics(initPos,endPos)`, which takes as input parameters the initial and final position of the hop where the metrics are to be computed. There are more input parameters which are omitted for the sake of clarity, but are implicitly used by the function such as the value of R_{tx}, the values of σ and L_{Pkt}, the set of positions of all the vehicles ve and the destination point $Dest$. This function returns all the metrics previously defined for a single hop in equations (15) to (23) as well as the delay probability matrix $\mathbf{P}$ for vehicles within $initPos$ and $endPos$ and two new metrics pc_1 and pc_2 which are to be referred to as *the average position of the two nodes involved in a packet collision which are more distant from the source*. The computation of pc_1 and pc_2 is provided in the Appendix. For each hop we have to consider two possible outcomes: success or collision, as described next. Finally, since we need to weight the hop metrics by the probability of occurrence of the outcome and accumulate them, we declare an auxiliary function `UpdateVariables()` to this purpose.

Success. Lines 12 to 20. In case of a successful transmission, in the next hop we will be exactly under the same conditions as in the first hop, so we only have to compute the basic metrics for the new contenders and weight it by the probability of success and the previous probabilities, which we keep track of with the variable p, called the probability of occurrence of the outcome. Then, for each hop of the packet, the metrics are computed and weighted by the probability of occurrence of the success (lines 13 to 15). In summary, in case of success the behavior is memoryless and we only have to repeatedly compute the metrics for each hop and weight them by the probability of success multiplied by the probabilities of the previous outcomes.

As an example, let us explain the process for the mean channel access delay. For the sake of clarity, we use a subscript in the variables to show the iteration number, and we omit in the notation the dependence of the variables on the matrix $\mathbf{P}$. We keep two auxiliary variables, $\sum T_a$ and $\sum p$. In the first hop we start with $p_0 = 1$ and compute `ComputeMetrics(0,`R_{tx}`)`, which returns $T_{a,1} = t_{s,1} \cdot \sigma + L_{Pkt}$, and accumulate it as $\sum T_a = \sum T_a + T_{a,1} \cdot S_1 \cdot p_0$ and $\sum p = \sum p + S_1 \cdot p_0$, and then update $p_1 = p_0 \cdot S_1$. That is, we average the mean access delay of the hop by its probability of occurrence. In the next iteration we compute again the metrics for the next hop according to the

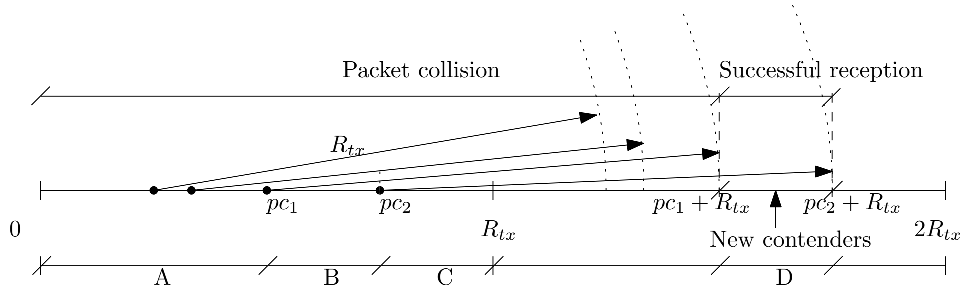

Figure 2: Top: four nodes transmit simultaneously and create a collision. The transmission range of each node involved is shown with an arrow. The position of the two nodes involved in the collision which are more distant from the source is shown as pc_1 and pc_2. The segment where the new contenders are located after a packet collision is labeled as "successful reception". Nodes in A, B and C contend again in the next attempt because they have experienced a collision, whereas nodes in D contend for the first time because they have received a new packet. Bottom: the segments considered for computation of collision-related metrics are shown.

average advance of the packet, that is `ComputeMetrics(`pos_1^*`,`$pos_1^* + R_{tx}$`)`, obtain the mean access time ($T_{a,2}$) and accumulate it, but now it is weighted by the product of the probability of success in this attempt and the previous probability of success ($S_2 \cdot p_1$). At the end of the algorithm we obtain the mean access time as $\sum T_a / \sum p$.

Collision. Lines 22 to 42. However, in case of collision the outcome of the following hop depends on the outcome of the previous one because new contenders are involved. In fact, in case of collision a packet always *advances*, in the sense that there are nodes that receive the packet correctly because they are in range of one colliding node but out of range of the other one, as shown in Fig. 2 for segment D. Let us remark that *we do not assume that only two nodes collide.* On the contrary, an arbitrary number of nodes may collide as shown in Fig. 2, but the segment of successful reception (D) is always defined by the relative position of the two nodes involved in a collision which are more distant from the source, that is, pc_1 and pc_2. As can be seen in Fig. 2, after a collision, in the next try, all the nodes in segments A, B, C and D contend to forward. The outcome of the contention resolution depends on the distance between nodes. Success of a node in D makes all nodes in C and some of B defer transmission but nodes in A do not sense the channel busy. So there is a hidden terminal problem. And the other way round when a node in A wins. On the other hand, a success in C makes all the rest of nodes defer transmission.

Therefore, in order to take into account the metrics in case of collision we approximate this situation by considering only the outcomes that make the packet advance again. Those metrics are computed in the function `ComputeCollisionMetrics(`pc_1`,`pc_2`,`$\mathbf{P_1}$`)` where pc_1 and pc_2 are the average positions of the last two nodes colliding, which define the segment D and are computed by `ComputeMetrics`. It returns the corresponding metrics for an arbitrary segment, such as the probability of success in a given segment H, S^H, or the mean channel access delay in case of success in segment H, T_a^H. To compute these metrics we construct an extended delay probability matrix $\mathbf{P_e}$, which includes the new contending nodes, and compute the success probability within two hops, so *explicitly taking into account the hidden terminal probability* in the computation of metrics. The details of these computations are provided in the Appendix. In the algorithm, we consider only the following relevant cases (lines 22 to 42) and neglect all other outcomes:

- A node in segment C successfully transmits. It wins the contention to all the rest of nodes trying to access the channel. This case is equivalent to a success but shifted to the position of the winner vehicle, pos^C. We update the metrics if we have finished or recursively start and compute a new try with the corresponding parameters.

- A node in segment D successfully transmits. It means that it wins the contention to all the nodes in C and B (according to the definition of success in the Appendix) trying to access the channel. In this case, a collision with a node in A is unavoidable. The nodes in common range of the winner nodes in A and B experience a collision. We neglect the effects of this collision in the metrics for the reasons discussed in the remarks below. The packet advances from the position of the winner, pos^D, and so we update the metrics if we have finished or recursively start and compute a new try.

To compute the metrics the algorithm in Fig. 3 must be run several times with different randomly-generated node positions in ve, and the results are averaged over all the replications. Let us finish with the following remarks:

- There is no global notion of probability of success in a multi-hop scenario, it is a local effect: some nodes may successfully receive a packet while other experience a collision. We adopt a pessimistic approach and, in both the algorithm and simulations, we consider that there is success only when *all the nodes* in range of the transmitter receive the packet correctly. According to this convention, we do not update the success probability $\sum S$ in case of success in D, since there is always a collision with A for some of the nodes.

```
Require: $R_{tx}$, $Dest$, $\sigma$, $L_{Pkt}$ and $ve$.
function UpdateVariables($at_s$,$\Delta pos$,$p_o$)
    ▷ $at_s$: mean slot number, $\Delta pos$: mean position difference, $p_o$: probability of occurrence
    $\sum T_a = \sum T_a + (at_s\sigma + L_{Pkt}) \cdot p_o$
    $\sum Pos = \sum Pos + \Delta pos \cdot p_o$
    $\sum p = \sum p + p_o$
end function
function ComputeNextTry($initPos$, $endPos$, $prevPos$, $p$, $T_{e,n-1}$)
    $\sum T_a$, $\sum T_e$, $\sum S$, $\sum Pos \leftarrow 0$, $\sum p \leftarrow 0$, $T_e \leftarrow T_{e,n-1}$
    ▷ Initialize accumulation variables. Mean access and end-to-end delays, $\sum T_a$ and $\sum T_e$,
success probability, $\sum S$, mean position, $\sum Pos$ and probabilities of occurrence, $\sum p$

    while $prevPos + R_{tx} < Dest$ do
        $S$, $t_s$, $pos^*$, $pc_1$, $pc_2$, $\mathbf{P} \leftarrow$ ComputeMetrics($initPos, endPos$)
        $\sum T_a$, $\sum Pos$, $\sum p \leftarrow$ UpdateVariables($t_s, pos^* - prevPos, S \cdot p$)
        $\sum S = \sum S + (S \cdot p)$
        $T_e = T_e + t_s\sigma + L_{Pkt}$                    ▷ Update accumulation variables

        if $pos^* + R_{tx} > Dest$ then                      ▷ Check if we have finished
            $\sum T_e = T_e \cdot (S \cdot p)$
            return $\sum S / \sum p$, $\sum T_a / \sum p$, $\sum Pos / \sum p$, $\sum T_e / \sum p$
        end if

        $S^D$, $t_s^D$, $pos^D$, $S^C$, $t_s^C$, $pos^C \leftarrow$ ComputeCollisionMetrics($pc_1, pc_2, \mathbf{P}$)
                                                             ▷ Compute Metrics for Collision
        if $pos^C + R_{tx} > Dest$ then
            $\sum T_a$, $\sum Pos$, $\sum p \leftarrow$ UpdateVariables($t_s + t_s^C, pos^C - prevPos, S^C \cdot (1-S) \cdot p$)
            $\sum S = \sum S + (S^C \cdot (1-S) \cdot p)$
            $\sum T_e = (T_e + (t_s + t_s^C)\sigma + L_{Pkt}) \cdot (S^C \cdot (1-S) \cdot p)$
                              ▷ Update accumulation variables in case of success in segment C
        else
            ComputeNextTry($pos^C$, $pos^C + R_{tx}$, $S^C \cdot (1-S) \cdot p$, $T_e + (t_s^C\sigma + L_{Pkt})$)
    ▷ Recursively compute the next try starting from the position of the winner vehicle in C
        end if

        if $pos^D + R_{tx} > Dest$ then
            $\sum T_a$, $\sum Pos$, $\sum p \leftarrow$ UpdateVariables($t_s + t_s^D, pos^D - pc_2, S^D \cdot (1-S) \cdot p$)
            $\sum T_e = (T_e + (t_s + t_s^D)\sigma + L_{Pkt}) \cdot (S^D \cdot (1-S) \cdot p)$
                              ▷ Update accumulation variables in case of success in segment D
        else
            ComputeNextTry($pos^D$, $pos^D + R_{tx}$, $S^D \cdot (1-S) \cdot p$, $T_e + (t_s^D\sigma + L_{Pkt})$)
    ▷ Recursively compute the next try starting from the position of the winner vehicle in D
        end if

        $prevPos = initPos \leftarrow pos^*$, $endPos \leftarrow pos^* + R_{tx}$, $p \leftarrow (S \cdot p)$
                              ▷ Update packet position, hop limits and probability of occurrence
    end while
end function
ComputeNextTry(0, $R_{tx}$, 1, 0)                            ▷ Initialization of the algorithm
```

Figure 3: Algorithm for computation of multi-hop metrics.

- Due to the above reason, the metrics have to be weighted by the number of nodes that actually would measure them. It is done in the functions though, for the sake of clarity, we do not show it in the algorithm in Fig. 3. In addition, in the last hop, the mean access delay returned by `ComputeMetrics` is that of eq. (23) in order to take into account successive collisions in the last hop.

- The outcomes we neglect contribute mainly to the mean channel access delay and the position of the winner vehicle, whereas have less influence on the end-to-end delay.
- Our evaluation framework provides enough flexibility to extend it to several scenarios and define alternative performance metrics. In fact, the computation of the metrics in case of collision only requires to substitute $\mathbf{P}$ by $\mathbf{P_e}$ and sum over the corresponding indexes, as discussed in the Appendix. The accuracy could be enhanced by considering actual distances between vehicles, though it is left as future work. In addition to that, different distributions for vehicle positions could also be used seamlessly.

As we show in Section 5.2, our simulation results validate this approximation even though in the simulations are included more realistic effects, such as, SINR evaluation or capture effects.

5. Validation and performance evaluation results

In this section we verify the correctness of our analytical model and perform a comparative study between some of the selected protocols, as well as an evaluation of the influence of different parameters on the performance metrics.

The protocols considered in the comparative study are shown in Table 2, including a standard contention procedure labeled as “Uniform”. We exclude from the evaluation those protocols that need too much extra context information, except for Fast Broadcast, for which we have implemented the transmission range estimation. We consider at least one protocol from each category and we use a parameter, K, to homogenize the size of the contention windows for the different protocols, trying to make the comparative study as fair as possible. All the values are presented in Table 2 as a function of the parameter K. For the proposals based on position we assume they know their position exactly, and those based on groups use a number of m groups. For EDCA* we have defined a map that replicates that of Smart Broadcast, that is, there are m groups and higher priority access categories are assigned to more distant groups.

Table 2: Deterministic delays and contention window sizes for the protocols under evaluation

Protocol	**Delay and contention window size**
Uniform	$t_D = DIFS$, $CW = 2K - 1$
Fast Broadcast	$t_D = DIFS$ $CW_{min} = K - 1$ $CW_{max} = 4K - 1$
EDCA*	$AIFSN[0] = 9, CW[0] = 2K - 1$ $AIFSN[1] = 6, CW[1] = 2K - 1$ $AIFSN[2] = 3, CW[2] = K - 1$ $AIFSN[3] = 2, CW[3] = K/2 - 1$
Smart Broadcast(with $m = 4$)	$t_D = DIFS$ $I_1 = [0, K - 1], I_2 = [K, 2K - 1]$ $I_3 = [2K, 3K - 1], I_4 = [3K, 4K - 1]$
Sift	$t_D = DIFS$, $CW = 2K - 1$
COMIC	$t_D = DIFS$, $CW = 2K - 1$

Table 3: Parameters used in the evaluation

Parameter	**Fig. 4**	**Fig. 5**
λ	$[0.03, 0.27]$ veh/m	0.21 veh/m
K	16	$[16, 64]$
L_{Pkt}	768 μs	
σ	9 μs	
DIFS	28 μs	
SIFS	10 μs	
R_{tx}	300 m	
$dist(Dest)$	600 m	
Hop Limit (HL)	10	

To validate our analysis, we have simulated the procedures with the OMNeT++ network simulator and its inemanet 2.0 extension [26]. In the simulations, the source sends a new packet every 10 s. All the simulations are run for 5000 s and all the scenarios, for every vehicle density, have been replicated with different seeds. For all the metrics, their 95% confidence intervals have been computed and are shown as error bars in the figures. Let us note that there are slight differences in the simulation with respect to the ideal situation analyzed in previous sections. The simulations are more realistic in the sense that nodes involved in a packet collision are not aware of the collision. Since there are no acknowledgments or error recovery, the involved nodes do not participate in a retransmission.

The evaluation is conducted for the scenario described at the beginning of the present section, varying the vehicle density and the size of the contention windows (with the parameter K). The values of the parameters used for the performance metrics computation are enumerated in Table 3. We consider no background data traffic, so that only the broadcast message is propagated over the network. The impact of node mobility is disregarded in this paper, since the variation of node positions is negligible for the duration of a packet exchange[3] and it has a minor influence on the performance of message broadcast with high data rates and short safety message lengths [27].

5.1. Single-hop Scenarios

First, we validate our model in a single-hop scenario with a deterministic free-space signal propagation model, where all the nodes are in range of each other. Therefore, all the proposals based on knowledge of the transmit range, R_{tx}, are using the exact value. Fig. 4 shows the performance metrics computed for different values of the vehicle density, while keeping the parameter K fixed to 16. The lines represent the results of our analytic model, averaged over 50 Poisson vehicle distributions per density, whereas the marks refer to the results obtained from the OMNeT++ simulation, with 30 replications per density. We only show results for success probability, average position of the winner vehicle and average access delay.

As expected our performance model approximates very well all the performance metrics, in spite of being more pessimistic. The mean square errors between our model and simulations do not exceed 0.07 for the probability of success, 6 m for the mean forwarder position and 353 μs for the mean access delay. As we said, for proposals prone to collision, such as EDCA*, fewer nodes participate in successive retransmissions (as expected in reality), which increases the success probability and decreases the mean access delay measured by the simulations. This is the reason for the differences observed between the analysis and simulation, specially for high vehicle densities. In Fig. 4(a), we can see how the Sift protocol outperforms the rest of them with respect to success probability, since it is an approximation of the optimal distribution that can be used in this scenario. EDCA*, on the contrary, shows poor performance due to the use of too small window sizes and overlapped CW ranges, whereas Smart Broadcast benefits from greater window sizes and disjoint contention windows. In the cases of Uniform, Fast Broadcast and EDCA*, the poor success probability is reflected in high access delays,

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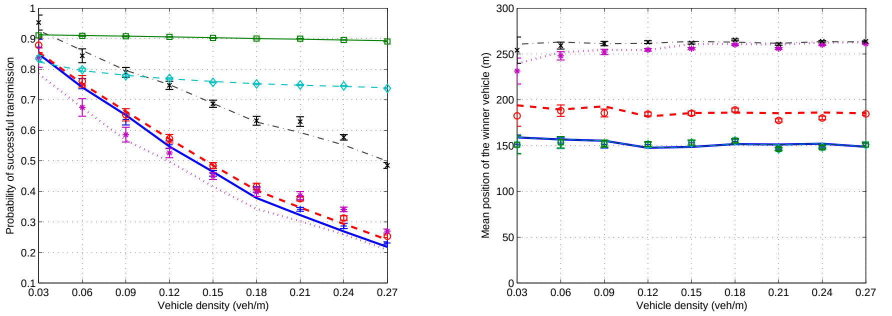
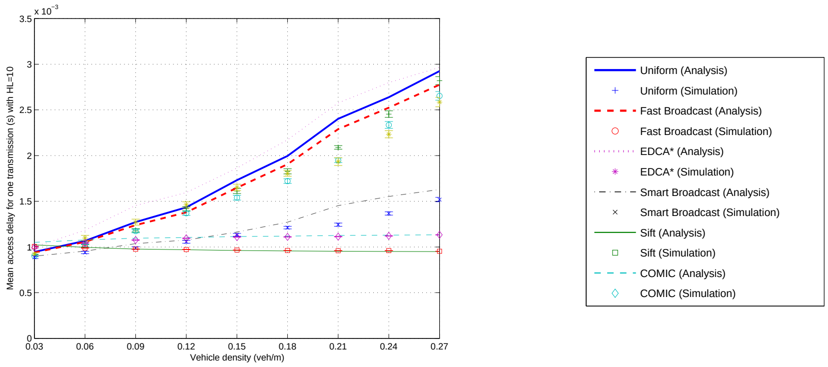
[3] In 10 ms, which is above the maximum end-to-end delay we obtain, a vehicle moving at 32 m/s only advances 0.32 m.



(a) Probability of successful transmission.

(b) Average position of the winner vehicle (m).



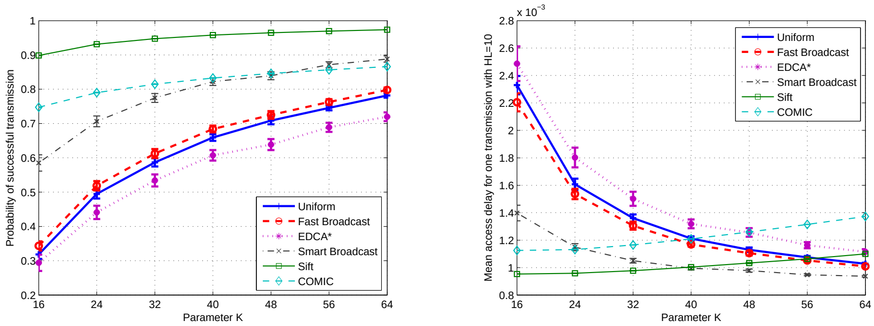
(c) Average delay for one successful transmission (s).

(d) Legend.

Figure 4: Performance metrics for vehicle densities varying between 0.03 and 0.27 veh/m and parameter $K = 16$. Single-hop scenario with all vehicles in range.

as shown in Fig. 4(c). However, the high success probability of Sift and COMIC is the reason for their low access delay, and more importantly, in both cases it is independent of the vehicle density, whereas the performance of the other proposals noticeably degrades as the number of vehicles in range increases.

However, as we said before, Sift and COMIC, being general-purpose proposals, do not take into account the position of the nodes. Therefore, all the vehicles have equal probability of success, and so the average position of the winner vehicle is in the middle of the range. On the contrary, both Smart Broadcast and EDCA*, and to a lesser extent Fast Broadcast, achieve their goal of increasing the average advance of the packet, *provided there is success*. It is shown in Fig. 4(b), where a higher value is considered better,



(a) Probability of successful transmission.

(b) Average delay for one successful transmission (s).

Figure 5: Performance metrics for parameter K varying between 16 and 64 with vehicle density fixed to 0.21 veh/m. Single-hop scenario with all the vehicles in range.

since in an emergency warning scenario and other situations it is usually assumed that the warning message has to advance as quickly as possible. Obviously in a single-hop situation packet advance is irrelevant, so we have to turn to multi-hop scenarios to find if this optimization is a real advantage for geo-routing or it is simply better to achieve a high success probability.

Before discussing multi-hop scenarios we examine the influence of the contention window size on the proposals. Once our model is validated, we can safely evaluate further experiments without requiring simulations. Fig. 5 illustrates the performance metrics computed for different values of the contention window size, while keeping the vehicle density fixed to 0.21 veh/m. Again, the computation is conducted through a Monte Carlo simulation with 50 replications per contention window size and the 95% confidence intervals are shown as error bars.

The success probability increases for all the proposals when increasing the contention window size, and it is more stable for the Sift and COMIC protocols. In fact, except for them, the rest of protocols clearly benefit from higher contention window sizes, reducing significantly the channel access delay. Obviously, the small extra delay due to higher window sizes is amply compensated by avoiding the delay due to collisions. For Sift and COMIC, on the contrary, the delay is slightly higher. This is due to the definition of the distribution for the slot selection, which concentrates the probability on the last slot (Sift) or on the middle one (COMIC), and therefore it grows with the contention window size. As expected, the influence of the contention window size on the position of the forwarder is not significant and it does not appear in the figure.

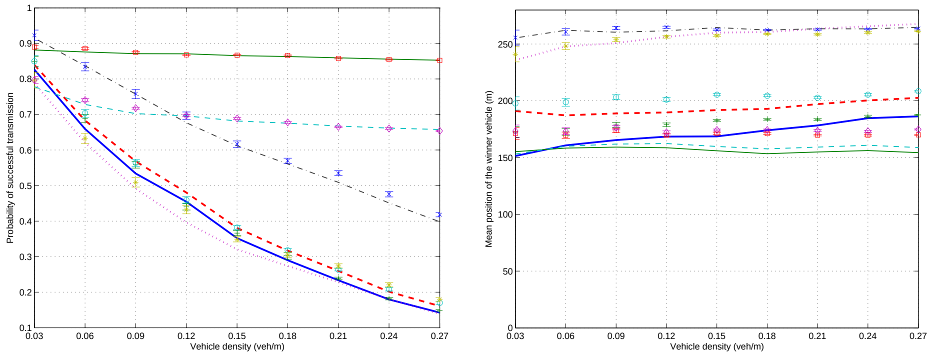
5.2. Multi-hop Scenarios

In this case vehicles are located on a road segment of 600 m of length and we set a deterministic free-space propagation model with transmission range $R_{tx} = 300$ m. These particular values are arbitrary and could have been scaled up, considering that the total number of contending vehicles is what have influence in the results. In real deployments one should probably expect higher transmission ranges. We think that two hops is also a reasonable distance as range for emergency messages, though the evaluation framework can be used with more hops. This scenario has also been simulated with OMNET++ with the same settings: the source sends a message every 10 s and simulations are run for 5000 s. All the simulations have been replicated 40 times to better capture the influence of position on the result. The rest of parameters are shown in Table 3. For our algorithm a Monte Carlo simulation is run and averaged over 40 replications per density.

In Fig. 6 we show the results again for probability of success, average channel access delay, average position of the winner vehicle and we have added the relevant metric end-to-end delay. First, as can be observed again the simulations validate our evaluation model, in particular our approximation for multi-hop scenarios. The mean square errors between the evaluation and the simulations do not exceed 0.031 for probability of success, 15.4 m for position, 115 μs for mean channel access delay and 97 μs for the mean end-to-end delay. Therefore, our evaluation framework provides a simple yet accurate tool to test this type of proposals. In a later section we exemplify its utility also as a design tool for alternative proposals made up as combinations of the considered ones.

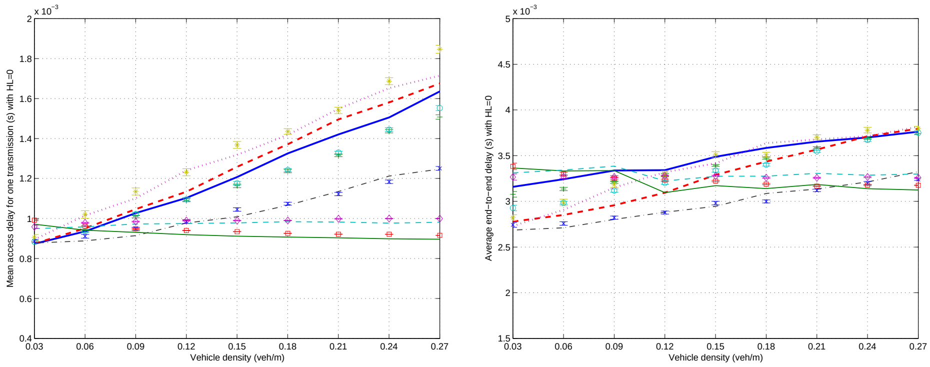
Regarding the performance of the different mechanisms, there is little variation with respect to the conclusions stated for one hop. The probability of success has decreased for all of them, but it should be recalled that we only assign success when all the nodes in range receive the packet. The probability of success for Sift and COMIC remains remarkably high because it is almost independent of the number of contenders [9]. This is again reflected in the average channel access delay.

It is also relevant for the end-to-end delay although not as much as should be expected. As can be seen in Fig. 6(d), the benefits of making the packet advance as much as possible are only noticeable for low vehicle densities. For EDCA* and Fast Broadcast the delay penalties due to the high number of packet collisions take over any advantage due to making the packet advance as much as possible, except for very low vehicle densities, even though the



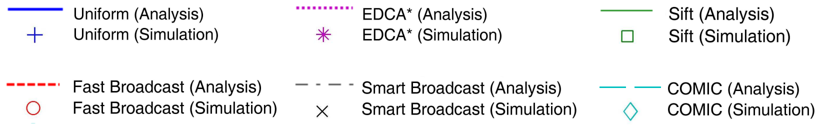
(a) Probability of successful transmission.

(b) Average position of the winner vehicle (m).



(c) Average channel access delay (s).

(d) Average end-to-end delay (s).



(e) Legend.

Figure 6: Performance metrics for vehicle densities between 0.03 and 0.27 veh/m and parameter $K = 16$. Multi-hop scenario with a length of 600 m and $R_{tx} = 300$ m.

end-to-end delay benefits from "advance" in case of collision, which makes this metric lower than expected if it was computed as the sum of the average channel access delay over the number of hops.

Let us also remark that the real goal for an emergency warning should be to reach as many vehicles in the vicinity as possible, that is, inform all nodes, rather than to quickly reach a distant location. In this sense, achieving lower end-to-end delays may be misleading because in a packet collision the packet may be received by a distant neighbor but lost for most of the closer ones. However, we have checked, though is not shown in the figures, that under ideal channel conditions, the time to inform all nodes is actually only slightly higher than the end-to-end delay. The reason is: for the proposals that do not take into account the position of the forwarders (Uniform, Sift, COMIC) the position of the nodes that determine the advance in case of collision (pc_1 and pc_2) are quite separated, around 2/3 of R_{tx} which implies that around 2/3 of the vehicles in the following hop are informed even when a collision occurs. On the contrary, the proposals that tend to concentrate the forwarders in a more distant sector also result in a narrower area of correct packet reception and do not benefit from this effect.

The overall conclusion from the above discussion is that, for this kind of emergency applications, it is preferable to achieve better probability of success rather than trying to make the packet advance as much as possible, especially when the latter requires an increase in the complexity of the implementation. Moreover, these delay penalties due to collisions depend on the packet size, so for greater sizes one should expect worse results. On the contrary, increasing the contention window size results in a general improvement for high vehicle densities and it tends to equalize the performance of the proposals.

6. Evaluation of Alternative Proposals

Our performance evaluation framework can be used as a quick design tool for new or alternative proposals. In this section we exemplify it and test the use of combined procedures in order to obtain the best of each one. More specifically, we wish to obtain a method with such a high and stable success probability as the Sift distribution, while getting a forwarder positioned as far as possible. To this aim we proposed in [25] two modifications to the Sift distribution which improve its performance with respect to the position of the forwarder, but not to the mean access delay. Here we additionally test the results of combining the Smart Broadcast and the Fast Broadcast with the Sift distribution.

Next, we briefly describe the two proposals in [25], as well as the new ones.

- **Weighted Sift**

  The first approach consists of weighting the Sift distribution according to the respective position of vehicles within the transmission range of the source node, assigning a higher success probability to the more distant nodes. For each contending vehicle v, the probability of choosing the slot j is given by:

$$g(i,j) = \begin{cases} \gamma_i \cdot g_{CW}(j), & j = 0, \dots, CW-1 \\ 1 - \gamma_i \sum_{k=0}^{CW-1} g_{CW}(k), & j = CW \end{cases} \tag{24}$$

where g_{CW} is the Sift probability distribution over CW slots, as defined in eq. (12). The details on how to properly select the coefficients γ_i can be found in [25]. Let us note that in this case the contention window size is fixed but each vehicle uses a slightly different contention distribution.

- **Per Groups Sift**

  The second method proposed in [25] is a variation of overlapped contention windows. In particular, as we assume the priority is given by the position, we divide the transmission range into m intervals. The group of vehicles located in each of these intervals select their contention slots by using the Sift probability distribution with different values for the contention window size (lower values for higher priorities). Therefore, for each group of vehicles G_j, $j \in \{1, \dots, m\}$, we associate a contention window size CW_{G_j}. Hence, the probability distribution used by all the vehicles in that group is the following:

  $$h_{CW_{G_j}}(r) = g_{CW_{G_j}}(r), \quad r \in \{1, \dots, CW_{G_j}\}, \tag{25}$$

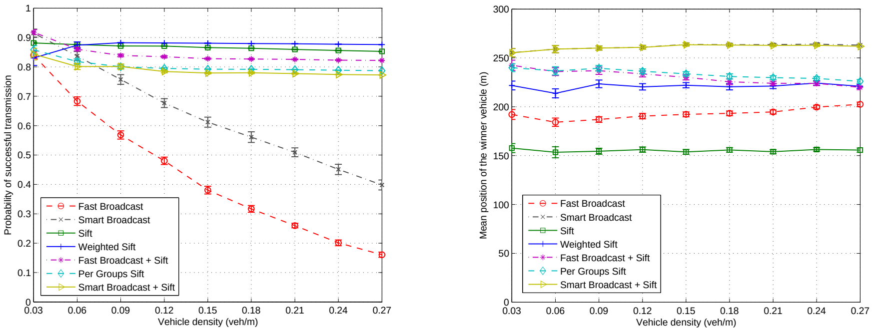
  where $g_{CW_{G_j}}$ is the Sift probability distribution over CW_{G_j} slots, as defined in eq. (12). Let us note that this procedure is similar to Smart Broadcast but with overlapped contention windows and a different distribution.

- **Fast Broadcast + Sift**

  In this case the contention window for each vehicle is computed according to its position with eq. (4), as in the Fast Broadcast protocol. However, instead of selecting the random delay $t_R(v)$ uniformly, each vehicle uses the corresponding Sift distribution over $CW(v)$ slots.

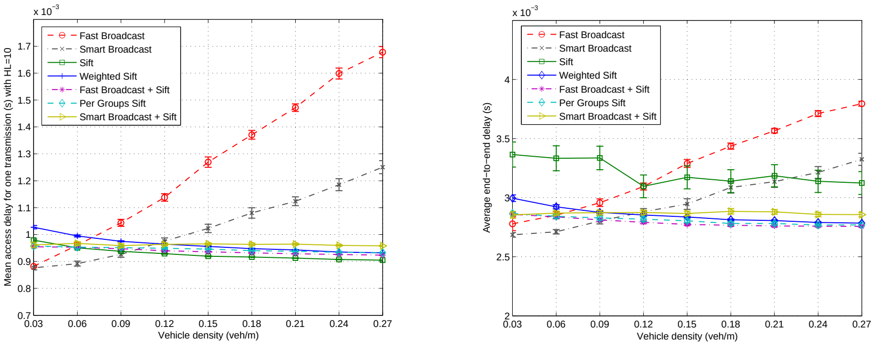
- **Smart Broadcast + Sift**

  Similarly, in this proposal each group of vehicles is assigned a contention window as in the Smart Broadcast protocol, but the random



(a) Probability of successful transmission.

(b) Average position of the winner vehicle (m).



(c) Average channel access delay (s) with HL=10.

(d) Average end-to-end delay (s).

Figure 7: Performance metrics for new proposals for vehicle densities between 0.03 and 0.27 veh/m and $K = 16$ in a multi-hop scenario.

delay t_R is selected using the Sift distribution instead of the Uniform one.

To qualitatively assess the evaluation time savings with respect to the regular simulation approach, consider the process of evaluation of this new proposals: one only needs to construct the delay probability matrix $\mathbf{P}$ for the alternative proposal and simply pass it as parameter to the Matlab scripts which compute the performance metrics (both single and multi-hop). That is, each new proposal requires only its corresponding matrix to be evaluated. This is not usually a complex task, provided the protocol description is clear. For instance, to evaluate COMIC instead of Sift we would only need to substitute the probability of choosing a slot with eq. (13) in the corresponding elements of the matrix. It provides a rather quickly method for evaluation of iterative modifications to an initial design.

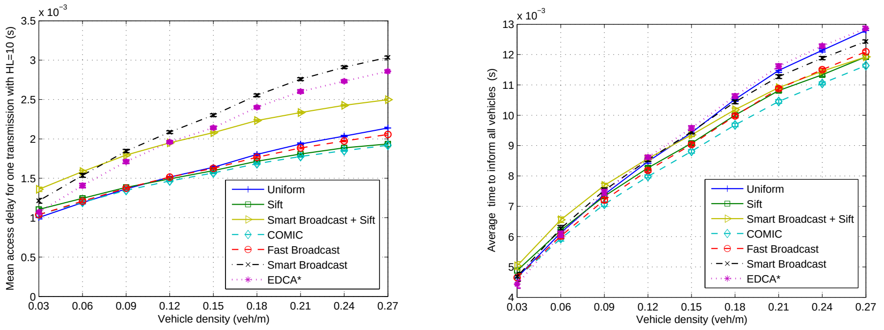
Fig. 7 we show the resulting performance metrics for the described proposals, as well as for the usual Sift, Fast Broadcast and Smart Broadcast protocols, in order to compare them. These performance metrics are computed for different values of the vehicle density parameter and $K = 16$. The results reveal that all the new proposals achieve a higher success probability than the original ones for Fast Broadcast and Smart Broadcast, getting closer to the Sift success probability and achieving a similar stability with respect to the number of vehicles.

Regarding the average winner vehicle, or forwarder position, the improvement is even more significant. For the Weighted Sift, the Fast Broadcast + Sift and the Per Groups Sift, the forwarder position is farther than for Sift and Fast Broadcast. On the other hand, a slightly lower distance is achieved for the Smart Broadcast + Sift, but the latter results in much higher success probabilities and lower channel access and end-to-end delays.

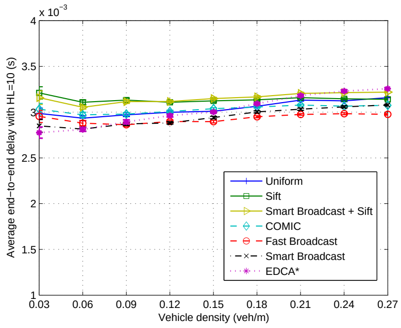
According to these results the intended goals are accomplished, and it seems reasonable to combine Smart Broadcast and Sift, since the implementation may be simpler than for the other ones. In any case, our main goal in this section has been to show the usefulness of our framework as a quick (no need of simulations) evaluation and design tool.

7. Realistic scenarios

Up to this point, we have compared the contention mechanisms that involve random procedures under ideal assumptions, such as deterministic free-space propagation. In this section we evaluate the standard CBF specification [4] implemented at the network layer and introduce more realistic effects. On the one hand, it has been shown that radio propagation in vehicular networks is subject to strong fading [28]. In that case, the assumptions for our evaluation model do not hold anymore, since there is a chance that nodes in the close vicinity of a contender do not sense the channel busy and defer transmission. Therefore, we have simulated the proposals, as well as the standard CBF, using a more realistic fading model. In particular, we use the Nakagami-m distribution, which can model a wide class of fading channel conditions and fits well the empirical data [28]. The noise level is set to -110 dBm and the sensitivity to -85 dBm. In addition, the simulator takes into account capture effects, since packets are only discarded when the *Signal to Interference Noise Ratio* (SINR) is below 4 dB. On the other hand, both real timers and location information have a certain accuracy. These



(a) Average channel access delay. (b) Average time to inform all vehicles.

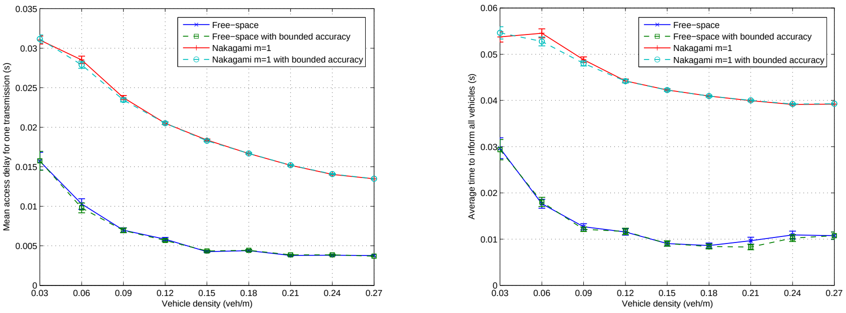


(c) Average end-to-end delay.

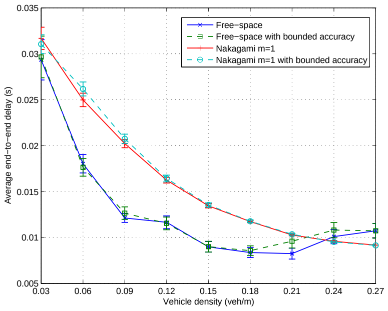
Figure 8: Performance metrics for vehicle densities between 0.03 and 0.27 veh/m and parameter $K = 16$. Multi-hop scenario with Nakagami-m fading model with $m = 1$.

effects may have particular influence on the deterministic CBF algorithm and have been simulated as well.

Performance metrics for the previous proposals in a strong fading scenario, modeled by Nakagami-m with m=1, are shown in Fig. 8. In presence of strong fading the basic carrier sense medium access is broken, since neighbor nodes may not sense the channel busy due to transmissions. The probability of reception decreases with the distance to the source, and with the simulated parameters, on average, 12% of nodes in the R_{tx} range do not receive a given transmission [29]. Therefore, specifically designed MAC mechanisms have little influence on most of the evaluated metrics. Let us recall that, in realistic situations, packet collisions are experienced locally and so we cannot use the global notion of probability of success anymore. Therefore, we use average delays to evaluate these scenarios. As can be seen in Fig. 8(b) and 8(c), both the average time to inform all nodes and the



(a) Average channel access delay. (b) Average time to inform all vehicles.



(c) Average end-to-end delay.

Figure 9: Performance metrics of GeoNetworking for vehicle densities between 0.03 and 0.27 veh/m and parameter $K = 16$. Multi-hop scenario with free-space and Nakagami-m fading model with $m = 1$. Clock accuracy set to $1\mu s$ and position accuracy set to 1 m.

average end-to-end delay are almost independent of the MAC mechanism in use. Strong fading actually benefits the end-to-end delay since there is a chance that packets reach directly the destination even if it is out of the ideal deterministic range R_{tx} of the forwarder. In addition, as discussed before, packet always effectively advances, even in the presence of collisions. The overall result is that end-to-end delay is practically independent of the MAC mechanism and the vehicle density. On the contrary, vehicle density has more influence on the time to get all nodes informed. As in the ideal case, it is directly related to the average channel access delay, and it increases with the vehicle density, but there is little difference between proposals.

If we look at the average channel access delay in Fig. 8(a), proposals with good performance in ideal scenarios, such as Smart Broadcast and Smart Broadcast + Sift, remarkably increase their channel access delay in realistic scenarios. The cause of this performance degradation is actually the fact that they have been designed to maximize the distance of the forwarder to the source. Accordingly, the more distant nodes select earlier slots, win contention and transmit, but then, since reception probability decreases with the distance, nodes closer to the source have a higher probability of not sensing the channel busy by the far away transmitters and so they also transmit, generating collisions. On the contrary, in the proposals that do not attempt to maximize the packet advance, the forwarder is at the middle of the range on average and so its transmission has a higher probability of being sensed by the surrounding nodes. That is, the MAC mechanism works properly more frequently. As the vehicle density increases, there are simply more packet collisions, though the use of Sift slightly improves the probability of success in the group closer to the source for Smart Broadcast + Sift.

The conclusion from these results is that any new proposal which intends to optimize the operation of GeoNetworking must take into account in its design the effects of realistic radio propagation models. In fact, as we discuss next, the basic CBF protocol specified by the standard works remarkably well under realistic conditions.

GeoNetworking CBF specifies that upon reception of a packet, nodes start a deterministic timer, *to*, whose value depends on the distance to the source, that is, $to(v) = maxTime + (minTime - maxTime) dist(x_s, x_i)/R_{tx}$. The goal is to select the most distant node as next forwarder. The standard specified parameters are $maxTime = 100\ ms$ and $minTime = 1\ ms$, and we set $R_{tx} = 300\ m$ to compare with previous proposals. Nodes use the standard IEEE 802.11p as MAC layer with a contention window of 32 slots. In Fig. 9 we show the average channel access delay, average time to inform all vehicles and average end-to-end delay for the standard GeoNetworking CBF. From these results it is clear that CBF GeoNetworking works well in all the cases. Moreover, its performance improves as the vehicle density increases, since there are more nodes available to forward the packets. Limited accuracy in vehicle position and timers has little influence on the performance. Delay values are higher than for MAC implementations, as expected, but they actually depend on the configured values for *maxTime* and *minTime*, and there is margin for tuning them. Let us just mention that, for the ideal free-space case, there are scenarios for the standard GeoNetworking CBF where no packet is actually transmitted. The reason is that the particular fixed positions of the vehicles result in continuous collisions. However, this pathological scenarios should be very rare in dynamical situations.

8. Conclusions

In this paper we provide a new performance evaluation methodology and fair comparison of the most relevant MAC-network cross-layer proposals for efficient geo-routing in the context of vehicular networks. Different contention-based mechanisms are described and a unified formal description is extracted. This formal description is later used in a common framework for their performance analysis in the critical scenario of emergency messages delivery. As a novelty, our performance model allows to analyze the case in which each vehicle selects its contention slot in a different way. Moreover, it is flexible enough to accommodate the evaluation of multi-hop effects by simple extensions of the delay probability matrix.

This model has been used to rigorously evaluate the selected proposals both in single-hop and multi-hop scenarios under ideal propagation conditions. Additionally, the evaluation has also been done by simulation, whose results further validate our approach. The evaluation shows the strengths and weaknesses of the different mechanisms and allows to conclude that in most cases it is preferable to achieve better success probability rather than trying to make the packet advance as much as possible, at least for small contention window sizes. We have also evaluated the proposals under more realistic channel fading conditions. This has been done by simulation, since our model cannot be directly applied to these cases. In this situation, however, there is actually little difference in the performance of the protocols. In fact, those proposals which attempt to maximize the progress of the packet suffer a noticeable degradation in performance. On the contrary, the basic CBF protocol specified by the GeoNetworking standard performs well in most of the cases.

According to these results, our next step is to modify our analytical model to introduce realistic radio propagation effects. In this case, major modifications of our model are needed since the reception probabilities depend on the positions of the receivers and there is no global notion of probability of success. We plan also to work on new MAC proposals which take into account those effects in their design.

9. Acknowledgements

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Appendix A. Computation of pc_1 and pc_2

In this section we show how to compute the performance metrics in case of collision of a multi-hop scenario.

Two vehicles i and j are the more distant vehicles involved in a collision in slot r if the following conditions are met: (1) Both i and j select slot r; (2) no other vehicle selects a slot previous to r and (3) no vehicle between i and j, and no vehicle after j, selects slot r. From them we can express the corresponding probability as:

$$\begin{aligned} G(i,j,r) = \mathbf{P}(i,r)\cdot\mathbf{P}(j,r)\cdot\prod_{k=1}^{i-1}\left(1-\sum_{s=1}^{r-1}\mathbf{P}(k,s)\right)\cdot \\ \cdot\prod_{l=i+1,l\neq j}^{N}\left(1-\sum_{s=1}^{r}\mathbf{P}(l,s)\right). \end{aligned} \tag{A.1}$$

Then, summing over r we obtain the probability that i and j are the more distant vehicles which collide in any slot. And we compute the average indexes summing over all the vehicles:

$$\begin{aligned} E(i) &= \sum_{i=1}^{N}\sum_{j=1}^{N} i\cdot(\sum_{r=0}^{W} G(i,j,r)) \\ E(j) &= \sum_{i=1}^{N}\sum_{j=1}^{N} j\cdot(\sum_{r=0}^{W} G(i,j,r)). \end{aligned} \tag{A.2}$$

Finally, we interpolate $E(i)$ to its corresponding position in ve to obtain pc_1 and $E(j)$ to obtain pc_2.

Appendix B. Computation of the collision metrics

We start from the delay probability matrix $\mathbf{P}$ corresponding to the nodes involved in the collision, that is, the nodes in the segment between the previous source and R_{tx}, which corresponds to segments A, B and C in Fig. 2. The additional contenders in the next attempt resulting from the correct reception of the packet are the nodes between $pc_1 + R_{tx}$ and $pc_2 + R_{tx}$, that is, those in segment D according to Fig. 2. We can construct their corresponding delay probability matrix $\mathbf{P_D}$. In order to compute the relevant metrics of all the vehicles contending after a collision, that is, all vehicles in segments A, B, C and D shown in Fig. 2, we construct an extended matrix for the probability of selecting a given delay, $\mathbf{P_e}$, simply concatenating both delay probability matrices:

$$\mathbf{P_e} = \begin{pmatrix} \mathbf{P} \\ \mathbf{P_D} \end{pmatrix}. \tag{B.1}$$

Therefore, the dimension of this new matrix $\mathbf{P_e}$ is $N_e \times W_e$, where N_e is the total number of vehicles in all the segments and $W_e = \max_i t_L(v)$. Once we have the extended matrix, the computation of the performance metrics is analogous to those of eq. (15) to (23) but using the extended matrix and the indexes corresponding to the vehicles involved in each case. As illustrative examples of this consider the following two. First, there is success in segment C when a vehicle in that segment transmits before any other vehicle in that or any other segment. Accordingly, the probability of success of a vehicle in segment C which selects slots r becomes:

$$S^C_{v,r}(\mathbf{P_e}) = \mathbf{P_e}(i,r) \prod_{j=1, j\neq i}^{N_e} \left(1 - \sum_{k=0}^{r} \mathbf{P_e}(j,k)\right), \tag{B.2}$$

which has the same form as eq. (15), but now the computation of the probability of success for segment C in a specific slot ($S_r^{S,C}$), for a specific vehicle ($S_v^{V,C}$) and the total probability (S^C) has to be summed only over the indexes corresponding to the vehicles in C, that is:

$$S^C(\mathbf{P_e}) = \sum_{i\in C} \sum_{r=0}^{W_e} S^C_{v,r}(\mathbf{P_e}). \tag{B.3}$$

Similarly, we define that there is success in segment D when a vehicle in that segment transmits before any vehicle in segments B and C. Since nodes in segment A are not in range of nodes in segment D a collision experienced by some of the nodes is unavoidable. As discussed before we neglect its influence on the metrics. In this case, the probability of success of a vehicle v in D in slot r has to be computed excluding nodes in A, that is:

$$S^D_{v,r}(\mathbf{P_e}) = \mathbf{P_e}(i,r) \prod_{j\in(B,C,D), j\neq i} \left(1 - \sum_{k=0}^{r} \mathbf{P_e}(j,k)\right), \tag{B.4}$$

and the total probability of success in segment D becomes:

$$S^D(\mathbf{P_e}) = \sum_{i \in D} \sum_{r=0}^{W_e} S^D_{v,r}(\mathbf{P_e}). \tag{B.5}$$

The rest of metrics can be computed in the same way. Let us note that the indexes of the nodes that belong to each segment are directly obtained once the indexes (position) of the more distant nodes involved in a collision are computed in eq. (A.2) above.

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