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Interoperability between Deterministic and non-Deterministic Vehicular Communications over DSRC/802.11p

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***Abstract*— In recent works, a priority-aware deterministic access protocol that is based on 802.11p/DSRC was introduced to allow vehicles to access the shared medium in collision-free periods. The VANET Deterministic Access (VDA) protocol as introduced in [8] has no mechanism that prevents a non VDA-enabled vehicle from accessing the channel in a scheduled VDA opportunity (VDAOP). A non VDA-enabled vehicle, i.e. a vehicle not configured with the optional VDA capability over 802.11p, may start transmitting on the shared channel just before or during the VDAOPs reserved for vehicles with VDA capabilities. Also, non VDA-enabled vehicles may be prevented from accessing the shared channel due to the transmission of VDA-enabled vehicles during their respective VDAOPs with a higher priority (shorter AIFS). In this work, we propose a new enhanced VDA scheme, called EVDA that avoids the above issues and prevents interfering transmissions from VDA-enabled vehicles and non VDA-enabled vehicles. We also analyzed the impact of several design tradeoffs between the Contention Free Period (CFP)/Contention Period (CP) Dwell-time ratios on the performance of safety applications with different priorities with EVDA. Simulations show that the proposed scheme clearly outperforms the VDA scheme in high communications density conditions while bounding the transmission delay of safety messages and increasing the packet reception rate.**

Index Terms—Vehicular ad hoc networks, Contention-free, safety services, deterministic access, VDA, non-VDA.

I. INTRODUCTION

Vehicular Ad hoc Networks (VANETs) is currently considered a key enabling technology for future road safety and telematics applications. To encourage the development and deployment of VANETs, the Federal Communications Commission (FCC) of the U.S. approved the 75MHz bandwidth at 5.850-5.925 GHz band for Intelligent Transportation Systems (ITS). This wireless spectrum is commonly known as the Dedicated Short-Range Communication (DSRC) spectrum allocated by the regulator to be used exclusively for Vehicle-Vehicle (V2V) and Vehicle-Road (V2R) communications. Devices operating in DSRC spectrum will be using IEEE 802.11p by following the WAVE operation mode [1-7].

DSRC spectrum is made up of seven 10 MHz wide channels. Channel 178 is the control channel (CCH), which is the default channel for common safety communications. The two channels at the ends of the spectrum band are reserved for special uses. The rest are service channels (SCH) available for both safety and non-safety use.

The VANET Deterministic Access (VDA) scheme studied in [8] extends the typical 802.11p/DSRC medium instantaneous reservation procedure into a more advanced reservation procedure using scheduled VDA OPportunities (VDAOPs) within a two-hop neighborhood. VDAOPs are first negotiated between neighboring nodes by exchanging broadcast setup messages then VDAOPs 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 our 802.11/EDCA MAC layer. The DCF MAC has been shown to require improvements in its backoff algorithm as shown in [2], without which the scalability of 802.11p in dense vehicular environments can be undermined.

VDA scheme [8] 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. As shown in [8], VDA ensures a very low delay, even for very high channel densities, with values lower than 0.00112616s. This is very desirable since emergency messages usually involve urgent life-critical situations.

Nevertheless, VDA [8] in its current version has no mechanism that guarantees 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. To improve VDA and overcome this shortcoming, we developed a scheme that prevents non VDA-enabled vehicles, (i.e., vehicles using 802.11p/DCF or 802.11p/EDCA access such in [2]), from accessing the scheduled VDAOPs when these VDAOPs are used by vehicles using 802.11p with the VDA option enabled.

Our contributions, in this paper, can be summarized as follows: (1) we propose an enhanced VDA scheme, called EVDA, that prevents interfering vehicles without VDA option from accessing the shared medium during reserved time-slots; (2) we study the impact on varying the time-ratio of CFP/CP on safety applications performance; (3) 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 (4) we evaluate the new model compared to standard 802.11/DCF and also to 802.11p/VDA in terms of delay and packet reception rate for safety messages.

The remainder of the paper is organized as follows. Section II gives an overview of the deterministic access VDA proposed for IEEE 802.11p/DSRC. Section III proposes our scheme named EVDA and presents a mathematical formulation of the key parameters. Section IV evaluates the proposed solution and compares it to existing works in the literature via simulations. Finally, Section V concludes the paper.

II. VDA OVERVIEW

An optional VANET Deterministic Access (VDA) scheme was proposed for DSRC/IEEE 802.11p [8] to provide much less contention, lower delays and higher packet reception rates in VANETs using a distributed process of advanced reservations of contention free transmission opportunities similar to the MDA scheme adopted for 802.11s [9].

VDA is able to significantly decrease collisions. Moreover, it supports two types of safety messages (emergency and routine safety messages) with different priorities and strict requirements on delay.

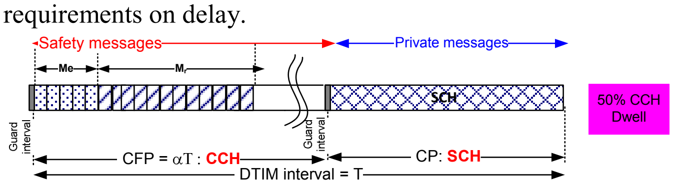

Fig.1 VDAOP schedule for emergency (M_e) and routine (M_r) messages in VDA during the CFP (50% Dwell time-ratio)

In VDA, that is inspired from the recently adopted MDA scheme of 802.11s [9], an advanced reservation procedure using scheduled VDA OPportunities (VDAOPs) within a two-hop neighborhood extends the basic CSMA virtual carrier sensing (V-CS) procedure. VDAOPs are negotiated between neighboring nodes by exchanging broadcast messages, then VDAOPs reservations are performed in multiples of a time-slot unit during the Delivery Traffic Indication Message (DTIM) periodic interval (see Fig.1). The time between consecutive DTIM frames is divided into time slots of length $32\mu s$. Nodes reserve the wireless medium for VDAOPs, which are multiples of time-slots during a given Contention Free Period (CFP) of a maximum access fraction (MAF= αT) of the DTIM interval T . The remaining part of the DTIM interval is the contention period (CP) that can be used for non-delay sensitive data. Note that the basic MDA does not support different services with different priorities and has the same behavior for all messages in the network, while VDA [8], that is more appropriate to vehicular networks, considers two types of messages, emergency and routine messages. In VDA, each VDAOP reservation request for message k is characterized 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 represents the number of times the specified VDAOPs repeat themselves equidistantly within a DTIM interval (T).

Fig.1 shows the details of VDA functionality in the presence of two types of services with different priorities in the CFP.

VDA establishes priority between safety messages and particularly, VDA prioritizes emergency safety messages (M_e) over routine safety messages (M_r) to maintain optimal resources utilization. VDA also serves private messages (M_p) in the CP period because such messages are not delay-sensitive. It is worth noting that while M_e messages happen only occasionally at emergency situations and require very high reliability and short delay, M_r messages are broadcasted periodically. M_r messages broadcast current information about a vehicle such as direction and position and they require lower reliability compared to M_e messages.

VDA operation assumes however that all vehicles accessing the shared medium either participate or at least are aware of the VDA reservation process that happens in their sensing range. In fact, in the presence of vehicles that do not have the VDA option enabled, VDA may not be able to provide deterministic access if the access to the shared medium is deferred by transmissions or interferences from some non-VDA vehicles that are not able to understand the VDA reservations protocol. Therefore, we propose to improve the VDA protocol by considering a new scheme, called EVDA that tackles VDA interference vulnerability with vehicles not having the VDA option. For that, we modify the VDAOP duration (see next section) to take into account interfering vehicles not having VDA in the transmitting range. In the rest of the paper, we will denote "VDA vehicle" a vehicle with the VDA option enabled with 802.11p, and a “non-VDA vehicle”, a vehicle that does not have the VDA option, i.e. a vehicle with basic 802.11p/DCF or 802.11p/EDCA.

III. INTEROPERABILITY BETWEEN VDA AND NON-VDA VEHICLES

A. *EVDA Overview*

Using VDA protocol to access the shared channel helps reduce contention in VANETs. However, interoperability issues can rise 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.

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

Let suppose we have vehicles 1,2, . . j, . . , 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 in order 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 Fig. 2). Then, for a message x, we express the duration period in terms of time slots for the corresponding VDAOP reservation in EVDA as follows:

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 the maximal delay for message x calculated in

Eq.2 below. With Eq. 1, we favor VDA vehicles since 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.

The maximum delay is denoted by $D_{M_x}^{\max}$, i.e., 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.

$$D_{M_x}^{\max} = \frac{D_{M_x}}{m} \quad (2)$$

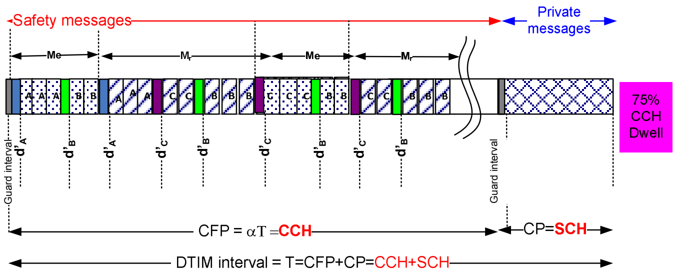

Fig.2 VDAOP schedule for emergency (M_e) and routine (M_r) messages in an example of EVDA (75% CFP/CP Dwell time-ratio) for vehicles A, B and C with VDA option.

B. Bounded Extra Delay

In EVDA scheme, the extra-added delay d' is bounded as per Eq.3 bellow.

$$DIFS < d' \leq DIFS + BT \quad (3)$$

Where DIFS is the DIFS (DCF Inter-frame Space) duration and BT is the backoff timer expressed as follows:

$$BT = BO \times SlotTime \quad (4)$$

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. In order 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 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.

C. 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 >> % 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' since the number of VDA vehicles is very high comparatively to non-VDA vehicles and this fact already favors that VDA vehicles will have more chance to hold the shared channel.

Case 2: ! (% VDA nodes >> % non-VDA nodes)

This case happens when a) the number of VDA vehicles is inferior to the number non-VDA vehicles or b) 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 would inevitably differ classical 802.11p/DCF or EDCA transmissions or cause their collisions.

IV. Simulation Results

In this section, we conduct a simulation study using ns-2 to evaluate and compare the performance of our proposed scheme, i.e., EVDA, with the existing scheme based on 802.11p VDA and with 802.11p/DCF[8]. We evaluate the: 1) the average delay and 2) the packet reception rate because these are the two parameters with the most impact on safety messages. The packet reception rate 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.

A. Simulation configurations

We use a topology composed of an 8 lanes highway, four in each direction, and we vary vehicles density from 10 to 100 vehicles per lane per km. In the simulation scenarios, we vary different parameters in order to evaluate the new scheme in different channel conditions. Channel load has been shown in previous works as the major factor that undermines 802.11p performances [4, 6]. Many parameters play into determining the channel load. We recall the concept of Communication Density (CD) defined in [4] as follows:

$$CD = Range * Message\ Frequency * Nr.\ Lanes * Vehicle\ Density \quad (5)$$

In Eq.5 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 expressed in m*pkt/s/vehicle*lane*vehicle/lane/km (i.e., pkt/ms).

We also evaluate the packet reception rate with respect to the distance between vehicles while parameters are fixed in combinations of <range, message frequency, Nr. lanes, data rate, message size>. This is to have different channel loads by varying vehicles density. The parameters are presented in Table I.

Table I. System parameters

PHY radio model	SINR
Carrier Sense Range	550m
Transmission range	200m
DTIM	32ms
Threshold packet loss	5%
α	0,68
Dwell time-ratio	50% CCH Dwell
Time slot	13 μs
SIFS	16 μs
MAC type	802.11 (used with DSRC)
Channel bandwidth [Mbps]	6, 9,12,24
Traffic type	CBR (UDP)
Message frequency [/s]	10
Message payload size [byte]	500
Speed [km/h]	80-120
Traffic density [veh/km/lane]	10-100
Number of lanes	8
Simulation time [sec]	60

B. Results Analysis

1) Delay Metric Study (with and without EVDA)

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

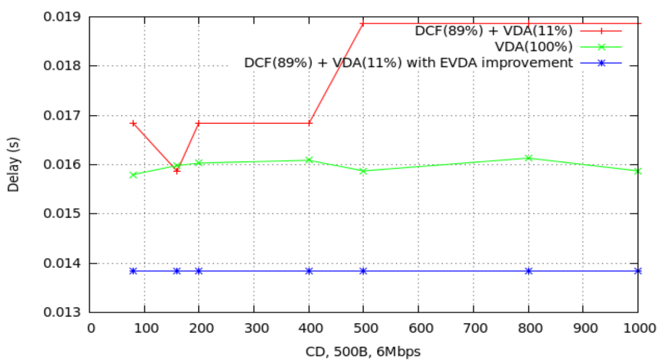

Fig.3 802.11p/VDA delay with and without EVDA improvement

Fig.3 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 (0,015s in average). However when we introduce DCF vehicles (89%) the delay of VDA vehicles increases to reach 0,0188s 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 89% of DCF vehicles. EVDA scheme reduces the one-hop delay for VDA vehicles to 0,013s which is very good for safety messages. Especially emergency messages, which requires a maximal delay of 150ms and might be relayed in a multi-hop manner by several vehicles.

This is the expected behavior from the EVDA scheme, since it prioritizes VDA vehicles messages over non-VDA vehicles when scheduling VDAOPs as shown in Fig. 2. For example, Fig 3 shows that when there is 89% of DCF vehicles and 11% of VDA vehicles, the delay of VDA is 0,013s with EVDA scheme. However, the delay of VDA nodes without EVDA is 0,018s.

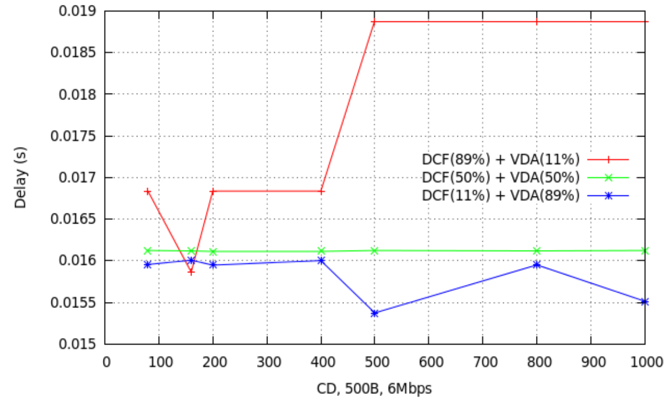

Fig.4 802.11p/VDA delay without EVDA improvement

In Fig.4, 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 to cases where the percentage of DCF nodes are 50% and 11% respectively (e.g., CD=1000, the VDA delay is 0,016s and 0,015s). 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.

2) Packet Reception Rate Metric Study (with and without EVDA)

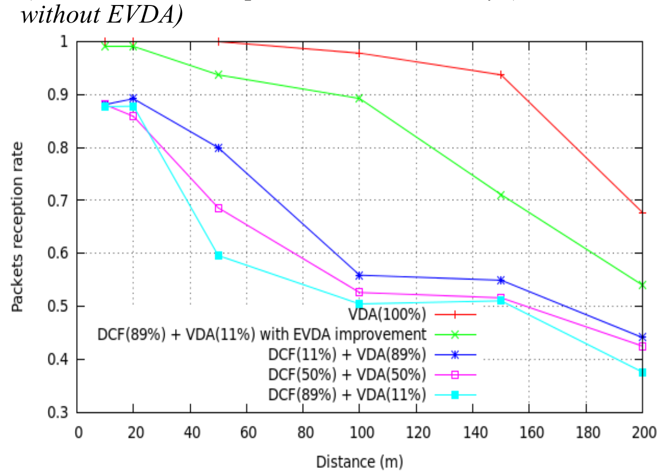

Fig.5 802.11p/VDA packet reception rate with and without EVDA improvement

Fig. 5 shows results of 5 scenarios with a data rate of 6 Mbps and the remaining parameters as shown in Table I. A distance of 20m corresponds to a value of CD of 160 and distance of 200m corresponds to a CD of 1000.

The figure clearly shows that when we introduce DCF vehicles with different percentages, the packet reception rate decreases significantly compared to the case where we have just VDA vehicles in the highway. In the one hand, Fig.6 shows the packet reception rate gap between different scenarios. For example at 100m distance, and for different DCF percentages (0%, 11%, 50%, 89%) the packet reception rates are respectively (97%, 60%, 52%, 50%). In the other hand, EVDA scheme improves significantly the results for the worst scenario having 89% of DCF vehicles, from a reception rate of 50% to 90%). Therefore, EVDA scheme outperforms the VDA scheme by 40% in presence of DCF vehicles.

At distance of 200m, when no DCF vehicles are present, VDA has a reception rate of 67%. The reception rate decreases though abruptly to values of (44%, 42%, 37%) in presence of DCF vehicles with percentages of (11%, 50%, 89%). 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 that can prevent this issue such the proposed EVDA improvement.

C. Impact on varying the time ratio of CFP/CP on safety messages in EVDA

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 1sec. We then define the dwell-time ratio as the time-percentage between CCH (CFP) and SCH (CP) interval (e.g., we could have 75% CCH Dwell and 25% SCH Dwell). 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 in order to look for the best adjustment, which allows a short delay and high reception rates for safety messages.

D. Results Analysis

While 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 DCF vehicles and 11% of VDA vehicles in the highway.

1) Delay Metric Study

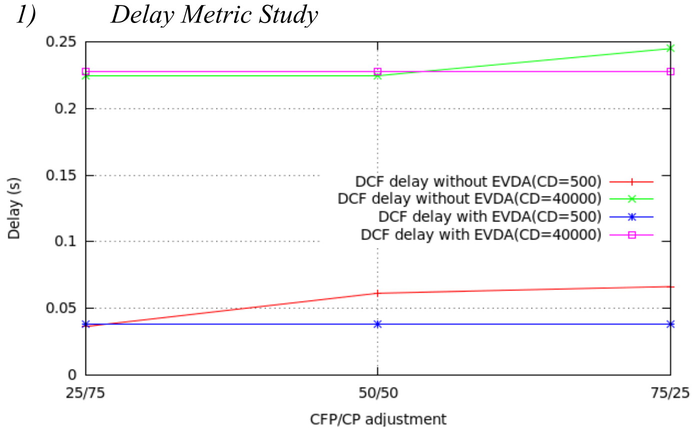

Fig.6 Delay for DCF vehicles with and without EVDA

Fig. 6 shows the delay for DCF vehicles with and without EVDA improvement in VDA vehicle when varying the CFP/CP adjustment for medium (e.g., CD=500) and high (e.g., CD=40000) communications densities. We remark that the DCF delay with EVDA scheme outperforms the DCF delay without EVDA for both medium and high communications densities by respectively (30% for CD=500 and 10% for CD=40000). 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 while for vehicles with VDA option, time slots are reserved for safety messages even for high channel loads, DCF only gets 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.

2) Packet Reception Rate Metric Study

We illustrate in Fig. 7 the packet reception rate 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 proposed in [8] over all the CFP/CP adjustments by almost 20%. This can be explained by the same reasons stated above.

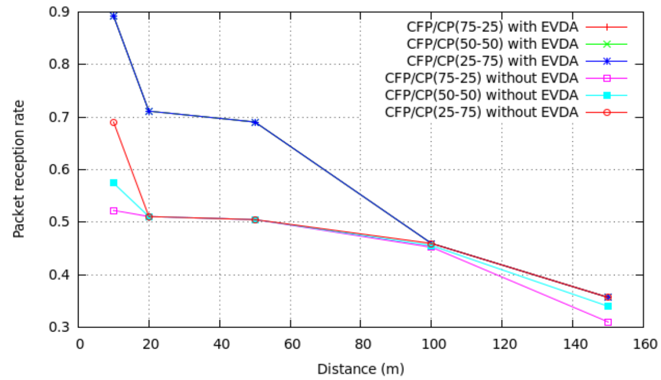

Fig.7 Packet reception rate for DCF Vehicles with and without EVDA

V. CONCLUSIONS AND FUTURE WORK

We investigated a mechanism called EVDA that prevents interfering 802.11p/DCF vehicles without deterministic access from accessing the scheduled transmission opportunities during the reserved time-slots for vehicles using deterministic VDA access over 802.11p/DSRC. Using simulations, we show that EVDA outperforms VDA scheme introduced in [8] and achieves a very good performance in terms of delay and packet reception rate for different percentage ratios of both types of vehicles for low, medium and high communication densities. 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.

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