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RESEARCH ARTICLE

About Deterministic and non-Deterministic Vehicular Communications over DSRC/802.11p

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ABSTRACT

In this work, we introduce a priority-aware deterministic access protocol called Vehicular Deterministic Access (VDA). VDA is based on 802.11p/DSRC and allows vehicles to access the shared medium in collision-free periods. Particularly, VDA supports two types of safety services (emergency and routine safety messages) with different priorities and strict requirements on delay. To avoid long delays and high packet collisions, VDA allows vehicles to access the wireless medium at selected times with a lower contention than would otherwise be possible within a two-hop neighborhood by the classical 802.11p Enhanced Distributed Channel Access or Distributed Coordination Function schemes. A non-VDA-enabled vehicle, that is, a vehicle not configured with the optional VDA capability over 802.11p, may start transmitting on the shared channel just before or during the VDA opportunities reserved for vehicles with VDA capabilities. To avoid the aforementioned issues and prevent interfering transmissions from VDA-enabled vehicles and non-VDA-enabled vehicles, we also proposed a novel scheme called extended VDA. We analyzed the impact of several design tradeoffs between the contention free period/contention period dwell time ratios on the performance of safety applications with different priorities for VDA and extended VDA. Simulations show that the proposed schemes clearly outperform the backoff-based schemes currently used by 802.11p in high communication density conditions while bounding the transmission delay of safety messages and increasing the packet reception rate. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
vehicular *ad hoc* networks; contention free; safety messages; deterministic access; VDA; non-VDA

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1. INTRODUCTION

Vehicular *ad hoc* networks (VANETs) are currently considered a key technology for bringing more safety on the road. The Federal Communications Commission of the USA approved the 75 MHz bandwidth at 5.850–5.925 GHz band for Intelligent Transportation Systems. This wireless spectrum is commonly known as the dedicated short-range communication (DSRC) spectrum allocated for an exclusive use by vehicle–vehicle (V2V) and vehicle–road (V2R) communications. Devices operating in DSRC spectrum will be using IEEE 802.11p by following the Wireless Access in Vehicular Environments (WAVE) operation mode [1].

There has been a vast literature [2–7] on the description and evaluation of DSRC and VANET technologies. A thorough survey can be found in [3]. Existing works that use DSRC/802.11p stress the importance of meeting the strict delay and low packet collisions requirements of safety applications, especially in high offered-load conditions. These works that try to find adequate solutions to different issues can roughly be divided into three categories: broadcast enhancement schemes [4], Medium Access Control (MAC) layer solutions for backoff algorithm improvement [2], and communication rate and/or power adjustment strategies [7].

Whereas a few works contribute on establishing delay bounds to guarantee a short delay in IEEE 802.11p [8,9], our novel proposed approach for Vehicular Deterministic Access, called VDA, complements previous solutions in terms of stringent delay bounds for safety messages; a preliminary version of VDA appears in [9]. VDA extends the typical 802.11p/DSRC medium instantaneous reservation procedure with a more advanced reservation procedure using scheduled VDA opportunities (VDAOPs) within a two-hop neighborhood. VDAOPs are first negotiated between neighboring vehicles by exchanging broadcast setup messages, and then VDAOP reservations are performed in multiples of a time-slot unit, during the delivery traffic indication message (DTIM) periodic interval. VDA scheme has been introduced as an option that is integrated to 801.11p protocol to allow vehicles using DSRC spectrum to have a deterministic access to the medium instead of the traditional 802.11/DCF or 802.11/EDCA MAC layer. Distributed Coordination Function (DCF) and Enhanced Distributed Channel Access (EDCA) schemes adopted in 802.11p have been shown to require improvements in their backoff algorithm [2,10]. Without such improvements, the scalability of 802.11p in dense vehicular environments can be undermined. In [10], the authors proposed a Space Orthogonal Frequency Time MAC (SOFT MAC) scheme, which allocates guaranteed transmission slots via reservations and uses a random access period for best effort traffic. This protocol provides a performance that is comparable with that of a random access under low traffic and to that of TDMA under heavy traffic, but authors evaluated only the network throughput, which is desirable for routine or private messages. To the best of our knowledge, we are the first to consider deterministic access as an option integrated with IEEE 802.11p to provide a strict delay for emergency messages.

Vehicular Deterministic Access scheme presents several advantages; it establishes delay bounds to guarantee a short message delivery delay in IEEE 802.11p, and subsequently, it complements previous solutions in terms of stringent delay bounds for safety messages. Besides, it processes two types of safety services (emergency and routine safety messages) with different priorities and strict requirements on delay. VDA aims to ensure a very low delay, even for very high channel densities. This is very desirable because emergency messages usually involve urgent life-critical situations.

Guaranteeing a good interoperability in terms of shared channel access between transmitting vehicles that have the VDA option enabled in 802.11p/DSRC and interfering vehicles with no VDA option using the same channels is challenging. To overcome this shortcoming, we developed an extension to VDA, called extended VDA (EVDA), that prevents non-VDA-enabled vehicles (i.e., vehicles using 802.11p/DCF or 802.11p/EDCA access such as in [2]) from accessing the scheduled VDAOPs when these VDAOPs are used by vehicles using 802.11p with the VDA option enabled. In the literature, we can find an interesting work [11] that proposed an enhanced channel access mechanism that ensures guaranteed access to the medium during a periodic transmission opportunity by an owner node using a deterministic access by means of a reduced interframe space (IFS). The work also uses a pre-emption capability based on the presumption of nodes using the same messages size. The study is proposed for a specific kind of wireless network referred to as wireless mesh network. In opposition to VANETs, it is a static network with infrastructure that is based on mesh clients and mesh routers forming a backbone to connect to the internet. Also, in wireless mesh network, messages are usually delivered by routing and are acknowledged by receivers. In VANETs, nodes are highly mobile, and the main means of delivery of safety messages is broadcast. Additionally, different message sizes are allowed, and there is no use of acknowledgments. Therefore, the proposed solution cannot be applied in our context as proposed.

Our contributions in this paper can be summarized as follows: (i) we first present and justify the introduction of a deterministic medium access to reduce packet collisions in IEEE 802.11p, with a scheme that is similar to the Mesh Coordinated Channel Access (MCCA) scheme adopted for 802.11s, also called Mesh Deterministic Access [12–14]; (ii) we improve and adapt the deterministic access in the context of vehicular safety communication with two levels of safety services covering most of safety applications; we call the new scheme VDA; (iii) we derive analytically the corresponding expressions of the periodicity and VDAOPs duration to guarantee stringent delay bounds for safety messages; (iv) we take into account vehicles in the carrier sensing range to guarantee that none of these vehicles transmits/contends with the sender to ensure as high packet reception rates and as low collisions as possible; (v) we propose an extension to the VDA scheme, called EVDA, that prevents interfering vehicles without the VDA option from accessing the shared medium during the reserved time slots; (vi) we study the impact of varying the time ratio of contention free period/contention period (CFP/CP) on safety applications performance for the new schemes; (vii) we take into account the percentage of the number of VDA and non-VDA vehicles present in the network while scheduling the VDAOPs in EVDA; and (viii) we evaluate our schemes compared with standard 802.11p in terms of delay, throughput, and packet reception rates for both routine and emergency safety messages.

The remainder of the paper is organized as follows. Section 2 presents the motivation behind the integration of a deterministic access to IEEE 802.11p. Section 3 proposes our scheme named VDA and presents a mathematical formulation of the key parameters. Section 4 presents the EVDA extended scheme. Section 5 evaluates the proposed solutions and compares them to standard 802.11p via extensive simulations. Finally, Section 6 concludes the paper.

2. MOTIVATION FOR THE USE OF A DETERMINISTIC ACCESS FOR IEEE 802.11P

When supporting safety applications over DSRC/802.11p, we have to take into account strict requirements on low collisions and delays, especially for emergency messages such as Forward Collision Warning or Electronic Emergency Break Light that require strict delay bounds; otherwise, many envisioned future safety systems would be useless to help the driver deal with emergency situations, avoid accidents, and save lives. The main points that motivate us to consider/adapt a deterministic access such as MCCA standard [12,15] in IEEE 802.11p are as follows:

(1) Most of safety messages are based on direct or single hop broadcast communication among vehicles within the transmission range of one another. This is justified by the fact that if an emergency message happens, the vehicles potentially affected are those that are close to the sender. Therefore, direct communication is enough to reach potentially affected vehicles. MCCA is proven [12–17] to be more efficient within two-hop range than classical DCF/EDCF and to guarantee a short delay.

(2) In a low-load condition, where collisions are very rare, Carrier Sense Multiple Access (CSMA) coupled with backoff schemes such as DCF or EDCA provides lower delays than MCCA because the former transmits almost instantaneously in a random time slot. In a low-load condition, MCCA has a slightly higher delay than CSMA primarily because of the problem of non-contiguousness of the reserved time slots. MCCA waits longer periods before being able to transmit in specific reserved contiguous time slots. However, in high-load conditions, the delay with MCCA is bounded by x*DTIM [16], x being the maximum number of hops in a path ($x = 1$ for broadcast messages). The delay provided by CSMA increases without any bounds with the increase of the offered load. This is because many more nodes are contending for the same channel, causing many more collisions and resulting in both longer binary exponential backoffs and more frequent MAC retransmissions. Therefore, it is interesting to investigate/adapt a deterministic access such as MCCA over IEEE 802.11p to take advantage of the bounded delay guaranties it offers.

(3) Vehicle safety communication networks are entirely distributed *ad hoc* wireless networks, and MCCA is a distributed deterministic medium access.

3. VEHICULAR DETERMINISTIC ACCESS SCHEME: VEHICULAR DETERMINISTIC ACCESS

3.1. Current IEEE 802.11p Communication Scheme

IEEE 802.11p adopts IEEE 802.11a layer specifications with minor modifications. This is a random access scheme for all vehicles located in the transmission range of the sender based on CSMA with collision avoidance (CSMA/CA). IEEE 802.11p uses CSMA/CA with EDCA as in IEEE 802.11e or DCF as in IEEE 802.11a and also uses four priorities queues with different Backoff and arbitrary IFS (AIFS) parameters. Nevertheless, the Backoff process with EDCA involves high probabilities of collisions, especially in high offered-load conditions.

There are two types of safety messages: emergency safety messages (M_e) and periodic beaconing (or routine: M_r) safety messages. Whereas emergency messages happen only occasionally and require very high reliability, less collisions and short delay, routine messages are broadcasted by all vehicles at a frequency of 10–20 times per second. Routine messages hold information about the state of a vehicle such as its position and direction, and they require lower reliability and less stringent latency compared with M_e [2]. However, one of the main concerns about 802.11p is how it will perform when DSRC devices will be largely adopted, making high offered-load conditions very likely in dense vehicular traffic situations, while having continuous routine messages beaconing sharing the medium with more urgent life-critical event-driven emergency messages.

3.2. Introducing Vehicular Deterministic Access Scheme in IEEE 802.11p/DSRC

Vehicular Deterministic Access scheduling is based on MCCA concepts; therefore, we start by introducing MCCA before going into detailing our proposed scheme VDA to show what we added and modified in basic MCCA. The interested reader can find a detailed survey of the IEEE 802.11s standard in [14,18,19]. Please also note that Table I shows the main notations used to later on describe the VDA and EVDA schemes.

In basic MCCA [12], the time between consecutive DTIM (see Figure 1) beacon frames is divided into time slots of length 32 μs. The periodic broadcast of beacon frames to all radios in the same transmission range allows the synchronization of these DTIM intervals. MCCA standard [19] allows any node to reserve a time interval, called MCCA opportunity (MCCAOP), for transmitting data to a neighbor in a periodic manner (see Figure 2). Initially, nodes reserve the wireless medium for MCCAOPs, which are reserved as multiples of time slots during a given CFP of a maximum access fraction (MAF $= \alpha T$) of the DTIM interval T. The remaining part of the DTIM interval, as illustrated in Figure 1, is the CP used for throughput-sensitive rather than delay-sensitive data applications (it could be used in the context of VANETs, e.g., for private service messages, M_p). Note that MCCA does not support different services with different priorities and has the same behavior for all service messages in the network. However, VDA takes into account different priorities to different messages types. The message types illustrated in Figure 1 rather refer to VDA scheme.

We characterize each MCCAOP (in MCCA) /VDAOP (in VDA) reservation request for message k by the triplet $< O^k, \pi^k, \delta^k >_{k \in N}$ where O^k is the VDAOP offset from the DTIM start period, Π^k is the VDAOP periodicity within the DTIM period, and δ^k is the VDAOP duration in number of time slots. Π^k is the number of times the specified VDAOPs repeat themselves equidistantly within

Table I. Parameter notations.

DTIM	Delivery traffic indication message periodic interval time (T)
O^k	The VDAOP offset from the DTIM start period for request message k
Π^k	The VDAOP periodicity within the DTIM period for request message k
δ^k	The VDAOP duration in number of time slots for request message k
τ	The time slot duration
L_{M_x}	The packet size (including PHY and above)
C_{M_x}	The IEEE 802.11 transmission rate
N_{M_x}	The number of messages of type x
$D_{M_x}^{\max}$	The maximal delay for message type x
x	e: emergency, r: routine or p: private message
P_{RR}	Probability reception rate
β	The network density (vehicles/m)
R	Transmission range
R'	The carrier sensing range
N_C	The average number of vehicles in C is equal to $2\pi C$
C	R'–R denoted by C
δ_S	The duration in number of time slots for of the sender S
O_S	The offset from the DTIM start period of the sender S
$P_{S',C_S}(\delta_S, O_S)$	The probability that none of the vehicles S′ in range Cs transmits in the time slots allocated to the sender vehicle S in range R_S during the CFP period.
P_0	The probability that a vehicle has an event or a routine safety messages to transmit.
BO	Selected as a random integer in [0..CW]
BT	Backoff timer
DIFS	DCF interframe space duration
CW	Contention window
d'	Extra bounded delay
$P(N_C, C)$	The probability to have N_C vehicles per transmission range R′–R

VDAOP, Vehicular Deterministic Access opportunity; CFP, contention free period; DCF, Distributed Coordination Function.

a DTIM interval (T). In fact, all vehicles in the same transmission range are aware of the reservation schedule due to the broadcast of VDA advertisement messages by the VDAOP requester node and the granter vehicles [12].

We recall that a VDAOP is a period of time within every DTIM interval that is set up between the VDAOP owner and the addressed vehicle.

In VDA scheduling, $\delta^k_{M_x}$ is the number of time slots reserved for safety messages of type x (see Equation (1)) in each of the $\Pi^k_{M_x}$ (see Equation (2)) sub-intervals that satisfies a hard constraint on a maximal delay $D^{\max}_{M_x}$ for a maximum number of hops m in a path. $D^{\max}_{M_x}$ is the maximal delay $D^{\max}_{M_x}$ for message of type x. We assume that $M_x \in \{M_e, M_r\}$ where M_x represents the safety message of type x; x being equal to e if it is an emergency message, and r otherwise (i.e., routine message). We note that this transmission occurs after duration $AIFS_{M_x}$. To prevent exceeding the one-hop delay, the periodicity $\Pi^k_{M_x}$ in the VDA reservation request has to be sufficiently lower bounded by $\Pi^k_{M_x} \geq T/D^{\max}_{M_x}$. For the sake of simplicity, we consider a uniform distribution of $D^{\max}_{M_x}$ over interfering links even though a better repartition may take into account the non-uniformity of traffic load over these links. Thus, the VDAOP duration (Equation (1)) and periodicity (Equation (2)) are expressed as follows:

$$\delta^k_{M_x} = \left\lceil \frac{AIFS_{M_x} + \frac{L_{M_x}}{C_{M_x}}}{\tau} \right\rceil \times \frac{N_{M_x}}{D_{M_x}} k \in N \qquad (1)$$

where τ is the time slot duration, L_{M_x} is the packet size (including PHY and above), C_{M_x} is the IEEE 802.11 transmission rate, N_{M_x} is the number of messages of type x, and $D^{\max}_{M_x}$ is a maximal delay for message x computed in Equation (3).

$$\Pi^k_{M_x} = \frac{DTIM}{D^{\max}_{M_x}} = \frac{T}{D^{\max}_{M_x}} \qquad (2)$$

Figure 1 shows the details of VDA functionality in the presence of M_e and M_r in the CFP. VDA establishes priority between both safety messages, and particularly, VDA prioritizes M_e over M_r. VDA also serves private messages in the CP period because such messages are not delay sensitive. It is worth noting that the standard multichannel switching operation in WAVE allows the control channel (CCH) and service channel (SCH) intervals to be different, as long as their total length is the DTIM interval. We then define the dwell time ratio as the time percentage between CCH and SCH interval (e.g., we could have 75% CCH Dwell and 25% SCH Dwell).

3.3. Packet transmission delay in Vehicular Deterministic Access

We define the delay as the sum of the service and queuing delays. The service delay is the sum of the VDA scheduling delay, the $AIFS_{M_x}$, and the transmission delay of the packet. We define VDA scheduling delay as the waiting time, of the next packet to be sent, for its reserved VDAOP during which it can transmit without contention. We assume that the backoff delay is negligible over a long period of time because we assume that a contention with other vehicles is very rare during the reserved VDAOP. And we define the queuing delay as the time a packet waits in the transmission queue.

For emergency messages, we are in the context of one-hop broadcast; each broadcast has π_1 packets to transmit in every DTIM interval. Then the service rate could be

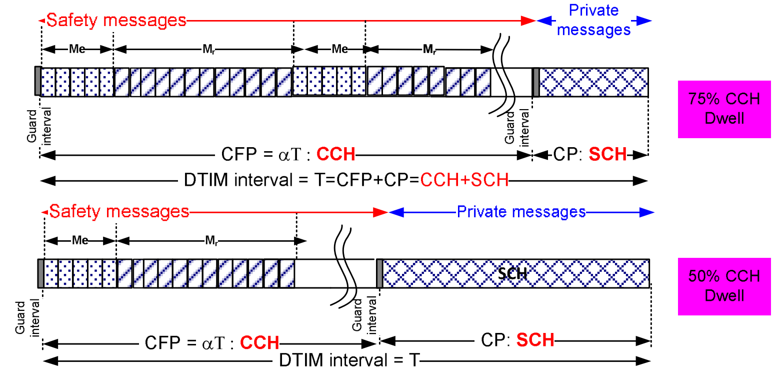

Figure 1. Vehicular Deterministic Access opportunity schedule for emergency (M_e) and routine (M_r) messages in Vehicular Deterministic Access. CFP, contention free period; CCH, control channel; CP, contention period; SCH, service channel; DTIM, delivery traffic indication message.

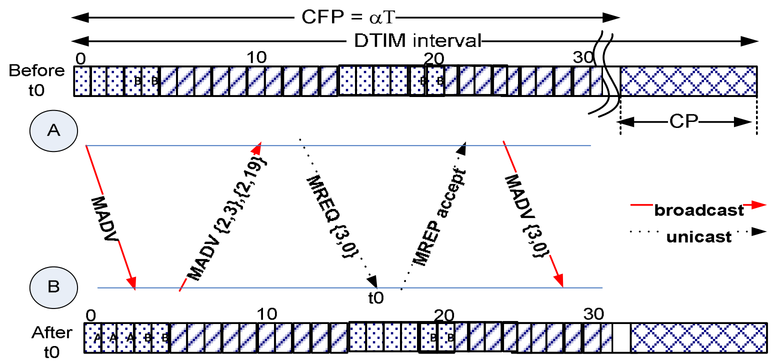

Figure 2. Example of the negotiation of an Mesh Coordinated Channel Access opportunity (MCCAOP) from node A to node B. Notation x, y means that the MCCAOP has duration x and offset y [5]. CFP, contention free period; CP, contention period; DTIM, delivery traffic indication message.

expressed by $S_{\text{rate}} = \pi_1/\text{DTIM}$ for one hop; otherwise, for m-hop. $S_{\text{rate}} = \pi_m/\text{DTIM}$

$$D_{M_x}^{\max} = \frac{D_{M_x}}{m} \tag{3}$$

The maximal delay is denoted by $D_{M_x}^{\max}$; that is, the hard constraint on maximal delay for a maximum number of hops m in a path and D_{M_x} is the required delay by the safety messages M_x.

3.4. Reception probability in Vehicular Deterministic Access

The reception probability is defined as the ratio of the number of packets successfully received to the number of packets transmitted. The reception probability can be seen as the probability that all vehicles within the transmission range of the sender vehicle receive the broadcast safety message successfully. We denote this probability P_{RR}.

We assume that vehicles are placed on the lane (see Figure 3) according to Poisson process with network density β (vehicles/m) [2]. We can express the probability to have v vehicles per transmission range R as follows:

$$P(v, R) = \frac{(2\beta R)^v e^{-2\beta(R)}}{v!} \tag{4}$$

We can also express the probability to have N_C vehicles per transmission range R'–R denoted by C, where R' is the carrier sensing range, as follows:

$$P(N_C, C) = \frac{(2\beta C)^{N_C} e^{-2\beta(C)}}{N_C!} \tag{5}$$

where N_C is the number of vehicles that could contend for the same time slots with the sender in its range R_s.

The reception probability (P_{RR}) in transmission range R_S can be expressed as follows:

$$P_{\text{RR}} = P(X, R_S) = P_{\text{RR}}(S, R_S) \times P_{X', R_X}(\delta_X, O_X) \times P_{X', C_X}(\delta_X, O_X) \tag{6}$$

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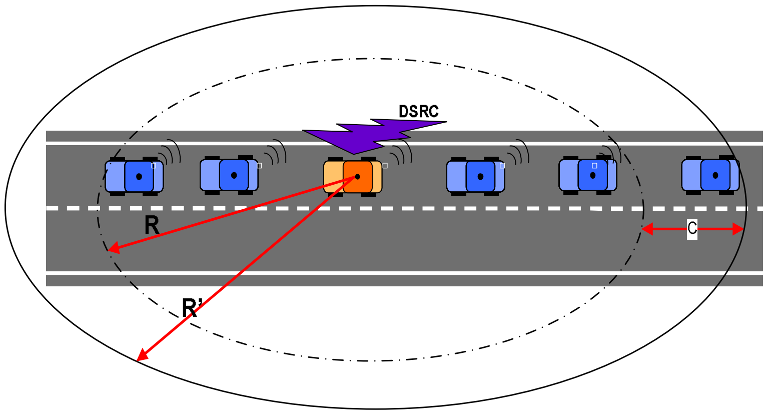

Figure 3. Scenario. DSRC, dedicated short-range communication.

The reception probability of any vehicle X, which is within the transmission range, denoted as R_S, of sender S, is equal to the reception probability of the vehicle S multiplied by the probability that any vehicle X', located in the transmission range R_X, transmits in the time slots allocated, without collision with another vehicle X in R_X. More specially, X' does not use δ_X and O_X which are allocated to a vehicle X which is located in both transmission ranges R_S and R_X.

Therefore, to expand $P_{\mathrm{RR}}(S, R_S)$, we describe two cases:

Case 1: No vehicles that could contend with the sender for the same time slots are within in its range $\mathrm{R_s}(N_C = 0)$.

$$P_{\mathrm{RR}}(S, R_S) = P(v, R_S) \times P_{s,R_S}(\delta_S, O_S) \quad (7)$$

where $P_{s,R}(\delta_S, O_S) \approx 1$ because the sender is the only owner of δ_S and offset O_S in its transmission range $\mathrm{R_s}$. Because we use a deterministic access in VDA, we expect low collisions to be happening. The average number of vehicles in R is equal to $2\pi R$, whereas in C, it is $N_C = 2\pi C$.

Case 2: N_C vehicles within the range $\mathrm{R_s}$ of the sender could contend with it for the same time slots $(N_C \neq 0)$

$$P_{\mathrm{RR}}(S, R_S) = P(v, R_S) \times P_{s,R_S}(\delta_S, O_S) \times P_{S',C_S}(\delta_S, O_S) \quad (8)$$

where $P_{S',C_S}(\delta_S, O_S)$ is the probability that none of the vehicles S' in range C_S transmits in the time slots allocated to the sender vehicle S in range $\mathrm{R_s}$ during the CFP period.

Let us define first P_0 as the probability that a vehicle has an event or a routine safety messages to transmit. To achieve deterministic access for vehicle S in its range $\mathrm{R_s}$, we compute the probability $P_{S',C_S}(\delta_S, O_S)$ that none of the vehicles in C_S range $(\forall S' \in N_C)$ transmits with number of time slots δ_S from the offset O_S.

The same explanations provided for equations (6) and (8) are valid to express the probability $P_{S',C_S}(\delta_S, O_S)$.

Proof. To formally express $P_{S',C_S}(\delta_S, O_S)$, we applied a standard technique of proof by cases. We express first the base cases of this probability for CFP equal to two slots with $N_C \geq 2$ (see Equation (9)) and for CFP equals to three slots $N_C \geq 3$ (see Equation (10)).

- For CFP = 2 slots; $N_C \geq 2$

$$P_{S',C_S}(\delta_S, O_S) = \frac{(1-P_0)^2}{A^2_{N_C} P_0^2 + A^1_{N_C} P_0(1-P_0) + A^0_{N_C}(1-P_0)^2} \quad (9)$$

- For CFP = 3 slots; $N_C \geq 3$

$$P_{S',C_S}(\delta_S, O_S) = \frac{(1-P_0)^3}{A^3_{N_C} P_0^3 + A^2_{N_C} P_0^2(1-P_0) + A^1_{N_C} P_0(1-P_0)^2 + A^0_{N_C}(1-P_0)^3} \quad (10)$$

Then similarly,

- For CFP = K slots and $N_C \geq K$, we express the following equations:

$$P_{S',C_S}(\delta_S, O_S) = \frac{(1-P_0)^K}{\sum_{k=0}^{K} A^k_{N_C} P_0^k (1-P_0)^{K-k}} \quad (11)$$

And for $N_C \leq K$,

$$P_{S',C_S}(\delta_S, O_S) = \frac{(1-P_0)^K}{\sum_{k=0}^{N_C} A^k_{N_C} P_0^k (1-P_0)^{N_C-k} (1-P_0)^{K-N_C}} \quad (12)$$

□

4. INTEROPERABILITY BETWEEN VEHICULAR DETERMINISTIC ACCESS AND NONVEHICULAR DETERMINISTIC ACCESS VEHICLES

4.1. Extended Vehicular Deterministic Access overview

In the following, we denote VDA vehicles as vehicles integrating the VDA option with 802.11p and non-VDA vehicles as vehicles using 802.11p without the VDA option. Using VDA protocol to access the shared channel helps reduce contention in VANETs. However, interoperability issues can arise if other non-VDA vehicles operate on the same channel. In that case, the performance of both VDA and non-VDA vehicles can be significantly degraded in the absence of adequate network planning considerations or scheme that can prevent this issue.

Let suppose we have vehicles $1, 2, \ldots, j, \ldots, K$ in a VANET that are scheduled to transmit N messages of type M_x (M_x being either an emergency message M_e or a routine message M_r) during their pre-reserved VDAOPs. In EVDA, in the presence of interfering non-VDA vehicles, we precede with a period of duration d', the VDAOP of a VDA vehicle j having a scheduled message M_x. During this d' period, extra/fake traffic is transmitted to pre-acquire the channel and enhance the chance of holding it during the subsequent reserved VDAOP. Therefore, the access to the shared DSRC channel by interfering non-VDA vehicles is prevented or delayed by artificially triggering their backoff procedure using the extra traffic during the period d' (see Figure 4). Then for a message x, we express the duration period in terms of time slots for the corresponding VDAOP reservation in EVDA as follows:

$$\delta^k_{M_x} = \left\lceil \frac{AIFS_{M_x} + \frac{L_{M_x}}{C_{M_x}}}{\tau} + \frac{d'}{\tau} \right\rceil \times \frac{N_{M_x}}{D_{M_x}}, \, j \in K, k \in N \quad (13)$$

With Equation (13), we favor VDA vehicles because we give them priority to access the channel and transmit fake traffic before the real reservation of the VDAOPs as a way to avoid the interference caused by non-VDA vehicles. This added duration period, d', allows both vehicles with VDA and without VDA option to access the shared channel without interference and thus insures their interoperability in the same channel with low collisions.

4.2. Bounded extra delay

In EVDA scheme, the extra-added delay d' is bounded as per Equation (14).

$$DIFS < d' \leq DIFS + BT \quad (14)$$

where DIFS is the DCF interframe space duration and BT is the backoff timer expressed as follows:

$$BT = BO \times SlotTime \quad (15)$$

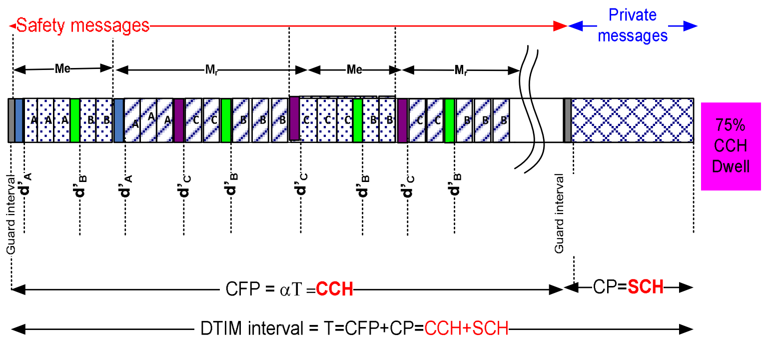

Figure 4. Vehicular Deterministic Access opportunity schedule for emergency (M_e) and routine (M_r) messages in an example of extended Vehicular Deterministic Access (75% contention free period/contention period (CFP/CP) dwell time ratio) for vehicles A, B, and C with Vehicular Deterministic Access option. CCH, control channel; SCH, service channel; DTIM, delivery traffic indication message.

where BO is selected as a random integer in $[0..CW]$ and CW is the contention window value for 802.11/DCF or 802.11/EDCF MAC. To have a minimum value of d' used, EVDA scheme fixes BO to 1.

Traffic for non-VDA vehicles will be delayed with d' period. A non-VDA vehicle will be using DCF MAC or EDCA MAC and so will wait for medium to become free before transmitting traffic. If the medium is idle, the vehicle will have access to the channel for no longer than DIFS duration. Otherwise, a random backoff is triggered to avoid collisions; the exponential backoff window increases for retransmissions, and the backoff timer elapses only when the medium is idle. EVDA extends the VDA scheme in such a way as to make changes into VDA vehicles operation and not into non-VDA vehicles while insuring their interoperability within the same 802.11p/DSRC channels. Thus, the EVDA scheme pre-acquires the medium before making the reservations of VDAOPs. For that, it creates the illusion for the other non-VDA vehicles that the medium is busy during a period d'. Similarly, it is as if EVDA increases the DIFS of the non-VDA vehicles.

4.3. Use of the extra bounded delay

The use of the period of duration d' for a VDA vehicle j and message M_x is triggered depending on the percentage of both types of vehicles using either a deterministic access 802.11p/VDA or a traditional 802.11p/DCF or EDCA. At a time t, each vehicle with the VDA option can roughly estimate this percentage by listening to the channel when other vehicles are communicating.

Case 1: % VDA nodes $\gg$ % non-VDA nodes
This case happens when the number of VDA vehicles is significantly superior to non-VDA vehicle (e.g., 75% VDA vehicles and 25% non-VDA vehicles). EVDA will then not activate the transmission of the additional extra traffic for a duration d' because the number of VDA vehicles is very high compared with non-VDA vehicles and this fact already favors that VDA vehicles will have more chance to hold the shared channel.

Case 2: ! (% VDA nodes $\gg$ % non-VDA nodes)
This case happens when (i) the number of VDA vehicles is inferior to the number non-VDA vehicles or (ii) when the number of VDA vehicles is superior to the number of VDA vehicles but not significantly (e.g., 55% VDA vehicles and 45% non-VDA vehicles). EVDA will then add the duration period d' before the pre-reserved VADOPs to give priority to VDA vehicles while differing/preventing non-VDA vehicles transmission. This can be explained by the fact that EVDA chooses favoring VDA vehicles to access the channel rather than permitting collisions and interference between communications of the two types of vehicles. These interferences would not only make VDA scheme completely non-operational to ensure deterministic access but also inevitably differ classical 802.11p/DCF or EDCA transmissions or cause their collisions.

5. SIMULATION RESULTS

In this section, we conduct a simulation study using ns-2 to evaluate and compare the performance of our proposed schemes, that is, VDA and EVDA, with the existing scheme based on 802.11p DCF. It is worth noting that we opt to compare the performance of VDA and EVDA with that of 802.11p/DCF because on the one hand we are interested mainly in avoiding transmission collisions that can occur because of near simultaneous message creation using 802.11p/DCF that is based on a backoff algorithm to access to the shared medium. On the other hand, we assume that two or more vehicles could select the same value for their backoff counter, which would occur with a probability of $1/CW_{\min}$ as shown in [20]. Therefore, this comparison evaluation is accurate even if we do not make a direct comparison with the EDCA scheme in 802.11p because our major aim is to tackle the backoff algorithm problem and to show how a deterministic access to the medium in VANETs behaves versus a non-deterministic access.

We evaluate several metrics: (i) the throughput; (ii) the reception probability; and (iii) the average delay.

We measure the throughput as the total number of bits that are correctly received for all messages in the VANET in the unit of time. The reception probability is the rate of messages received within a one-hop range. The average delay is the average delay within a one-hop range.

Moreover, we study the impact of the extra-added period d' on performances depending on the percentage of VDA vehicles versus that of non-VDA vehicles. In addition, we investigate the possible impact of the time ratio of CFP/CP on safety messages delivery performance in these schemes.

5.1. Simulation configurations

We use a topology composed of a circular eight lane highway (four lanes/direction). The radio transmission range r takes one of the following values: 150, 200, and 250 m; the transmission interference R of each vehicle is 550 m. Although 802.11p/DSRC can be used with longer ranges in theory, 150, 200, and 250 m are the transmissions ranges that are most used in literature [2]. This is mainly because of the desired range of the targeted safety applications and because having a longer range may saturate and disturb the communication of vehicles situated farther away without a real benefit. It is worth mentioning that in our work, our aim is to take into account the eight high-priority cooperative vehicular safety applications as chosen by the National Highway Traffic Safety Administration and the Crash Avoidance Metrics Partnership in 2006. These applications require strict pre-determined delay constraints. For example, the maximum latency of traffic signal

Table II. System parameters.

PHY radio model	SINR
Carrier Sense Range	550 m
Transmission range	150, 200, 250 m
DTIM	32 ms
Threshold packet loss	5%
α	0.68
Dwell time ratio	50% CCH Dwell
Time slot	13 μs
MAC type	802.11 (used with DSRC)
Channel bandwidth [Mbps]	6, 9, 12, 24
Traffic type	CBR (UDP)
Message frequency [message/s] per vehicle	10–25, 500, 1250
Message payload size [byte]	500, 1000
Number of vehicles	80
Speed [km/h]	80–120
Traffic density [veh/km/lane]	10–100
Number of lanes	8
Simulation time [s]	60

SINR, signal-to-noise ratio; DTIM, delivery traffic indication message; CCH, control channel; MAC, Medium Access Control; DSRC, dedicated short-range communication; CBR, constant bit rate; UDP, User Datagram Protocol.

violation, forward collision, lane change warning, stop sign assist, and left turn assist applications are equal to 100 ms, and their transmission ranges are about 250, 150, 150, 300, and 300 m, respectively. The rest of the parameters takes values among those presented in Table II, and as shown in the figures corresponding to each particular set of simulations.

5.2. Results analysis (Vehicular Deterministic Access versus Distributed Coordination Function)

5.2.1. Delay of emergency and routine messages.

From vehicle safety point of view, it is crucial for vehicles in the highway to receive status updates (routine messages) from each neighboring vehicle in the transmission range frequently enough and in an evenly timed manner. For event-driven messages (emergency messages), the transmission delay requirements are even more strict. That is why it is very useful to have an efficient scheduling scheme such as VDA that provides lower transmission delays especially for emergency safety messages.

To evaluate the new scheme in different channel conditions, we vary vehicles density from 10 to 100 vehicles per lane per kilometer, and we vary the other parameters to obtain different channel loads. Channel load has been shown in previous works as the major factor that undermines 802.11p performances [4]. Many parameters play into determining the channel load. We recall the concept of communication density (CD) defined in [4] as follows:

$$\mathrm{CD} = \mathrm{Range}^{*}\ \mathrm{Message\ Frequency}^{*}\ \mathrm{Nr.\ Lanes}^{*}\ \mathrm{Vehicle\ Density} \quad (16)$$

In Equation (16), vehicle density is the number of vehicles per meter per lane, and message frequency is the message generation rate. The channel Load [4] is determined by the triplet <CD, data rate, message size>.

To measure the average delay, in each channel load level, parameters are varied in combinations of <range, message frequency, Nr. lanes, vehicle density, data rate, message size>. The unit of CD used in graphs is m*pkt/s/vehicle*lane*vehicle/lane/km (i.e., pkt/ms).

Figure 5 illustrates the delay for both VDA and DCF schemes when varying the packet size and the communications density. We remark that when we increase packet size, the delay of emergency messages increases, but it is still very lower compared with the DCF delay. In high communication density conditions, the delay of VDA is stable and outperforms in average the DCF delay by 97%. Using deterministic access for safety messages is clearly commendable to guarantee a bounded delay and therefore to transmit warning messages with a very acceptable delay.

Figure 6 shows that VDA scheme gives priority to emergency messages over routine messages and is capable to maintain this priority in high communication density conditions. Not only this statement is very important in VANETs, because emergency messages require a lower delay than routine messages, but also the delay of routine messages must be bounded. This is what VDA scheme succeeds to achieve as shown by the figure.

Figure 7 shows, when varying the transmission range, the delay of emergency and routine safety messages using VDA scheme versus the delay using DCF method. The purpose is to see if varying the transmission range in dense channel scenarios can enhance DCF performance well enough to be similar to that of VDA. Message frequency, vehicle density, data rate, and message size are set to the

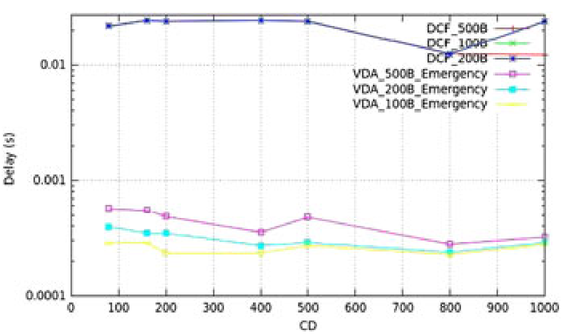

Figure 5. The delay of Vehicular Deterministic Access (VDA) emergency messages and Distributed Coordination Function (DCF) schemes while varying communication density and packet size.

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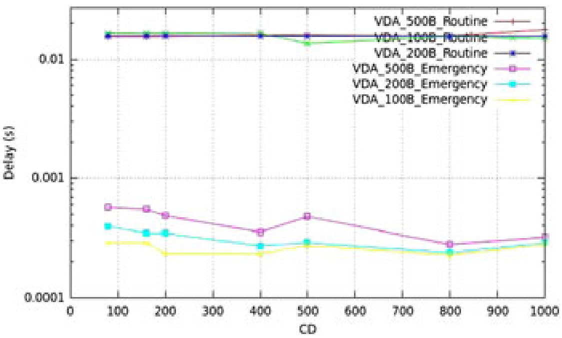

Figure 6. The delay of both emergency and routine messages in Vehicular Deterministic Access (VDA) scheme while varying communication density and packet size.

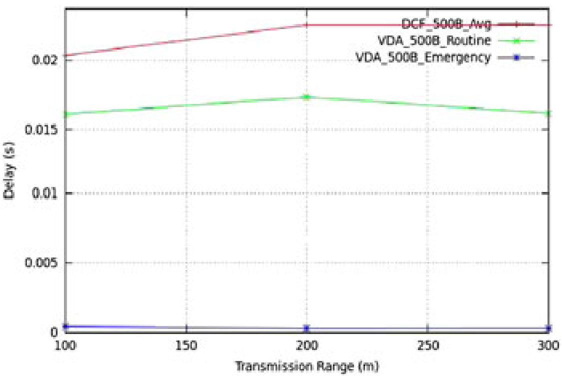

Figure 7. The delay of both emergency and routine messages in Vehicular Deterministic Access (VDA) scheme compared with Distributed Coordination Function (DCF) scheme: *messages frequency: 25 messages/s; vehicle density: 10–100 vehicle/km/lane; data rate: 6 Mbps; message size: 500 bytes.*

values shown in the figure. We note that the delay of emergency messages of VDA is very low over all the transmission range and in average it is equal to 0.0003504 s, which is very desirable in VANETs. However, the delay of the DCF method is equal in average to 0.0219 s and is 62 times bigger than the delay of emergency messages using the VDA method. We notice also that routine messages delay is very acceptable using VDA scheme (e.g., range = 200 m, 0.0173 s). This is the expected behavior from VDA, because the scheme prioritizes emergency messages over routine messages when scheduling VDAOPs as shown in Figure 1.

We were also interested in evaluating the reception rate within the transmission radio range of the emitting node, depending on the distance from the latter. Figure 8 shows the performance curves for both DCF and VDA schemes with the message size being 500 B, the transmission range being 200 m, message frequency being 500 pkt/s, and data rate being 6 Mbps. The reception probability with VDA outperforms DCF by 25%. Moreover, we notice that with VDA, at higher communication densities

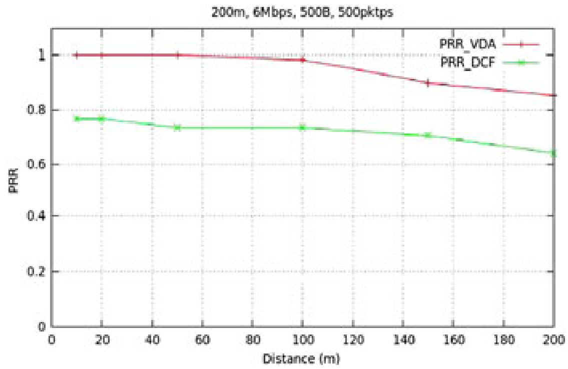

Figure 8. The reception probability of both Vehicular Deterministic Access (VDA) and Distributed Coordination Function (DCF) while varying the distance – *range: 200 m; message frequency: 500 packets/s; data rate: 6 Mbps; size message: 500 bytes.* PRR, packet reception rate.

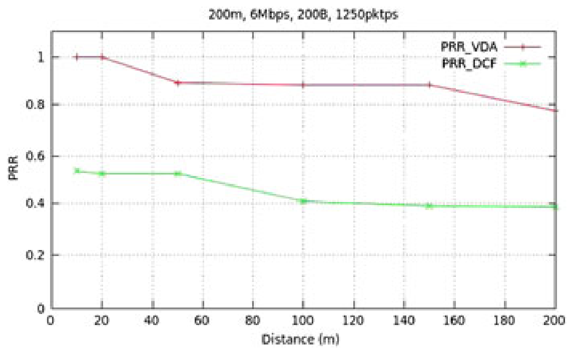

Figure 9. The reception probability of both Vehicular Deterministic Access (VDA) and Distributed Coordination Function (DCF) while varying the distance – *range: 200 m, message frequency: 1250/s; data rate: 6 Mbps; message size: 200 bytes.* PRR, packet reception rate.

(e.g., distance = 50 m), the packet reception is equal to 99%. For similar communication densities with DCF, the reception probability is equal to 73%.

When we increase messages frequency to 1250 pkt/s with packet size being 200 B, which means increasing channel load, the gap between the two curves of DCF and VDA schemes deepens as shown in Figure 9. An example to illustrate this, for a distance = 50 m, the packet reception rates are 52% and 89% for DCF and VDA schemes, respectively. The reception probability with the VDA scheme increases significantly compared with the DCF scheme over all the distances (e.g., in average, the packet reception rates are 90% and 46% for VDA and DCF, respectively).

5.2.2. Network throughput.

In Figure 10, we compare the network throughput provided by the two access methods. Figure 10 shows that

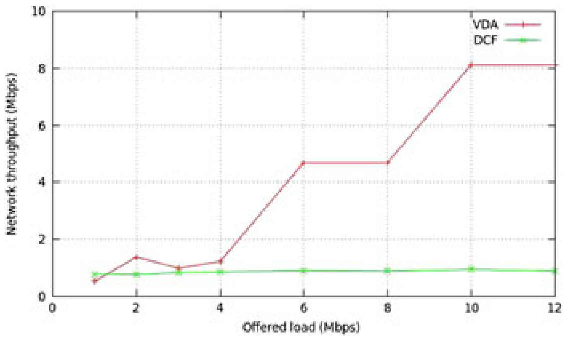

Figure 10. The network throughput of both Vehicular Deterministic Access (VDA) and Distributed Coordination Function (DCF).

a much lower throughput is provided by the DCF compared with VDA. DCF throughput degrades much more in a high offered-load condition. This is explained by the fact that much more collisions happen with DCF, and therefore, much more message losses. VDA scheme outperforms DCF in terms of throughput particularly starting from 4 Mbps and presents an improvement for all loads of 70%.

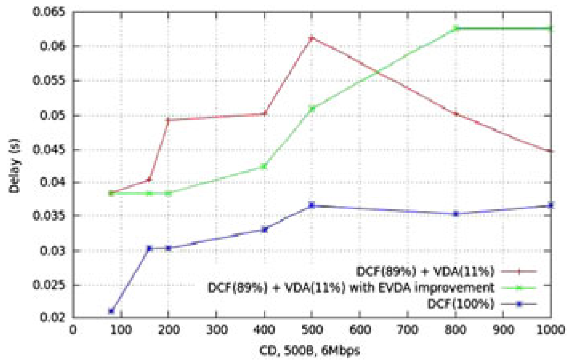

Figure 11. 802.11p/DCF delay with and without EVDA improvement. VDA, Vehicular Deterministic Access; DCF, Distributed Coordination Function; EVDA, extended VDA; CD, communication density.

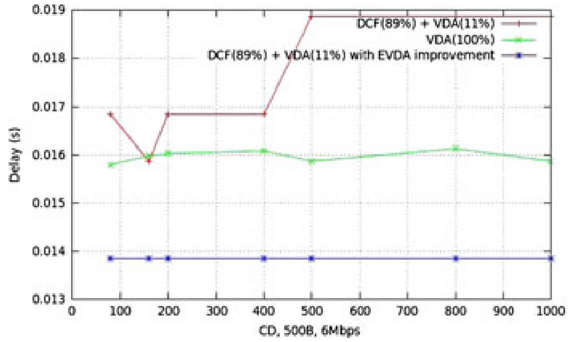

Figure 12. 802.11p/VDA delay with and without EVDA improvement. VDA, Vehicular Deterministic Access; DCF, Distributed Coordination Function; EVDA, extended VDA; CD, communication density.

5.3. Results analysis (interoperability between Vehicular Deterministic Access and Distributed Coordination Function vehicles)

In the following sections, we were interested to see how VDA and DCF performances are when both types of vehicles are co-existing on the same road and contending on using the same channels. We also were interested to investigate whether EVDA enhances the performance of VDA vehicles, non-VDA vehicles, or both in such situations.

5.3.1. Delay metric (with and without extended Vehicular Deterministic Access).

We studied the delay for 802.11p/VDA vehicles and for 802.11/DCF vehicles with and without EVDA extension in cases where both types of vehicles are co-existing.

Figure 11 shows the average delay for DCF with and without the EVDA scheme when both types of vehicles are present. It also shows, for comparison purposes, the average delay when only DCF vehicles are present. We can see that DCF delay when no VDA vehicles are present is the lowest delay over all CD values. This is coherent with the fact that both VDA and EVDA schemes intend to give priority to VDA vehicles. In the presence of 89% of DCF vehicles and only 11% of VDA vehicles, DCF delay increases. Results for medium and high communication density conditions are as follows: in medium communication density conditions (100–500), Figure 11 shows that the EVDA scheme is able to reduce the delay for DCF vehicles by an average of 13% compared with the VDA scheme alone. In high communication density conditions (600–1000), EVDA improvement leads to a slightly higher DCF delay that can be explained both by the higher communication density and the fact that EVDA favors VDA vehicles over DCF vehicles to access the medium. It is worth noting that the delay stays reasonable for safety messages in such high communication density conditions (e.g., for CD = 1000, the DCF delay is 0.06 s).

Figure 12 shows the delay for VDA vehicles with and without the EVDA scheme when both types of vehicles are present. It also shows, for comparison, the average delay when only VDA vehicles are present. Delay for the VDA-only case is very acceptable for emergency safety messages (0.015 s on average). However, when we introduce DCF vehicles (89%), the delay of VDA vehicles increases to reach 0.0188 s for communication densities between 400 and 1000. In fact, with EVDA improvement, the delay of VDA vehicles is better than without EVDA by 22% in presence of a ratio of 89% DCF vehicles. EVDA scheme reduces the one-hop delay for VDA vehicles to 0.013 s, which is very good for safety messages. This is particularly

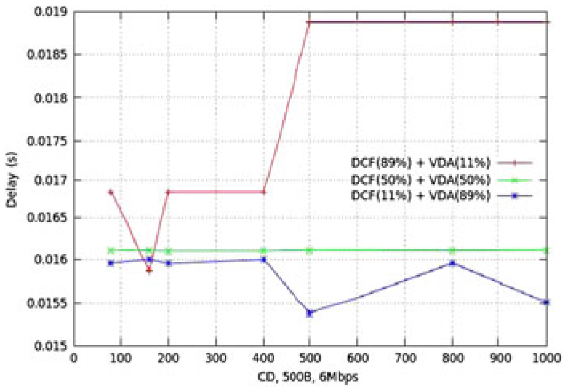

Figure 13. 802.11p/VDA delay without EVDA improvement. VDA, Vehicular Deterministic Access; DCF, Distributed Coordination Function; EVDA, extended VDA; CD, communication density.

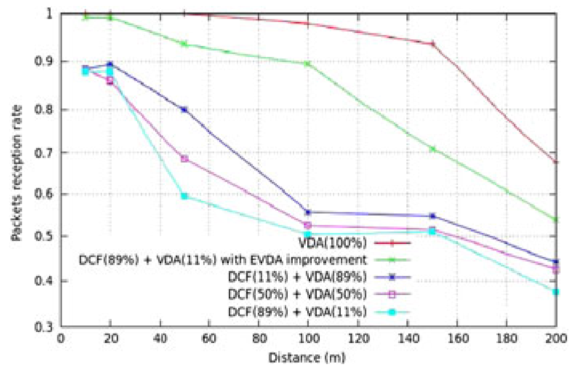

Figure 14. 802.11p/VDA reception probability with and without EVDA improvement. VDA, Vehicular Deterministic Access; DCF, Distributed Coordination Function; EVDA, extended VDA.

important for emergency messages, which requires a maximal delay of 150 ms. This is the expected behavior from the EVDA scheme because it prioritizes VDA vehicles messages over non-VDA vehicles when scheduling VDAOPs as shown in Figure 1.

In Figure 13, the purpose is to investigate VDA delay in the presence of different percentages of both types of vehicles to highlight our motivation to introduce EVDA. We remark that when the percentage of DCF nodes is about 89%, the delay of VDA scheme increases significantly compared with cases where the percentage of DCF nodes are 50% and 11%, respectively (e.g., CD = 1000, the VDA delay is 0.016 and 0.015 s). This shows how DCF nodes interfere with VDA nodes to access the shared medium, which leads to higher VDA delays. Thus, it is important to introduce a scheme such as EDCA to guarantee a good interoperability between both types of vehicles communications.

5.3.2. Reception probability metric (with and without extended Vehicular Deterministic Access).

Figure 14 shows results of five scenarios with a data rate of 6 Mbps, a range of 200 m, a message size of 500 B, and a message frequency of 25/s. A distance of 20 m corresponds to a value of CD of 160, and a distance of 200 m corresponds to a CD of 1000.

The figure clearly shows that when we introduce DCF vehicles with different percentages, the reception probability decreases significantly with the distance from the transmitter compared with the case where we have just VDA vehicles in the highway. On the one hand, Figure 14 shows the reception probability gap between different scenarios. For example at 100 m distance, and for different DCF percentages 0%, 11%, 50%, and 89%, the packet reception rates are respectively 97%, 60%, 52%, and 50%. On the other hand, the EVDA scheme improves significantly the results for the worst scenario having 89% of DCF vehicles, from a reception rate of 50% to 90%. Therefore, the EVDA scheme outperforms the VDA scheme by 40% in presence of DCF vehicles.

At a distance of 200 m, when no DCF vehicles are present, VDA has a reception rate of 67%. The reception rate decreases though abruptly to values of 44%, 42%, and 37% in presence of DCF vehicles with percentages of 11%, 50%, and 89%. The EVDA scheme manages to keep the packet reception rates at 54% for the worst scenario of 89% DCF vehicles. This shows that when the channel is saturated, the performance of both VDA and non-VDA vehicles is significantly degraded in the absence of adequate network planning considerations or scheme such as the proposed EVDA improvement, which can prevent this issue.

5.4. Impact of varying the time ratio of contention free period/contention period on safety messages in extended Vehicular Deterministic Access

The standard multi-channel switching in WAVE allows the CCH and SCH intervals to be different, as long as their total length is a divisor of 1 s. We then define the dwell time ratio as the time percentage between CCH and SCH interval (e.g., we could have 75% CCH dwell and 25% SCH dwell).

In EVDA, we use *CCH=CFP* interval and *SCH=CP* interval, and their sum, the synchronization interval, is the DTIM interval. The CFP and CP intervals can be dynamically adaptable in EVDA scheme. We proceed in the next section to trigger different values of the dwell CCH time to look for the best adjustment, which allows a short delay and high reception rates for safety messages.

Although the results for VDA vehicles showed no significant impact of the dwell time variations on results with or without EDVA, the results were different for DCF vehicles. For the next two figures, we consider that we have 89% of

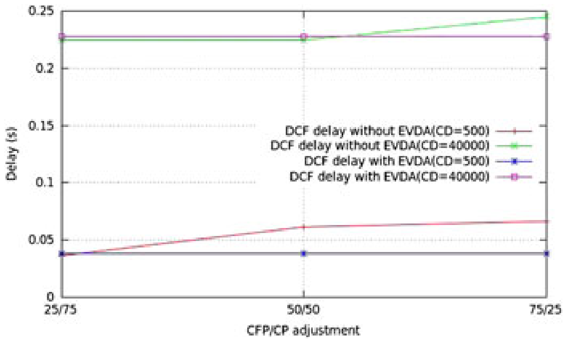

Figure 15. Delay for Distributed Coordination Function (DCF) vehicles with and without Extended Vehicular Deterministic Access (EVDA). CD, communication density; CFP, contention free period; CP, contention period.

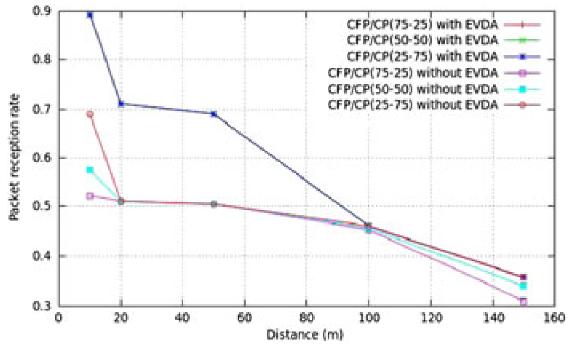

Figure 16. Reception probability for Distributed Coordination Function Vehicles with and without Extended Vehicular Deterministic Access (EVDA). CFP, contention free period; CP, contention period.

DCF vehicles and 11% of VDA vehicles in the highway. We still are in a high channel density scenario where the data rate is 6 Mbps, the range is 200 m, the message size is 500 B, and the message frequency is 25 messages.

5.4.1. Delay metric.

Figure 15 shows the delay for DCF vehicles with and without EVDA improvement for VDA vehicles when varying the CFP/CP adjustment for medium (e.g., CD $=$ 500) and high (e.g., CD $= 40,000$) communication densities. We remark that DCF vehicles delay when using EVDA scheme with VDA vehicles, outperforms DCF vehicles delay, when not using EVDA scheme with VDA vehicles for both medium and high communications densities. This improvement is 30% for CD $=$ 500 and 10% for CD $= 40,000$. However, we notice that without EVDA, the impact of CFP/CP is important especially when CFP/CP $= 75\%/25\%$. This can be explained by the fact that although for vehicles with VDA option time slots are reserved for safety messages even for high channel loads, DCF only obtains the remaining CCH time. With EVDA, when the d' bounded delay is added, EVDA gives even more chances to DCF vehicles to transmit when CFP/CP is high.

5.4.2. Reception probability metric.

We illustrate in Figure 16 the reception probability with and without EVDA for DCF vehicles. We notice that the introduction of EVDA scheme in VDA vehicles allows DCF-only vehicles to have higher packet reception rates. EVDA outperforms the VDA scheme over all the CFP/CP adjustments by almost 20%. This can be explained by the same reasons stated previously.

It is worth noting though that VDA and EVDA improvements come at the cost of a slight overhead introduction. This overhead can be computed as the [number of control packets/(number of control packets + number of data packets)] where the number of control packets for VDA-based schemes includes VDA advertisements, VDA setup requests, and so on (see Figure 2). The overhead of deterministic-based schemes versus CSMA-based schemes was studied in [15], and this study confirms that VDA or EVDA will have an acceptable slight bigger overhead than DCF scheme. Under high traffic conditions, the cost of this slight added overhead pays very well in terms of improved packet reception and delay. This is very important as high traffic conditions are most challenging for safety vehicular communications. Under light traffic conditions, the traditional MAC CSMA (e.g., DCF) shows a slight better performance in terms of throughput (see [10,15]) but does not outperform significantly our deterministic scheme.

6. CONCLUSIONS AND FUTURE WORK

In this paper, we show how we minimize contention between high-priority safety-oriented routine or emergency traffic and non-safety application traffic using a deterministic access method over 802.11p called VDA. VDA provides bounded delays and low losses particularly for emergency messages.

We investigated a mechanism called EVDA that prevents interfering 802.11p/DCF vehicles, with deterministic access enabled, from accessing the scheduled transmission opportunities during the reserved time slots for vehicles using deterministic VDA access over 802.11p/DSRC. EVDA guarantees a good interoperability in terms of shared channel access between transmitting vehicles that have the VDA option enabled in DSRC/802.11p and interfering vehicles with no VDA option.

Using simulations, we showed that the VDA and EVDA proposed approaches over 802.11p, which integrate deterministic access, outperform the current backoff-based mechanism used in 802.11p. They achieve good performances in terms of delay and packet reception rate.

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Soumaya Cherkaoui is a full professor at the Department of Electrical and Computer Engineering of Université de Sherbrooke, Canada, which she joined in 1999. She holds a bachelor's degree in Computer Engineering from EMI Engineering School (École Mohammedia D'Ingénieurs), Rabat (Morocco) and a PhD in Electrical Engineering from Université de Sherbrooke. Since 2005, she has been the director of INTERLAB, a research Laboratory that conducts research funded both by government and industry. Prior to her appointment at U.Sherbrooke, Cherkaoui worked for industry as a project leader on projects targeted at the Aerospace Industry. Cherkaoui has more than 70 publications in reputable journals, conferences, and workshops in the area of communication networks. She has participated as a General Chair, Editor, Member of Technical Committee, Session Chair, and Program Committee Member of numerous conferences or referenced journals. Her research and teaching interests are in wireless ad hoc and sensor networks. Particularly, she works on V2V and V2I communications, MAClayer issues, quality of service, and security provisioning. She is an accredited Professional Member of the Order of Engineers of Quebec and an IEEE member.