On improving delay performance of IEEE 802.11p vehicular safety communication

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Abstract: In this work, we present the design of an efficient Deterministic medium Access (DA) for Dedicated Short-Range Communication (DSRC) vehicular safety communication over IEEE 802.11p, called Vehicular DA (VDA). VDA supports two types of safety services (emergency and routine safety messages) with different priorities and strict requirements on delay, especially for emergency safety messages. VDA processes both types of safety messages to maintain a balance between two conflicting requirements: reducing chances of packets collisions and lowering the transmission delay. VDA allows vehicles to access the wireless medium at selected times with a lower contention than it would otherwise be possible within two-hop neighbourhood with the classical 802.11p EDCA or DCF schemes. Besides, we propose an improvement of VDA called Dynamic VDA opportunities Re-assignment (DVR) to avoid network performance degradation caused by interference outside the two-hops. Particularly, our scheme provides an efficient adaptive adjustment of the Contention Free Period (CFP) duration to establish a priority between emergency and routine messages. Simulations show that the VDA scheme, used with 802.11p, clearly outperforms 802.11p alone in high-offered load conditions while bounding the transmission delay of safety messages. Furthermore, beyond two-hops, DVR is able to efficiently tackle the interference phenomenon by reducing losses and delays of safety applications.

Keywords: vehicular ad hoc networks; contention-free; safety messages; deterministic access.

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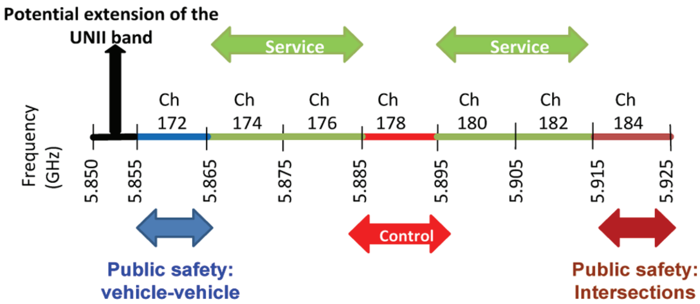
1 Introduction

Vehicular Ad hoc Networks (VANETs) is currently considered an essential technology for future road safety and telematics applications. The Federal Communications Commission (FCC) of the U.S. approved the 75 MHz 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 to be used exclusively for Vehicle-to-Vehicle (V2V) and Vehicle-to-Road side units (V2R) communications. Devices operating in DSRC spectrum will be using IEEE 802.11p by following the WAVE operation mode (Su and Zhang, 2007).

DSRC spectrum is made up of seven 10 MHz wide channels as shown in Figure 1. 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.

There has been a vast literature (Xiaomin et al., 2009), (Fan et al., 2006; Jiang et al., 2006; Zhe and Mahbub, 2008; Qi et al., 2009; Ching-Ling et al., 2010) on the description and evaluation of DSRC and VANET technologies. A thorough survey can be found in Fan (2006). Existing works that use DSRC/802.11p, stress the importance of meeting the strict delay and low packet collision requirements of safety applications, especially in high offered-load conditions and try to find adequate solutions to these issues. These works can roughly be divided into three categories: broadcast enhancement schemes (Jiang et al., 2006), MAC layer solutions for backoff algorithm improvement (Xiaomin et al., 2009) and communication rate and/or power adjustment strategies (Ching-Ling et al., 2010).

Figure 1 DSRC spectrum and channels in USA (see online version for colours)



Although IEEE 802.11p/EDCA or DCF was specifically designed to offer good performances in terms of delay and delivery rates for vehicular communications, it offers no guaranties neither on the former or the latter (Mangharam et al., 2007). Our novel proposed approach for Vehicular Deterministic Access, called VDA, establishes delay bounds for safety messages when used with 802.11p. To reach this goal, VDA uses deterministic access for safety applications and establishes a priority between routine and emergency messages. To the best of our knowledge, we are the first to consider DA over IEEE 802.11p.

Some of the factors that affect most IEEE 802.11p performance and reliability, especially at high vehicular densities, are its channel access priority mechanism and its CSMA backoff process. Emergency safety message requirements of low delay and low packet collisions are difficult to guarantee in dense vehicular scenarios, because of the random contention used by the traditional CSMA/CA MAC in IEEE 802.11p. Some studies tried to solve this problem by enforcing a contention-based MAC with complex schemes or by proposing modifications to the backoff algorithm (Xiaomin et al., 2009).

The development of a robust and efficient MAC protocol will be essential to the capability of DSRC devices in enabling reliable safety applications. To achieve such a protocol, we propose enhancements to the 802.11p medium access that are inspired from the optional Mesh Deterministic Access (MDA) mechanism proposed for IEEE 802.11s (Hiertz et al., 2007). This mechanism allows deterministic access to the medium at selected times to reduce the probability of collisions.

MDA aims to provide stringent MAC delay guarantees for real-time services such as Voice over IP (VoIP), which is a condition that can hardly be satisfied in classical IEEE 802.11 standard. The MDA scheme (Hiertz et al., 2007; Hiertz et al., 2008; Cicconetti et al., 2008) extends the IEEE 802.11 medium instantaneous reservation procedure, also known as the Virtual Carrier Sensing (V-CS), to a more advanced reservation procedure using scheduled MDA OPportunities (MDAOPs) within a two-hop neighbourhood. MDAOPs are first negotiated between neighbouring nodes by exchanging broadcast setup messages, then, MDAOPs reservations are performed in multiples of a time-slot unit, during the Delivery Traffic Indication Message (DTIM) periodic interval. To limit the message broadcast signalling overhead, MDA-related messages are sent only within two-hop neighbourhood.

It is worth noting though that while the MDA scheme is known to reduce to a certain extent the delay bounds, it lacks the concept of differentiating frames with different priorities. Basically, MDA provides a channel access with equal probabilities for all stations contending for the deterministic access in a distributed manner. However, equal access probabilities are not desirable among safety messages with different priories. Some recent studies as in Rezgui et al. (2010) show that enforcing MDA with an efficient adjustment of the Contention Free Period (CFP) allowing differentiation between different classes of services outperforms the Enhanced Distributed Channel Access (EDCA) in terms of delay and packets loss probability for IEEE 802.11s.
Our contributions: in this paper, can be summarised as follows:

- we first introduce and justify the adaptation of the mesh deterministic medium access named MDA to reduce packet collisions in IEEE 802.11p
- we improve and adapt MDA in the context of vehicular safety communication with two levels of safety services covering most of the possible safety applications; we call the new scheme VDA
- we derive analytically the corresponding expressions of the periodicity and VDA opportunity (VDAOP) duration in order to guarantee stringent delay bounds for safety messages
- we take into account the vehicles in the Carrier Sensing Range (CSR) to guarantee that none of these vehicles transmits/contends with the sender in order to ensure as high packet reception rates and as low collisions as possible
- we improve VDA to tackle interference outside two-hops
- we evaluate our model compared to standard 802.11p alone in terms of delay, packet loss and packet reception rate for both routine and emergency safety messages.

The remainder of the paper is organised as follows. Section II presents the motivation behind the integration of deterministic access in IEEE 802.11p. Section III proposes our scheme named VDA and presents a mathematical formulation of the keys parameters. Section IV introduces a new scheme, DVR that re-assigns slots to reduce interference outside two-hops. Section V evaluates the proposed solution via simulations. Finally, Section VI concludes the paper.

2 Motivation for the use of 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 (FCW) or Electronic Emergency Break Light (EEBL) which 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 MDA in IEEE 802.11p are as follows:

- 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 situation happens, the vehicles potentially affected are those which are nearby. Therefore, direct communication is enough to reach potentially affected vehicles. MDA is proven (Hiertz et al., 2007) to be more efficient within two hops range than classical DCF/EDCF and to guarantee a short delay.

- In low-load conditions, where collisions are very rare, CSMA provides lower delays than MDA since the former transmits almost instantaneously in random time slots. In low-load conditions, MDA has a slightly higher delay than CSMA primarily due to the problem of non-contiguousness of the reserved time-slots. MDA waits longer periods before being able to transmit in specific reserved contiguous time slots. However, in high-load conditions, the delay with MDA is bounded by x*DTIM (Rezgui et al., 2010); 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 MDA over IEEE 802.11p to take advantage of the bounded delay guaranties its offers.
- Vehicle safety communication networks are entirely distributed ad hoc wireless networks and MDA is a distributed deterministic medium access.

3 Proposed vehicular deterministic access scheme: VDA

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/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 AIFS parameters. Nevertheless, the Backoff process with EDCA involves a high probability of collisions, especially in high offered-load conditions.

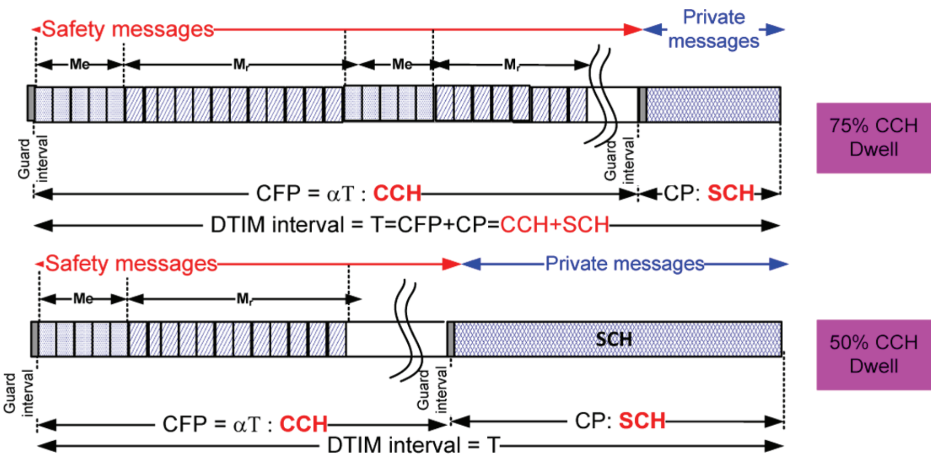
There are two types of safety messages: emergency safety messages (M_e) and periodic beaconing (or routine: M_r) safety messages. While emergency messages happen only occasionally and require very high reliability, less collisions and short delay, routine messages are broadcasted by all vehicles at a frequency up to 20 times per second. Routine messages contain the state of a vehicle such as its position and direction and they require low reliability and long latency compared to M_e (Xiaomin et al., 2009). In fact, one of the main concerns about 802.11p, is how it will perform when DSRC devices will be largely adopted thus making high-offered-load conditions very likely in dense traffic situations. There will be, in fact, continuous routine messages beaconing from most vehicles which share the medium with more urgent life-critical event-driven emergency messages.

3.2 Introducing VDA process in IEEE 802.11p

VDA scheduling is based on MDA concepts; therefore, we start by introducing MDA before going into detailing our proposed scheme VDA to show what we added and modified in basic MDA.

In basic MDA (Hiertz et al., 2007), the time between consecutive DTIM beacon frames is divided into time slots of length *32 μs*. The periodic broadcast of beacon frames to all radios in the transmission range allows the synchronisation of these DTIM intervals. Initially, nodes reserve the wireless medium for MDAOPs, which are reserved as multiples of time-slots during a given Contention Free Period (CFP) of a Maximum Access Fraction (MAF $= \propto T$) of the DTIM interval T (see Figure 2). The remaining part of the DTIM interval, as illustrated in Figure 2, is the Contention Period (CP) used for throughput-sensitive rather than delay sensitive data applications (it could be used in the context of VANETs for example for private service messages, M_p). Note that MDA does not support different services with different priorities and has the same behaviour for all service messages in the network. The message types illustrated in Figure 2 rather refer to VDA scheme.

Figure 2 VDAOP schedule for emergency (M_e) and routine (M_r) messages in VDA (see online version for colours)



We characterise each MDAOP (in MDA) / 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 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 nodes (Hiertz et al., 2007).

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. 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, *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: $\Pi^k{}_{M_x} \geq T / D^{\max^x}_{M_x}$. 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 (Eq. 1) and periodicity (Eq. 2) are expressed as follows:

$$\delta^k{}_{M_x} = \left\lceil \frac{AIFS_{M_x} + \frac{L_{M_x}}{C_{M_x}}}{\tau} \right\rceil \times \frac{N_{M_x} k \in N}{D_{M_x}} \text{ and} \tag{1}$$

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 $D_{M_x}^{\max}$ is a maximal delay for message x computed in Equation 3.

$$\Pi^k{}_{M_x} = \frac{DTIM}{D_{M_x}^{\max}} = \frac{T}{D_{M_x}^{\max}} \tag{2}$$

Figure 2 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 prioritises 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 multi-channel switching operation in WAVE allows the CCH and 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 Dwell time-ratio in VDA

In VDA, we use **CCH = CFP** Interval (**ICCH = ICFP**) and **SCH = CP** Interval (ISCH=ICP). As mentioned before, WAVE allows CCH and SCH to be different, just as long as the length of the Synchronisation Interval (ISynchronisation = ICCH+ISCH) which is in our case equal to DTIM interval. We assume that the DTIM is a divisor of 1sec. The ICFP and ICP are dynamically adaptable in VDA scheme.

3.4 Packet transmission delay in VDA

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 since we assume that a contention with other nodes 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 1-hop broadcast; each broadcast has π_1 packets to transmit in every DTIM interval. Then the service rate could be expressed by

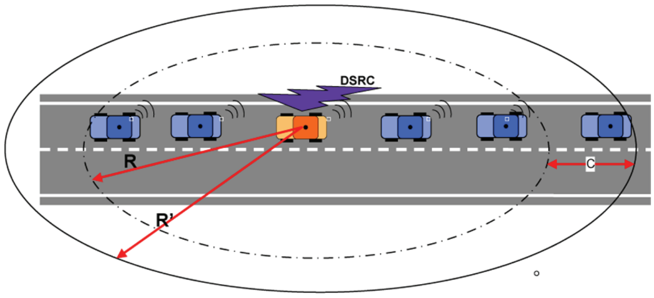
$$S_{rate} = \frac{\pi_1}{DTIM} \text{ for one-hop, otherwise for m-hop } S_{rate} = \frac{\pi_m}{DTIM} \quad D_{M_x}^{\max} = \frac{D_{M_x}}{m} \tag{3}$$

The maximal 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.

3.5 Probability of reception rate in VDA

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

Figure 3 Scenario (see online version for colours)



We assume that vehicles are placed on the line (see Fig. 3) according to Poisson process with network density β (vehicles/m) (Xiaomin et al., 2009). We can express the probability to have v vehicles per transmission range R as follows:

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

And the probability to have N_c vehicles per transmission range R'-R denoted by C as follows where R' is the carrier sensing range:

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

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 Probability of Reception Rate (P_{RR}) in transmission range R_s can be expressed as follows:

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

Therefore, we describe two cases:
Case1: $N_C = 0$

$$P_{RR}(S,R_s) = P(v,R_s) \times P_{s,R_s}(\delta_s,O_s) \tag{7}$$

where $P_{s,R}(\delta_s,O_s) \approx 1$ since the sender is the only owner of δ_s and offset O_s in its transmission range R. Since we use a deterministic access in VDA, we expect low collisions to be happening. The average number of vehicles in R is equal to 2πR while in C it is $N_c = 2\pi C$.
Case2: $N_c \neq 0$

$$P_{RR}(S,R_s) = P(v,R_s) \times P_{s,R_s}(\delta_s,O_s) \times P_{S',C_s}(\delta_s,O_s) \tag{8}$$

Where $P_{S',C_s}(\delta_S, O_S)$ is 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.

Let us define first P_0 as the probability that a vehicle has an emergency or a routine safety messages to transmit. In order to achieve deterministic access for vehicle S in its range 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.

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 equals to 2 slots with $N_c \geq 2$ (see Equation 9) and for CFP equals to 3 slots $N_c \geq 3$ (see Equation 10)

For CFP=2 slots; $N_c \geq 2$

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

For CFP=3 slots; $N_c \geq 3$

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

Then similarly,

For CFP=K slots and $N_c \geq K$ we express the following equations:

$$P_{S',C_s}(\delta_s, O_s) = \frac{(1-P_0)^K}{\sum_{k=0}^{K} A^k_{N_c} P_0^k (1-P_0)^{K-k}} \tag{11}$$

And for $N_c \leq K$,

$$P_{S',C_s}(\delta_s, O_s) = \frac{(1-P_0)^K}{\sum_{k=0}^{N_c} A^k_{N_c} P_0^k (1-P_0)^{N_c-k} (1-P_0)^{K-N_c}} \tag{12}$$

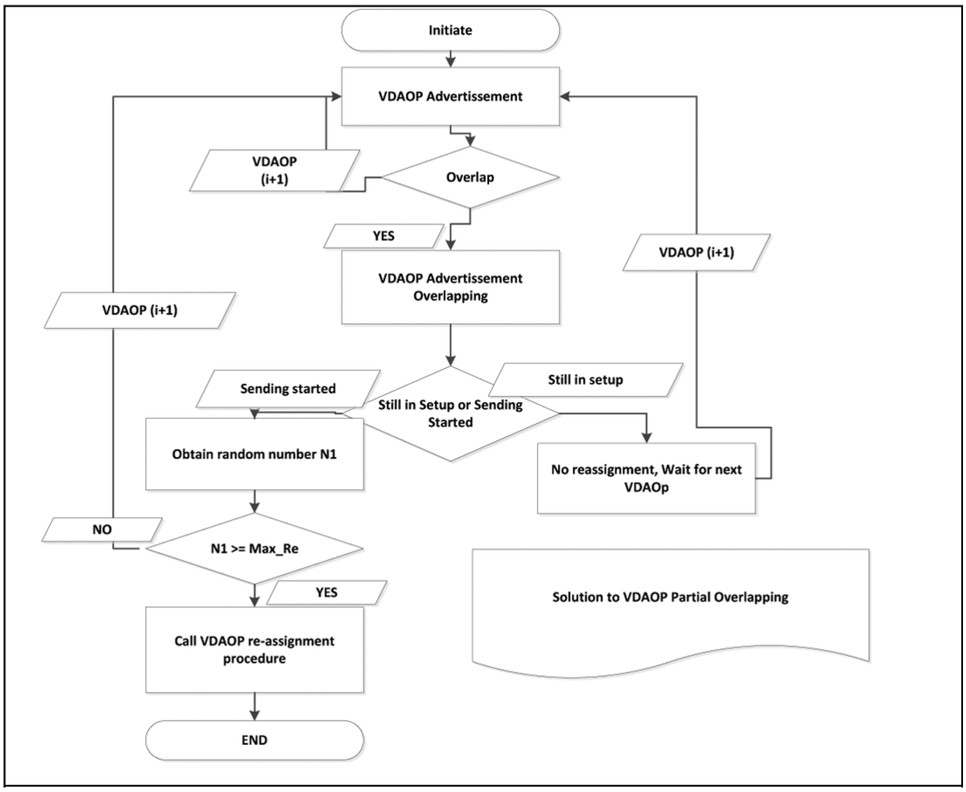
4 Dynamic vdaops re-assignment scheme: DVR

VDA mainly aims to satisfy the reliability of 802.11p message transmission within two-hop range from a vehicle. This is strict enough for the 15 types of routine and safety messages currently defined in SAE J2735 standard (Hartenstein and Laberteaux, 2009). In fact, VDA presents very good performances in terms of short delay, few packet losses and high reliability as will be shown in section V. However, VDA scheme may allow the overlapping of VDAOPs between two vehicles that are at least three hops away or more. Although not currently of concern, it may be useful in the future to ensure DA beyond a two hop range. For this we propose an optional improvement called Dynamic VDAOPs Re-assignment (DVR) as shown in Fig.4 and Algorithm. I. DVR allows addressing two types of concerns:

4.1 Partial overlapping of VDAOPs concern (addressed in Figure 4(a))

In this case a vehicle does not know anything about some possible concurrent setup between other vehicles outside its transmission range, but which are in its interference range so it can potentially accept a set of slots that are also being reserved among these vehicles. Although DVR addresses this issue efficiently as will be shown in the simulation sections, it is worth noting that this concern cannot be avoided completely because each vehicle has a different view of the DTIM utilisation.

Figure 4(a) Diagram chart of Dynamic VDAOPs Re-assignment (DVR) scheme (Partial overlapping of VDAOPs)

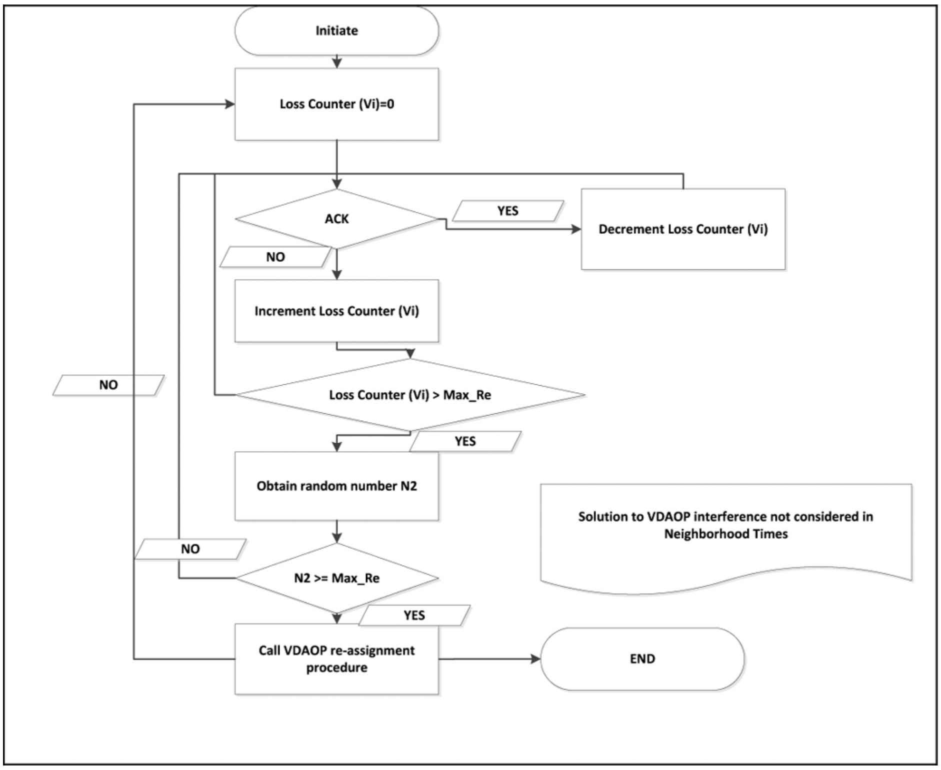


4.2 Interference with other VDAOPs reserved outside a two-hop range concern (see Figure 4(b))

VDA allows the overlapping of VDAOPs for vehicles at least three hops away. We illustrate with a diagram chart in Figure 4(b) an efficient algorithm that addresses this case.

DVR permits to overcome VDA limits mentioned above by re-assigning VDAOPs based on statistics collected during transmission times. Therefore, we add data structures for DVR. These structures contain the statistics obtained during transmission and information about current state. When a vehicle wants to select a set of contiguous slots to use for new VDAOPs, the VDAOP setup procedure is called.

Figure 4(b) Diagram chart of dynamic VDAOPs re-assignment (DVR) scheme (Interference with other VDAOPs reserved outside a two-hop range)



First a vehicle builds up a bit vector whose length equals the number of slots inside a DTIM, then sets all bits corresponding to VDAOP locations already in use, according to its own slots and all neighbour slots data structures. To tackle the two concerns mentioned above, we proposed a diagram chart for each of them in which we call a VDAOPs re-assignment procedure to re-assign the slots and to update a blacklist as detailed in Algorithm. I.

A vehicle sets bits that cannot be used because they are blacklisted or have been chosen by a VDAOP setup procedure still in progress.

The problem of placing demands (in terms of time slots) of vehicles within DTIM interval time resembles that of memory or file system management (Adan and Resing, 2001), which is well known in operating systems literature. So, a vehicle will select one or more of these slots according to either a 'random' and 'best' algorithms as expressed below.

With random allocation algorithm, a vehicle chooses the contiguous slots within DTIM interval randomly among the set of feasible slots (see Equation 13).

$$\{O_{first}, D_{first}\} = random\{O_i, D_i\} \quad (13)$$

In the best allocation algorithm a vehicle selects the smallest free contiguous slots $\{O_{best}, D_{best}\}$ which is able to contain a demand of D duration and O offset{O, D}, i.e.

$$\{O_{best}, D_{best}\} = \arg_{\{O_{best}, D_{best}\}} \min\{D_i - D\} \quad (14)$$

The effectiveness of VDA improved with dynamic re-assignment in a scenario with realistic safety application traffic is then confirmed via simulation analysis.

Algorithm I VDAOPs Re-assignment procedure

Algorithm. I. VDAOPs Re-assignment procedure
1. Call random/best allocation algorithm to allocate VDAOPs (VDA scheme). 2. Re-assign dynamically VDAOPs so as to achieve stable performance of the message that uses VDA. /*Losses could be involved due to **collision or interference** however, since we use deterministic access such VDA, a collision is prevented from occurring because of the schedule negotiation through VDA REQuests and VDA advertisement messages.*/ 3. VDAOP (V_i) is torn down by means of the VDA reservation messages; 4. The past location of the VDAOP is added to a **blacklist** of locations that cannot be scheduled to transmit to the granter of VDAOP (V_i); 5. A new location is selected using the scheduling algorithm employed for allocation (step 1); 6. Assign new slots **(Offset, Period, Duration)** to these messages; 7. Initiate the procedure for setting up a renewed VDAOP. 8. Timer ++; **if** $timer \geq timeout$ for each blacklisted location **then** the location can be used again for allocation;(reinitialize the blacklist)

5 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., VDA, with the classical 802.11p without VDA. We evaluate several metrics:

- the end-to-end delay
- the outage probability
- the packet reception rate
- the average delay.

We conduct also simulation outside two-hops to evaluate VDA and the improvement of VDA, named DVR.

The end-to-end delay is involved when safety related messages need to be relayed to other vehicles in a multi-hop manner (ex., post-crash message). The outage probability is defined as the ratio of the number of vehicles experiencing packet losses higher than the given threshold to the total number of vehicles in the VANET. The packet reception rate is rate of messages received within a one-hop range. The average delay is the average delay within a one-hop range.

5.1 Simulation configurations

We use a topology composed of 80 vehicles with 10 vehicles in each lane in an 8 lane highway (4 lanes/direction). The radio transmission range *r* takes one of the following values: 150 m, 200 m and 250 m and the Carrier sense range 550 m. Also, we fix the packet size to 1000Bytes. The parameters are presented in Table 1.

Table 1 System parameters

PHY radio model	*SINR*
Carrier sense range	550 m
Transmission range	150 m, 200 m, 250 m
DTIM	32 ms
Threshold packet loss	5%
a	0,68
Dwell time-ratio	50% CCH Dwell
Time slot duration	20 fx
MAC type	802.11 (used with DSRC)
Channel bandwidth [Mbps]	6, 9,12,24
Traffic type	CBR (UDP)
Period of message dissemination [ms]	100
Message payload size [byte]	1000
Number of vehicles	80
Speed [km/h]	100
Traffic density [veh/km/lane]	10-100
Number of lanes	8
Simulation time [sec]	60

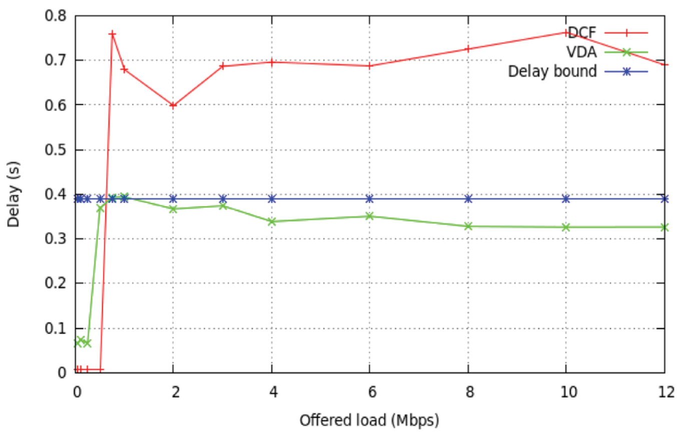
5.2 Results analysis (VDA scheme)

5.2.1 The delay study

We studied the performance of access methods DCF and VDA when transmitting data on the shared channel. We distinguish between low and high offered load conditions:

In light offered load conditions (0.05 Mbps-0.5 Mbps), where collisions are very rare, DCF access method provides lower delays, as shown in Figure 4, since it transmits almost

Figure 4 The end-to-end delay of both VDA and DCF (see online version for colours)



instantaneously in a random time slot no later than 0.68 ms. In low offered load conditions, VDA waits longer periods before transmitting in a specific reserved contiguous time slots. This is because VDAOPs cannot be scheduled to start until the end of a DTIM period of 32 ms. This scheduling is performed regardless to the absence of interferences and even if earlier time slots are available, since it needs contiguous available time slots to transmit packets. Therefore, the average access delay is higher with VDA compared to that of DCF when the offered load is low. However, one should note that in low offered load conditions, delays are very low both in DCF and VDA and the extra delay introduced by VDA is very low.

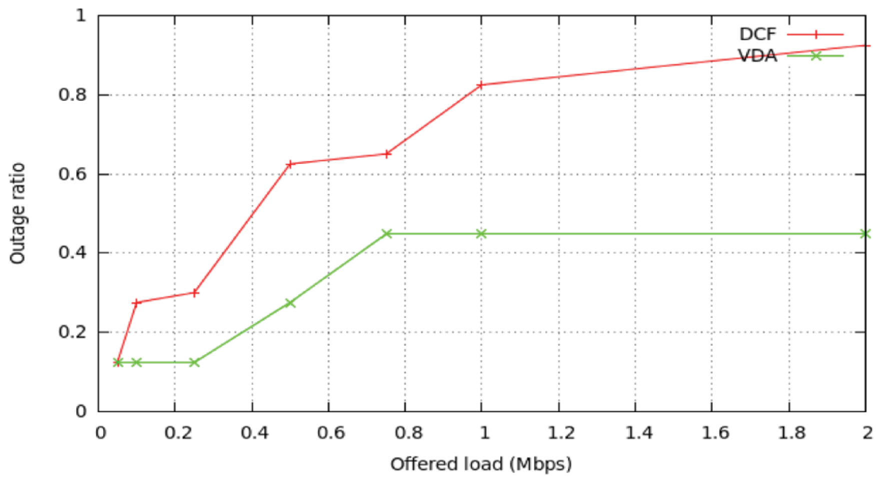
In high offered load conditions (0.75 Mbps-12 Mbps), VDA outperforms DCF and decreases the delay by a factor of two (i.e., VDA-0.34s and DCF-0.7s in average).

The end-to-end delay with VDA in simulations does not exceed 390 ms; it is bounded by the DTIM interval, which is equal to 32 ms, multiplied by the maximum number of hops in a path. Whereas the delay provided by DCF increases without any bounds with the increase of the offered load. For example, the delay with DCF reaches 725 ms at 8 Mbps and it results in many more vehicles contending for the communication channel, causing many more collisions and resulting in both longer backoffs and more frequent retransmissions. The delay improvement (for all loads) is about 40% for VDA compared to DCF.

5.2.2 The outage probability study

Figure 5 shows the outage for both VDA and DCF methods when varying the offered load. VDA outage is much lower since the VDA scheme allows vehicles to access the wireless medium at selected times with a lower contention than would otherwise be possible within two-hop neighbourhood by the classical 802.11p DCF scheme. Therefore, VDA outage which is related directly to message losses will obviously outperform DCF method. It presents an improvement of 46% over all loads as shown in Fig. 5.

Figure 5 The outage ratio of both VDA and DCF (see online version for colours)

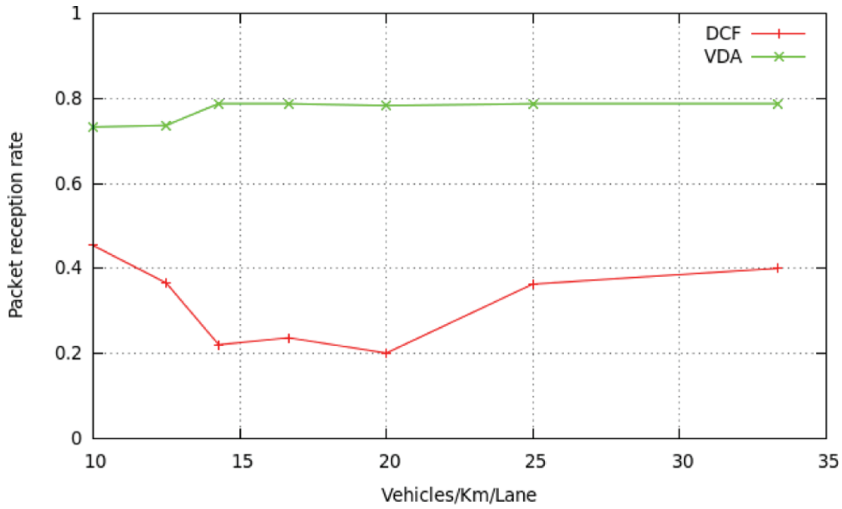


In the following set of experiments we fixed the offered load to 2 Mbps and varied vehicles density in order to assess the packet reception rate and the average delay in a one-hop range when many vehicles are contending for the medium in dense vehicular scenarios both for DCF and VDA methods.

5.2.3 The packet reception rate study

Figure 6 clearly illustrates the difference of results between DCF and VDA methods. DCF method suffers from inevitable collisions. Therefore, it has a significant drop in reception probability. The fact that VDA takes into account the vehicles in the carrier sense range to guarantee that none of them contends with the sender ensures high packet reception rates and low delays. VDA outperforms DCF by 42% in terms of reception probability. We note that in average for all densities, VDA packet reception ratio reception probability equals 0.78 and for DCF it equals 0.44.

Figure 6 The packet reception rate of both VDA and DCF (see online version for colours)

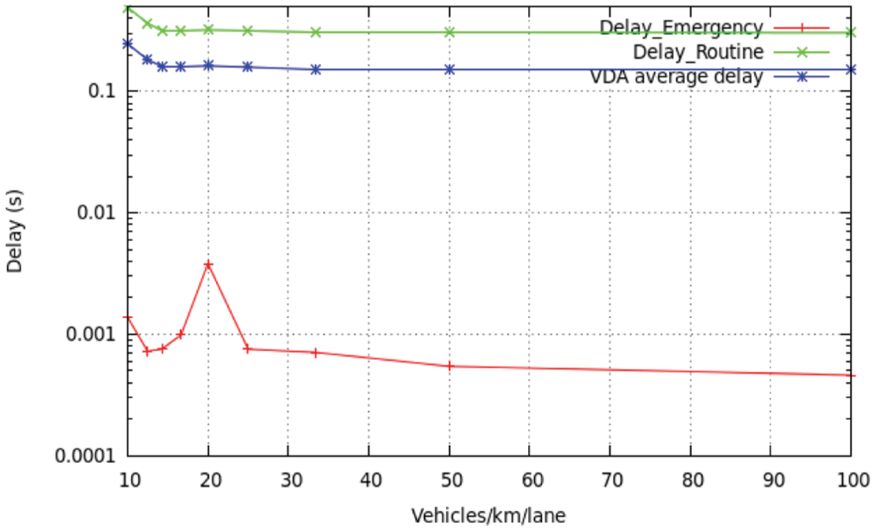


5.2.4 The delay of emergency and routine messages study

From vehicle safety point of view, it is crucial for vehicles in the highway to receive status updates (routine messages) from each neighbouring 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.

Figure 7 shows the delay of both emergency and routine safety messages when varying vehicle density. From the figure, we can see that, on the one hand, VDA ensures a very low delay for all densities that is less than 0.00112616s. This is very desirable since emergency messages usually involve urgent life-critical situations. On the other hand, routine messages have an average delay equal to 0.33s which is higher than the delay of emergency message but good enough for routine messages. This is the expected behaviour from VDA, since the scheme prioritises emergency messages over routine messages when scheduling VDAOPs as shown in Figure 2.

Figure 7 The delay of both emergency and routine messages in VDA scheme (see online version for colours)



5.3 Results analysis (DVR versus VDA) outside two-hops

With DVR scheme, we compute the average delay within a one-hop range while we reduce the interference of possible contending vehicles outside two-hops (within x-hops ($x > 3$)). Particularly, when a vehicle sends safety messages on its range, DVR scheme re-assigns new slots accordingly to avoid that outside two-hops, vehicles contend with the sender as shown in the chart diagrams above (see Figure 4(a) and Figure 4(b)). Both possible contention cases are taken into account; i.e., partial overlapping of VDAOPs and interference with other VDAOPs reserved outside a two-hop range.

Figure 8 shows the delay of both emergency and routine safety messages when varying vehicle density. We compared VDA scheme to DVR using two algorithms to place slots within DTIM; random and best fit algorithms. It is true that most of safety messages are based on direct or single hop broadcast communication among vehicles within the transmission range of one another. However, an additional improvement of the delay is required outside two-hops. DVR scheme tackles this issue by re-placing slots within DTIM while keeping packet loss rate under the predefined threshold loss as shown in Algorithm I. DVR is able to reduce significantly the delay as shown in Figure 8 using both slots placement algorithm from the literature i.e., the random and best fit. Using the random algorithm placement within DTIM, DVR reduces the delay by 41% compared to VDA for emergency messages. On the other hand, for routine messages DVR scheme reduces delay 40 times than VDA outside two-hops.

Figure 9 shows the packet loss rate for both VDA and DVR methods when varying the density. DVR loss is much lower since the DVR scheme re-assigns slots outside two-hop neighbourhood to avoid interference. VDAOPs should be relocated as few times as possible and only if this is required, e.g., if VDA transmissions experience significant performance degradation or cannot take place at all. We remark that DVR outperforms VDA in such case by 99%.

Figure 8 The delay of both VDA and DVR (see online version for colours)

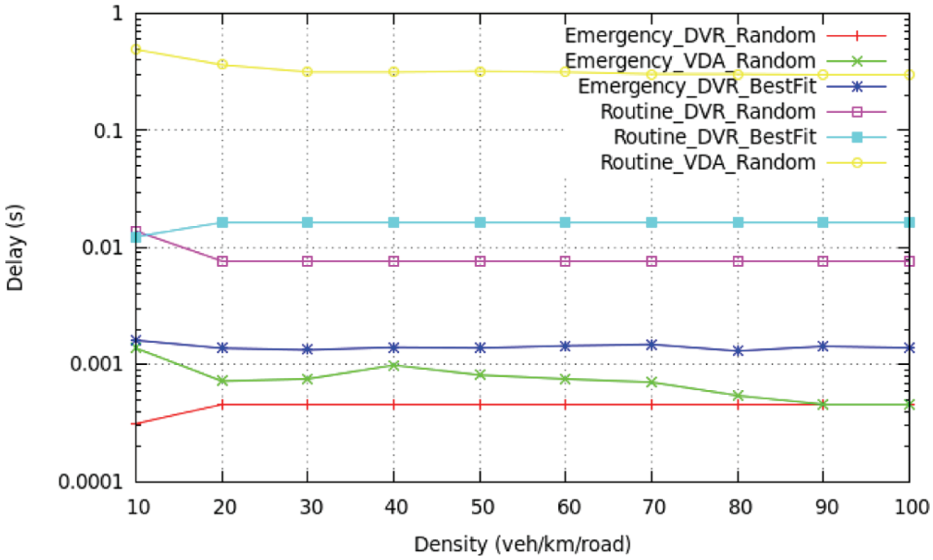


Figure 9 The packet loss rate of both VDA and DVR (see online version for colours)

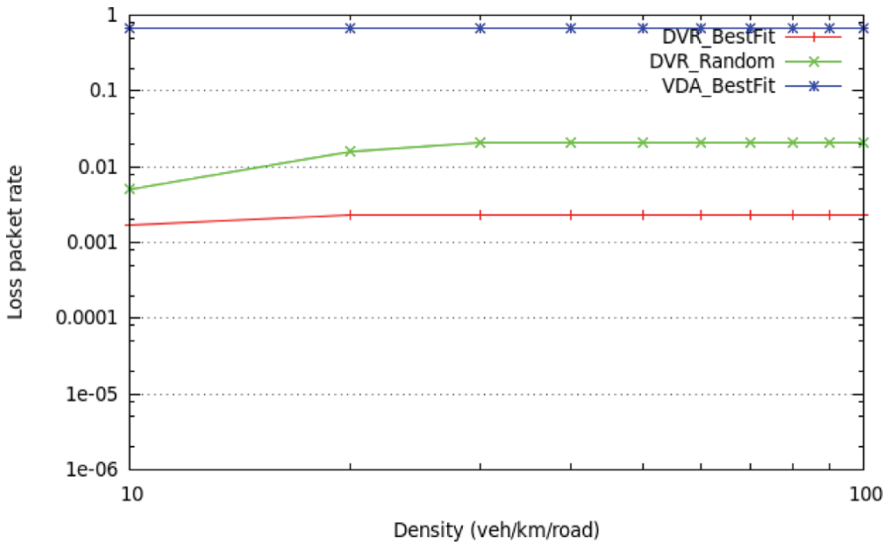
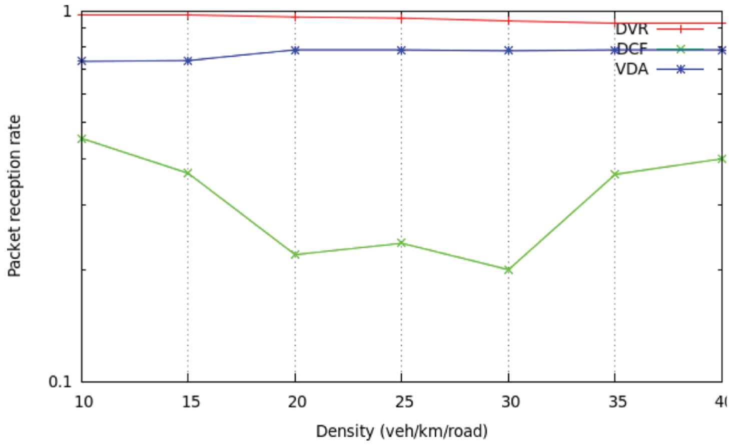


Figure 10 shows the packet reception rate for DCF, VDA and DVR. VDA presents a good performance compared to DCF but compared to DVR the packet reception rate is reduced by almost 23%.

We conclude that DVR outperforms VDA particularly in outside two-hops in terms of delay, packet reception and losses due to the efficient slots re-assignment when interferences happen outside two-hops.

Figure 10 The packet reception rate of DCF, VDA and DVR (see online version for colours)



6 Conclusions and future work

In this paper, we show how we minimise 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. An additional mechanism is also used to tackle interference outside two-hops by re-assigning slots and placing them using known algorithms in the literature such random and best fit when VDA transmissions experience significant performance degradation. using simulations, we show that the proposed approach, integrating deterministic access, outperforms DCF and achieves good performances in terms of delay and packet reception rate.

Currently, we plan to investigate a mechanism that prevents DTIM fragmentation during placement of VDAOPs within DTIM so as VDA or DVR schemes take into account this phenomenon when placing slots.

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