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Prioritizing and scheduling messages for congestion control in vehicular ad hoc networks

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A B S T R A C T

Vehicular Ad Hoc Networks (VANets) is considered as a technology which can increase safety and convenience of drivers and passenger. Due to channel congestion in high density situation, VANets' safety applications suffer of degradation of performance. In order to improve performance, reliability, and safety over VANets, congestion control should be taken into account. However, congestion control is a challenging task due to the special characteristics of VANets (e.g. high mobility, high rate of topology change, frequently broken rout, and so on). In this paper, DySch and TaSch strategies are proposed. Those strategies assign priorities to the safety and service messages based on the content of messages (static factor), state of network (dynamic factor) and size of messages. DySch and TaSch strategies schedule the messages dynamically and heuristically, respectively. Their performance is investigated using highway and urban scenarios while the average delay, average throughput, number of packet loss, packet loss ratio, and waiting delay in queues are considered. Simulation results show that DySch and TaSch strategies can significantly improve the performance of VANets in comparison to the best conventional strategies. Employing the proposed strategies to control congestion in VANets helps increase reliability and safety by giving higher priority to the safety messages.

1. Introduction

Vehicular Ad hoc Network (VANet) is a sort of Mobile Ad hoc Network (MANet) that aims at employing wireless technologies within Intelligent Transport Systems (ITSs). Dedicated Short Range Communication (DSRC) defines protocols and standards for conducting the Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications in VANets. VANet has special characteristics such as high rate of topology change, high mobility of nodes, high nodes density, sharing the wireless channel, and frequently broken rout. Those special characteristics in VANets give rise to some challenges in data transferring and scheduling [1–4].

When the channels are saturated due to the increasing number of vehicles, congestion happens in the networks. In other words, when the vehicles send messages simultaneously in high density situations, the shared channels are easily congested. Congestion indeed leads to overload the Medium Access Control (MAC) channels, increases the packet loss and delay, and consequently decreases the performance of VANets. Therefore, congestion should be controlled for enhancing the reliability of VANets [5–8]. Congestion control strategies aim at controlling the load on the shared channels and provide a fair channel access among the vehicles. Various strategies have been designed in each layer of network communication to control the congestion in VANets. Some of these strategies, which are designed for MAC layer, define priority for the messages and schedule them in different communication channels [9,10]. Data prioritizing and scheduling help serve more requests, reduce download delay and packet loss, and so on [11,12].

DSRC uses a 75 MHz bandwidth at 5.9 GHz for performing V2V and V2I communications and transferring the safety and service messages in VANets. DSRC employs IEEE 802.11p and IEEE 1609 standards for managing the performance of network by Wireless Access in Vehicular Environment (WAVE) systems. IEEE 1609.4 standard is also used to implement multi-channel in VANets. The DSRC bandwidth is composed of eight channels that consist of six 10 MHz service channels (SCH) for non-safety communications, one 10 MHz control channel (CCH) for safety communications, and one 5 MHz reserved channel for future uses. Fig. 1 shows channel allocation within DSRC. Normally, the control and service communication channels are used for different prioritized messages. Control channel is used to transmit high priority safety messages including emergency and beacon messages, and service channels are used to transmit low priority service messages [4,13,14].

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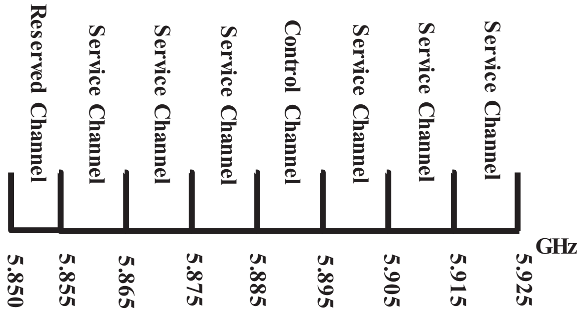

Fig. 1. DSRC channel allocation [13].

Table 1
CW boundaries for each kind of the message in EDCA.

Messages	CW_{min}	CW_{max}	AIFS
Background	CW_{min}*	CW_{max}*	7
Best Effort	CW_{min}	CW_{max}	3
Video	$(CW_{min}+1)/2-1$	CW_{min}	2
Voice	$(CW_{min}+1)/4-1$	$(CW_{min}+1)/2-1$	2

* $CW_{min}=15$ and $CW_{max}=1023$ as the default in DSRC [17–19].

All vehicles are synchronized by Coordinated Universal Time (UTC) to operate multi-channel on a single radio transceiver in VANets. The UTC is obtained based on information acquired from Global Positioning System (GPS) or the other vehicles. The vehicles adjust their time based on UTC and synchronously switch between CCH and SCH intervals. The IEEE 1609.4 WAVE protocol results in high delay to deliver high priority safety messages due to periodically switching between the channels [15,16].

To solve this issue, Enhanced Distributed Channel Access (EDCA) mechanism was considered in DSRC. EDCA assigns priorities to the messages such that the high priority messages have a higher chance to be sent. In other words, the high priority messages wait less than the low priority messages to occupy channel. This is accomplished by determining a shorter Contention Window (CW) and Arbitration Inter-Frame Space (AIFS) for high priority messages, as shows in Table 1 [17–19].

As it was mentioned before, when the number of vehicles increases, the control and service channels overload, and consequently congestion happens in the network that leads to increase delay and packet loss. Congestion in control channel can also occur when load of beacon messages increases due to high vehicle density. In this situation, safety messages (especially emergency messages) cannot be properly transmitted due to deficiency in the messages scheduling. It should be also noted that the scheduling in VANets is faced to some challenges because of sharing wireless communication channel, and employing multi-channel technology with single-radio transceivers. Therefore, an efficient scheduling is required to have more safe and reliable VANets [7,20,21].

In this paper, two congestion control strategies are presented to prioritize and schedule the safety and service messages. The proposed strategies consist of priority assignment unit, and message scheduling unit. The priority assignment unit assigns priority to each message based on static and dynamic factors. Then, the message scheduling unit reschedules the prioritized messages in the control and service channel queues. The performances of the proposed strategies are evaluated using various performance metrics including number of packet loss, packet loss ratio, average delay, and average throughput. The rest of the paper is organized as follows. Section 2 reviews the existing congestion control and messages scheduling strategies in VANets. Section 3 proposes the new strategies to control congestion that prioritize and schedule the messages. Section 4 applies the proposed strategies in a highway and urban scenarios and discusses the obtained results.

2. Background and related works

Congestion Control strategies are employed to achieve high communication reliability and bandwidth utilization within the networks. Generally, there are two types of congestion control mechanisms in networks: 1) open-loop mechanism that avoids the congestion before it happens, and 2) closed-loop mechanism that controls the congestion after it happens [22]. Congestion control strategies in VANets can be classified in to three categories: 1) controlling the power of transmissions, 2) controlling the rate of transmissions, and 3) prioritizing and scheduling the messages in communication channels [20].

The prioritizing and scheduling the messages is a very common open-loop congestion control strategy in communication channels. Some performance metrics should be considered to increase efficiency of message scheduling in VANets such as fairness, reliability, responsiveness, time constraint, data size, service ratio and data quality [23]. In the following, some existing algorithms to schedule the messages for transferring through the channels are introduced.

First-In First-Out (FIFO) algorithm is one of the simplest scheduling algorithms. In FIFO, the earliest arrival request is served first. Longest Wait Time (LWT) and Maximum Request First (MRF) algorithms schedule the messages based on the deadline of messages in the broadcast environment. Longest Total Stretch First (LTSF) algorithm considers a stretch metric for reducing waiting time. The stretch metric is defined as the ratio of request response time to its service time. First Deadline First (FDF) algorithm serves the most urgent requests, but it does not consider the service time for data. In Smallest Data Size First (SDF) algorithm, the data with smallest size serves first. However, the urgency of messages is not considered in SDF [23].

Maximum Quality Increment First (MQIF) algorithm schedules the messages based on Quality of Service (QoS) and Quality of Data (QoD) factors that consider the responsiveness and staleness of data, respectively. Least Selected First (LSF) algorithm gives opportunity to the messages that had least opportunity to be served before. Finally, D∗S algorithm defines priorities of messages based on Deadline (D) and Size (S) of message [23]. In the rest of this section, some of the proposed congestion control strategies in VANets are presented.

Torrent-Moreno et al. [24] developed a distributed congestion control strategy called Distributed-Fair Power Adjustment for Vehicular environment (D-FPAV). In this strategy, after congestion detection, the beaconing transmission range is dynamically tuned based on vehicle density. However, when transmission range of beacon messages is decreased in congestion situation, the probability of receiving the beacon messages in far distances reduces. Therefore, the performance of applications that need information through beacon messages is disrupted.

Bai et al. [25] proposed Context Awareness Beacon Scheduling (CABS) strategy to control congestion that may occur due to the high broadcasting rate of beacon messages within dense vehicular networks. The proposed congestion control strategy was a distributed strategy. CABS scheduled the beacon messages dynamically by employing piggybacked context information in beacon messages like velocity, direction and position. Then, a time slot was assigned to each node using TDMA-like transmission. Although CABS improved channel access delay and packet reception rate by scheduling the beacon messages, MAC layer interworking was not considered during adjusting time slot to each node.

Taherkhani and Pierre [26], proposed Uni-Objective Tabu search (UOTabu) congestion control strategy in order to increase reliability of applications in VANets. In this strategy, the congestion was first detected by monitoring the channel usage, and then Tabu Search algorithm was used for tuning transmission rate and range. UOTabu determines transmission rate and range by considering the minimum delay. The application of UOTabu showed that this strategy can reduce the average delay and packet loss more than the other strategies.

Taherkhani and Pierre proposed Uni-Objective Tabu search (UOTabu) [26] and Multi-Objective Tabu search (MOTabu) [27] congestion control strategies in order to increase reliability of applications in VANets. In these strategies, the congestion is detected by monitoring the channel usage, and then Tabu Search algorithm is used for tuning transmission rate and range. In UOTabu strategy, delay is considered as objective function of Tabu Search algorithm, whereas in MOTabu, delay and jitter are considered as objective functions of Tabu Search algorithm. In addition, MOTabu strategy consider the short-, mid-, and long-term memories in proposed Tabu searched for determining near optimal transmission range and rate. The application of UOTabu and MOTabu showed that these strategies can reduce the average delay and packet loss more than the other strategies.

Felice et al. [21] introduced WAVE-enhanced Safety message Delivery (WSD) that is compatible with IEEE 1609.4 and IEEE 802.11p standards. WSD solved the problems of multi-channel technology in VANets, and single-radio transceivers in vehicles by scheduling safety and non-safety messages. Although the proposed strategy reduced delivery delay of the safety messages, multi-hop communications in VANets were not considered.

The most of congestion control strategies in VANets are performed by prioritizing messages in MAC layer. Suthaputchakun et al. [28] proposed a priority-based strategy using EDCA mechanism to increase safety in highway environments. Each inter-vehicle communication message was prioritized based on urgency and average delay. This strategy increased the reliability in vehicular environments by giving more chance of transmission to messages with higher priority (emergency messages). This strategy improved the delay and ratio of successful retransmission.

Bouassida et al. [29] introduced a congestion control strategy that controlled the load of the wireless channels. The introduced strategy reduced congestion in control channel, and delay of safety messages. In this strategy, the priorities were assigned to messages based on utility and validity of messages, and speed of senders and receivers. Then, the messages were scheduled in the control and service channel queues. The simulation results showed that the delay of safety messages decreased in this strategy. However, in worse-case scenario, the delay was more than 50 milliseconds.

There are several deficiencies associated with these congestion control strategies when they are applied in practice. In the following, it is tried to point out these deficiencies. Some of the congestion control strategies do not pay enough attention to the emergency messages; the emergency messages are broadcasted with high delay [3], or the packet loss ratio of emergency messages is high [21] that leads to unsafe and unreliable situations in VANets.

Moreover, in some strategies that control the congestion by changing contention window size, congestion costs increases and throughput decreases. In these strategies, CSMA/CA protocol, which is used for accessing to communication channel, employs the exponential back-off mechanism [30]. Since this mechanism is not efficient for broadcasting the beacon messages in dense vehicular networks, in the case the messages have time-out, dropped packets increase before transmission [30–32]. We present a summary of iterated congestion control strategies for VANets in Table 2.

3. Problem statements and solving strategies

IEEE 1609.4 WAVE enabling multi-channel communications in VANets prioritizes and schedules various messages. Prioritizing and scheduling the messages are crucial tasks in VANets due to the large number of parameters should be considered, especially in large networks, [7,20,21,23,33]. In this section, two different congestion control strategies are proposed by employing more efficient scheduling and prioritizing mechanisms in order to enhance safety and reliability of VANets. To assign the priority to the messages and schedule them in the control and service channels queues, many factors related to content of messages and situation of vehicles are taken into account such as size and type of messages, velocity of senders and receivers, validity of messages, and so on.

Fig. 2 depicts the schematic of the proposed congestion control strategies. These strategies consist of two units: A) priority assignment unit, and B) message scheduling unit. The priority assignment unit defines priority of messages based on static and dynamic factors. The message scheduling unit reschedules the prioritized messages in the control and service channel queues. The operation of message scheduling unit is different in two strategies. These strategies are distributed because each node in VANets independently prioritizes and schedules the messages. The proposed congestion control strategies are also open-loops strategies that avoid congestion occurrence by prioritizing and scheduling messages.

3.1. Priority assignment unit

In the priority assignment unit, priorities are assigned to the messages generated by applications in the vehicle or received from the other vehicles. Then, the relative times of transmission are determined for the messages based on the assigned priorities. In this paper, the priority of each message is defined based on static and dynamic factors as well as size of message:

$$Priority_{Message} = \frac{Static_{Factor} \times Dynamic_{Faactor}}{\mathrm{Message}_{Size}} \tag{1}$$

$\mathrm{Priorit}y_{Message}$ is directly proportional to $Static_{Factor}$ and $Dynamic_{Factor}$. However, because the emergency and high priority safety messages have smaller size compared to the other messages, $Priority_{Message}$ is opposite proportional to $Message_{Size}$.

The $Static_{Factor}$ is defined based on the content of messages and type of applications. $Static_{Factor}$ for a message is considered to be 1, 2, 3, 4, or 5 if the message belongs to $Priority_{Service\text{-}Low}$, $Priority_{Service\text{-}High}$, $Priority_{Safety\text{-}Low}$, $Priority_{Beacon}$, or $Priority_{Emergency}$ category, respectively [29]. In the following, each category is defined:

1. $\boldsymbol{Priority_{Service\text{-}Low}}$ is assigned to the messages generated by low priority service applications such as instant messaging (between vehicles), parking spot locator, electronic toll payment, internet service provisioning, and so on [34,35].
2. $\boldsymbol{Priority_{Service\text{-}High}}$ is defined for the messages generated by high priority service applications such as intelligent traffic flow control and map download/update/GPS correction, and so on [34,35].
3. $\boldsymbol{Priority_{Safety\text{-}Low}}$ is considered for low priority safety messages generated by the applications of forward collision, lane change warning, left turn assist, stop sign assist, and so on [34,35].
4. $\boldsymbol{Priority_{Beacon}}$ is considered for the safety beacon messages which are periodically transmitted in VANets for broadcasting the vehicular information such as position, speed, direction, and so on. This information is important for many of the safety applications and some of the service applications.
5. $\boldsymbol{Priority_{Emergency}}$ is considered for the emergency messages. These messages have the highest priorities and should be delivered without any delay. Some of the applications that generate the emergency messages are emergency brake lights, emergency vehicle approaching warning, emergency vehicle at scene

Table 2
Comparison of congestion controls strategies for VANETS.

Proposed strategy	Used technique	Considered parameters	Limitations
EDCA [17–19]	Message prioritizing	CW and AIFS	High delay for service messages
D-FPAV [24]	Tuning beacon transmission power	Beacon load	Small probability of receiving beacon in far distance when the transmission power of beacon messages is reduced
CABS [25]	Beacon scheduling	Time slot assignment	Mac layer internetworking was not considered
UOTabu [26]	Tuning transmission range and rate	Minimum delay for transferring safety and service messages	Hidden terminal problem and Mac layer internetworking are not considered
MOTabu [27]	Tuning transmission range and rate	Minimum delay and jitter for transferring safety and service messages	Hidden terminal problem and Mac layer internetworking are not considered
WSD [21]	Message scheduling	Scheduling safety and service messages	Multi-Hop communications are not considered
Suthaputchakun et al. [28]	Message prioritizing	Urgency and average delay	Disruption of ongoing transmissions on SCHs and Safety Messages suffer due to switching between channels, especially in dens network
Bouassida et al. [29]	Message prioritizing	Speed of vehicles, utility and validity of messages	High delay and system overhead

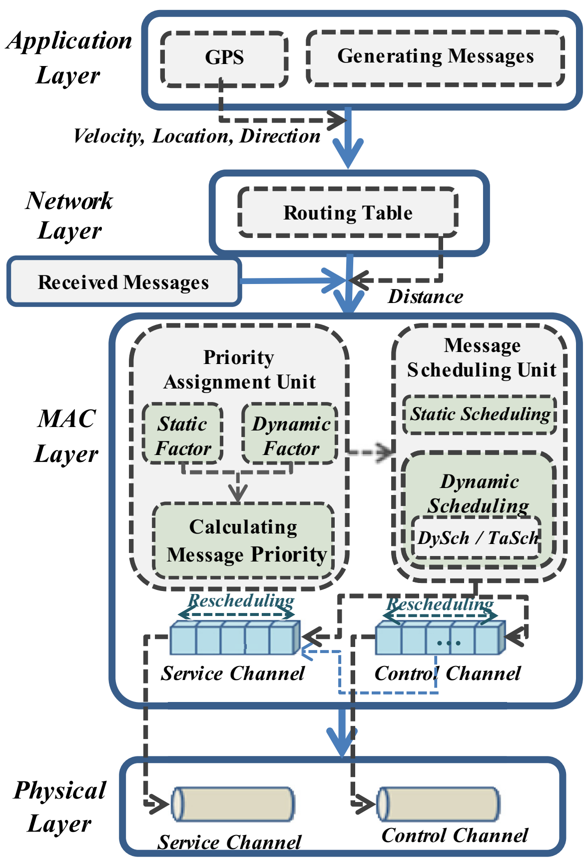

Fig. 2. Schematic of the proposed congestion control strategies.

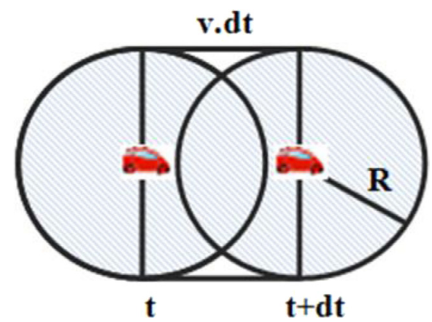

Fig. 3. Velocity metric (Vel.).

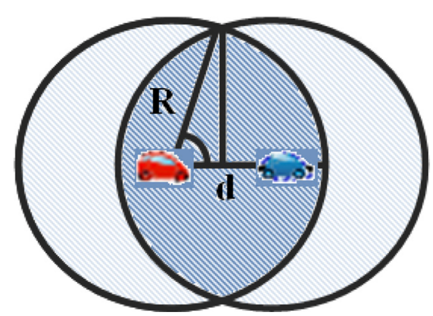

Fig. 4. Usefulness metric (Use).

warning, intersection collision warning, pedestrian crossing information, and so on [34,35].

In contrast of static factor defined based on the content of messages and type of applications, dynamic factor is defined based on circumstances of VANets. The metrics considered for calculating the dynamic factor are velocity of vehicles, usefulness of messages, validity of messages, directions of sender and receiver vehicles, distance between sender and receiver vehicles. In the following, these metrics are described in details.

1. ***Velocity metric (Vel):*** This metric represents the relative speed of message sender that is defined based on the total coverage area of a vehicle traveling with velocity v during time dt (Fig. 3):

$$Vel = \frac{\pi \times R^2 + 2 \times R \times v \times dt}{\pi \times R^2} \tag{2}$$

where R is communication range, and v is average speed of vehicle in time dt. Indeed, for affecting the speed of the vehicle on dynamic factor, the area covered by the vehicle in a specific short time is calculated. This factor is normalized using divide by the communication range of vehicle [29]. A higher priority should be assigned to the message with higher Vel metric. In the other words, a vehicle moves with higher speed, covers a higher area in unit of time; however, the probability of disconnection for this vehicle is high.

2. ***Usefulness metric (Use):*** This metric is defined according to the probability of message retransmissions by the neighbor vehicles. The usefulness is determined by ratio of total communication area and overlapped area (Fig. 4):

$$Use = \frac{Communication_{Area}}{Overlapped_{Area}} \tag{3}$$

where the $\text{Overlapped}_{\text{Area}}$ is calculated using (4):

$$Overlapped_{Area} = 4 \times \left(\arccos\left(\frac{d}{2 \times R}\right) \times \frac{R^2}{2} - \frac{d}{4} \times \sqrt{R^2 - \left(\frac{d}{2}\right)^2} \right) \quad (4)$$

where d is distance between sender and receiver vehicles. Therefore, the usefulness metric is:

$$Use = \frac{\pi \times R^2}{4 \times \left(\arccos\left(\frac{d}{2 \times R}\right) \times \frac{R^2}{2} - \frac{d}{4} \times \sqrt{R^2 - \left(\frac{d}{2}\right)^2} \right)} \quad (5)$$

Based on (5), when the $Overlapped_{Area}$ is relatively high, usefulness metric is low. In this case, because there is a high possibility that the message will be received again from the neighbor vehicles, it is not necessary to assign a high priority to the message to be sent. Thus, a lower priority should be assigned to the messages with lower *Use* metric. Therefore, to consider the possibility for retransmission of messages, the overlapped area between the communication range of sender and receiver vehicles is calculated and then using communication area of receiver vehicle is normalized [29].

3. ***Validity metric (Val):*** Validity metric is posed as the age of the messages. In other words, it is defined as the remaining time to the message deadline in real-time applications. When the remaining time to the message deadline is short, the priority of a message is high. Therefore, the priority of message as well as dynamic factor is opposite proportional to the validity [29]. The validity can be given by (6):

$$Val = \frac{Remaining\ Time\ to\ the\ Deadline}{Transferring\ Time} \quad (6)$$

Transferring Time in this equation, which is used for normalization, shows an estimated time to transfer message between sender and receiver vehicles.

4. ***Distance metric (Dis):*** This metric is considered as a relative distance between message sender and receiver. If the distance metric is high, the probability of disconnection between two vehicles is also high; therefore, a higher priority should be assigned to the message. On the other hand, if the distance between two vehicles is low, a lower priority should be assigned to the message because the connection duration is relatively long; there is enough time for the message to be sent. This metric is therefore directly proportional to the message priority.
5. ***Direction metric (Dir):*** direction metric shows that two vehicles (sender and receiver) are driving closer to each other (Dir=0) or they are driving away from each other ($Dir = 1$). If the sender vehicle is being close to receiver, the probability of connecting increases; thus, the lower priority should be assigned to the message. In contrast, if two vehicles drive away from each other, the probability of disconnection and breaking the route between them increases; thus, a higher priority should be assigned to the message.

By combining (2) to (6), the dynamic factor is calculated by (7):

$$Dynamic_{Factor} = \begin{cases} \dfrac{Vel \times Use}{(Val + 1) \times Dis} & Dir = 0 \\ \dfrac{Vel \times Use \times Dis}{(Val + 1)} & Dir = 1 \end{cases} \quad (7)$$

Based on (7) and (1), dynamic factor and consequently message priority are directly proportional to *Vel* and *Use* metrics. However, dynamic factor and message priority are opposite proportional to *Val* metric [29]. In this equation, *Val* metric is added to 1 to avoid ambiguous result when the validity is equal to zero.

Eq. (7) shows that dynamic factor is opposite proportional to *Dis* metric when *Dir* is equal to 0. However, dynamic factor is directly proportional to *Dis* when *Dir* is equal to 1. When *Dir* is equal to 0, two vehicles are driving closer to each other and the distance between them decreases. Thus, lower (higher) priority should be assigned to the messages transmitted by the vehicles that are being close to each other and have a high (low) distance. The lower (higher) priority is given to this message because there is a high (low) chance that two vehicles have longer connection. On the other hand, when *Dir* is equal to 1, two vehicles are driving away from each other and the distance between them increases. Thus, higher (lower) priority should be assigned to the messages transmitted by the vehicles that are driving away from each other and have a high (low) distance. The higher (lower) priority is given to this message because there is a low (high) chance that two vehicles stay in communication range of each other.

Here, it should be mentioned that the required information for calculating dynamic factor is obtained from GPS and the routing table. In addition, for prioritizing the messages, EDCA is carried out in the background. EDCA is the default strategy of prioritizing in VANets [17–19].

Finally, the priorities of messages are calculated using (1) based on static factor, dynamic factor and message size. Then, the calculated priorities are embedded in the header of packets.

3.2. Message scheduling

To provide a reliable data transferring, the message scheduling is crucial. However, it is a challenging task in VANets due to unique characteristics of these networks (i.e. high mobility, high rate of topology change, distributed control, high speed of vehicles, and so on). In this paper, in order to enhance reliability and safety in VANets, IEEE 1609.4 multi-channel MAC was improved. Indeed, in the message scheduling unit, the control and service channel queues are rescheduled before transferring to the channels. For this purpose, the message scheduling is conducted in two steps of static and dynamic scheduling.

In the static scheduling step, the messages are transferred to either control channel queue or service channel queue based on static factor defined in priority assignment unit. Here, two channel queues (control and service) were assumed due to two types of channels (control and service) in VANets. In static scheduling step, the messages with $Priority_{Emergency}$, $Priority_{Beacon}$, and $Priority_{Safety\text{-}Low}$ priorities are transferred to control channel queue, and the messages with $Priority_{Service\text{-}High}$ and $Priority_{Service\text{-}Low}$ priorities are transferred to service channel queue. In addition, when the control channel queue is full, the messages with $Priority_{Emergency}$, $Priority_{Beacon}$, and $Priority_{Safety\text{-}Low}$ priorities are transferred to service channel queue for improving safety in VANets. Fig. 5 shows the static scheduling process in the message scheduling unit.

The dynamic scheduling step is carried out in two different methods: i) using the message priorities calculated in priority assignment unit, and ii) using the meta-heuristic techniques for rescheduling the messages in each queue. For dynamic scheduling based on the message priorities (i), the packets in each queue are rescheduled when a new packet is entered to the queue. Indeed, the packets in each queue are reordered descending based on their priorities calculated by (1). Then, the packets are dequeued from the control or service channel queues to transfer to the control or service channels. The strategy uses this method for dynamic scheduling is referred as “DySch”. Indeed, DySch is used to refer a strategy that just used the defined priorities to schedule the control and service queues for dynamic scheduling.

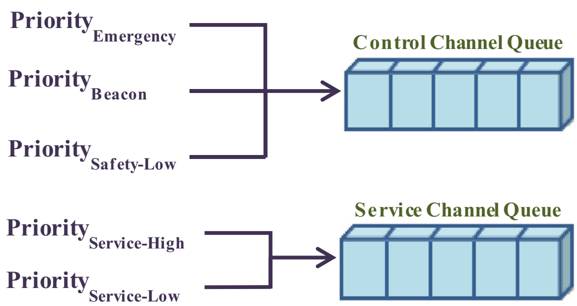

Fig. 5. Static scheduling process.

For dynamic scheduling, the meta-heuristic techniques can be also employed (ii). Considering that the simple scheduling problems are NP-hard [36], the message scheduling is also an NP-hard problem due to the constraints of the vehicular environments. The meta-heuristic techniques can find near-optimal solutions in reasonable time for these kinds of the problems [37]. Tabu Search algorithm, which is one of the best meta-heuristic techniques, is usually used for graph theory problems, scheduling, vehicle routing, multi criteria optimization, and real-time decision problems, and so on [38]. Therefore, it can be used for dynamic scheduling in order to reschedule the packets in each queue. The strategy using Tabu Search for dynamic scheduling is referred as "TaSch". TaSch strategy is used to address a strategy that just used the Tabu Search algorithm to heuristically schedule the control and service queues for dynamic scheduling. Indeed, in TaSch strategy, a Tabu Search algorithm is employed to schedule the control and service channel queues in a reasonable time. For this purpose, the delay and jitter of messages delivery are minimized, as well as the priority of messages are considered.

Main elements of Tabu Search are objective function, memory mechanisms, Tabu list, initial solution, neighborhood set, candidate list, termination rules, and so on [38,39]. In the following, Tabu Search elements are described in more details.

To provide a safe and reliable environment in VANets, delay and jitter of the message transferring should be minimized. Also, higher chance should be given to the more important messages to be sent. Therefore, in this paper, to minimize the delay, jitter is considered as the objective of the Tabu search algorithm. In the Appendix, the equations used for calculating the delay and jitter are presented.

Memory mechanisms of Tabu Search include short-, mid-, and long-term memories. The tabu list is considered as a short-term memory that keeps the best generated solutions. When a new solution is selected as a best solution, this solution is put on the tabu list. A new solution is compared with the solutions in tabu list to avoid selecting the repeated solutions. In this paper, the size of tabu list is assumed to be 50. Therefore, it is limited to add the best solutions in tabu list. If the tabu list is full, the oldest solution will be deleted from the list.

The mid-term memory is used to intensify the search in order to find the better new near-optimal solutions. The mid-term memory is considered as a list of best solutions found in specific areas. In this paper, the size of this list is assumed to be 5. The proposed Tabu Search algorithm periodically selects the initial solution among the mid-term memory list to generate a new solution. Initial solution of the Tabu Search algorithm is the current state of control and service channel queues. The long-term memory is used to diversify the search to help avoid entrapment in local optimum. In the proposed Tabu Search algorithm, new initial solution is periodically generated far from the best solutions of the tabu list to generate diverse solutions.

The neighborhood set is defined by changing the order of packets in the queues. The feasible solutions is selected among the solutions in the neighborhood set and then put in the candidate list. Feasible solutions are the solutions that are not included in tabu list. The last element of Tabu Search algorithm is termination rule that is the number of iterations. In the proposed Tabu Search algorithm, based on some preliminary simulations, the number of iterations is assumed to be 25, which is half of the queues length in VANets. Fig. 6 shows the pseudo code of the proposed Tabu Search algorithm.

4. Performance evaluation

4.1. Scenarios and simulation parameters

For evaluating the performance of the proposed scheduling strategies in VANet, mobility and network simulators should be employed. In this paper, Simulation of Urban Mobility (SUMO) [40,41] and Network Simulator (NS) version 2.35 [42] were used for mobility and network simulation, respectively. Mobility model generator for Vehicular networks (MOVE) was also used for making connection between SUMO and NS2 [43].

In this paper, a six-lane highway and Manhattan-pattern urban scenario were simulated to assess the performance of the proposed strategies. Table 3 shows the parameters used in the simulations of highway and urban scenarios. IEEE 802.11p was considered as the communication protocol. CSMA/CA strategy was also used as transmission strategy in MAC layer. TwoRayGround and Nakagami were employed to model the propagation in highway and urban scenarios, respectively. The Poisson distribution was also used for generating the data traffic. A table-driven routing protocol like Destination-Sequenced Distance-Vector (DSDV) is assumed in simulations.

4.2. Simulation results and performance evaluation

In this section, the performance of the proposed scheduling strategies are compared with four congestion control/scheduling strategies including FIFO [23], EDCA [17–19], D-FPAV [24], and CABS [25]. Note that DySch represents the scheduling strategy using the dynamic factor while TaSch represents the scheduling strategy using multi-objective Tabu Search. For evaluation of the performance of DySch and TaSch strategies, five performance metrics are evaluated:

Average Delay: The average time required to transfer the packets from senders to receivers;

Average Throughput: The rate of successfully received packets over communication channels in unit of time.

Number of Packet Loss: The number of packets loss during simulation time;

Packet Loss Ratio: The ratio of the number of packet loss to the number of transmitted packets;

Waiting Delay in Queue: The average time that the packets should wait in service or control channel queues before dequeuing and transferring to the channels.

Before simulation results, we show the expression of the average end-to-end delay in Appendix. Fig. 7 reveals the variations of the average end-to-end delay resulting from mathematic formulas with the packet arrival rate and the number of vehicles in transmission range. The figure shows that, without providing any congestion control strategy in VANet, the end-to-end-delay is increased with increasing packet arrival rate for all numbers of vehi-

Input:
Max size of TabuList
Number of Iteration
Diversification Counter

Output:
Sbest (Best_Delay, Best_Jitter, Packet_Queue_Order)

1. S0 ← genInitSolution() // current delay and jitter based on current situation of queue
2. Sbest ← S0
3. Divers_count ← 0

4. insert TabuList(Sbest)
5. i ← 0
6. Intensific_Counter ← 0
7. Intencifict_Variable ← 0
8. Intencifict_Variable ← Rand (1, Iteration)
9. while (i< Iteration) do
10.   N(s) ← Identify (Neighborhood set) // Changing the order of packets in the queue with considering Mid-Term Memory
11.   T(s) ← Identify (TabuList) // Short-Term Memory
12.   CandidateList(s) ← N(s) – T(s)
13.   Intensific_Counter++
14.   If (Intensific_Counter== Intensific_Counter) //Mid-Term Memory
15.   Sbest ← Select (MidTermList)
16.   End if
17. if empty (CandidateList(s)) // Long-Term Memory
18.   *Divers_Count++*;
19.   if *Divers_Count ==Diversification Counter* // entrap in local minima
20. S_0 ← *genNewSolution()*
21.   Go to 2
22.   End if
23.   End if
24.   while (! empty (*CandidateList(s)*))
25.   if ($Delay(S_{candidate}) < Delay_{best}$ AND $Jitter(S_{candidate}) < Jitter_{best}$)
26. $S_{best} \leftarrow S_{candidate}$
27.   *Divers_Count* ← 0;
28.   break;
29.   End if
30.   End while
// Update-Tabu-List
31.   if (*LengthTabuList* < *MaxSizeTabuList*)
32.   Add S_{best} to *TabuList*
33.   else
34.   Delete the oldest item in *TabuList*
35.   Add S_{best} to *TabuList*
36.   End if
37. End while
38. Return (S_{best})

Fig. 6. Pseudo code of Tabu search algorithm in TaSch strategy.

cles in transmission range. In addition, the amount of end-to-end delay is higher than acceptable delay for transferring messages in VANets. Therefore, we show in simulation results that by controlling congestion, the average delay is decreased in comparison to the mathematical result shown in Fig. 7.

In the following, the impact of number of vehicles, message generation rate, and simulation time on the above performance metrics is evaluated. Figs. 8 to 12 show the simulation results of highway scenario, while Figs. 13 to 17 show the simulation results of urban scenario. Moreover, Fig. 18 shows the impact of various

Table 3
Configuration parameters for simulation of the highway and urban scenarios.

Parameters	Value
Total road length	2400 m*, and 652 m × 752 m**
Number of lanes	6 (3 in each direction)*, and 4 (2 in each direction)**
Number of vehicles	50,80,100,120,150,200
Vehicles speed	80–120 km/h* and 0–40 km/h**
Transmission rate	6 Mbps
Bandwidth	10 MHz
Message size	Beacon: 522 Bytes, Emergency: 500 Bytes
Beacon messages generation rate	10 packet/s
MAC type	IEEE 802.11p
Propagation model	TwoRayGround*, and Nakagami ($m = 3$)**
Routing protocol	DSDV
Simulation time	200 s
Simulation runs	20

* Highway Scenario
** Urban Scenario

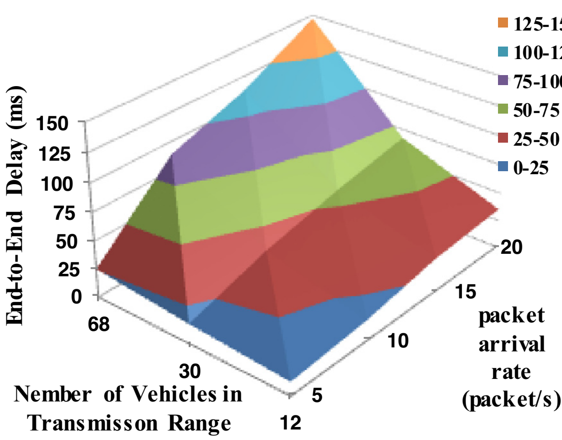

Fig. 7. Impact of the packet arrival rate and the number of vehicles in transmission range on average end-to-end delay in analytical model.

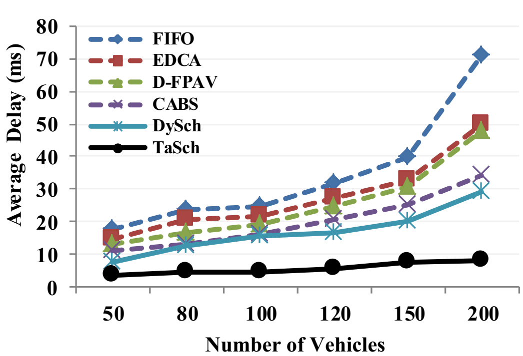

Fig. 8. Impact of the number of vehicles on average delay in the highway scenario.

packet queue size, which shows the length of queue based on the number of packet, on performance of proposed strategies in highway scenario to investigate the trade-offs of the proposed strategies.

Fig. 8 shows the variations of average delay resulting from different congestion control/ scheduling strategies with numbers of vehicles in the highway scenario. The figure shows that the average delay increases with increasing the number of vehicles for all congestion control/scheduling strategies. However, the figure shows that the average delay resulted from DySch and TaSch strategies are less than the other strategies. TaSch strategy leads to the lowest average delay. The reason for this observation is that TaSch

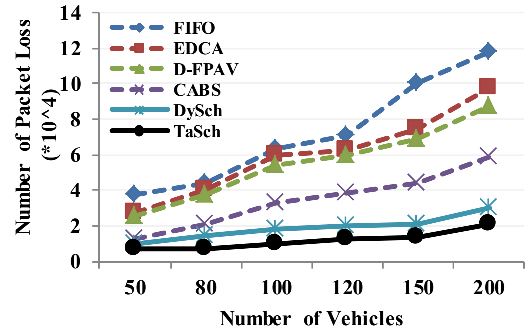

Fig. 9. Impact of the number of vehicles on number of packet loss in the highway scenario.

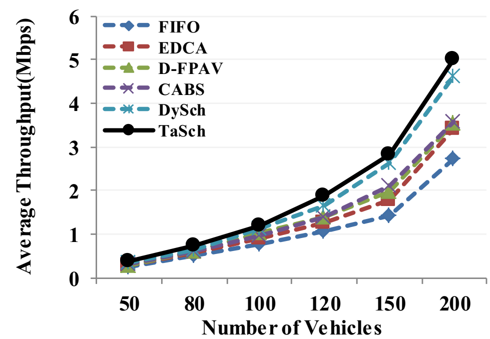

Fig. 10. Variation of the average throughput with number of vehicles in the highway scenario.

strategy minimizes the delay and jitter during message transferring for all the messages, especially high priority messages. DySch strategy can also reduce the average delay in some extend in compare to FIFO, EDCA, D-FPAV, and CABS strategies. Considering static and dynamic factors by DySch strategy leads to such an improvement.

FIFO cannot control congestion in high mobility vehicular environments since this algorithm dequeues the packets without any prioritizing. EDCA prioritizes messages to control congestion; however, when the number of high priority messages is high, the delay of transferring low priority messages increases. D-FPAV controls congestion by varying the transmission rate and power; CABS control congestion by scheduling of messages. However, both of these strategies are implemented only on beacon messages.

Fig. 9 reveals the impacts of the number of vehicles on the number of packet loss for each congestion control/scheduling strategy. It can be observed that the number of packet loss in DySch and TaSch strategies is less than the other strategies. By scheduling and prioritizing all messages (safety and service messages), congestion is controlled; thus the number of collisions and consequently the number of packet loss decrease.

Fig. 10 presents the plot of the average throughput versus the number of vehicles for each congestion control/scheduling strategy. Using FIFO, EDCA, D-FPAV, CABS, DySch and TaSch strategies, the average throughput for the number of vehicles equal to 200 is 2.72, 3.40, 3.53, 3.57, 4.63 and 5.01 Mbps, respectively. The results show that the proposed strategies outperform the other strategies and can improve the performance of VANets. DySch and TaSch strategies increase the average throughput by dynamically and heuristically scheduling the queues, respectively. Such improvement in the average throughput was obtained due to the reduction in the average delay and number of packets loss shown in Figs. 8 and 9.

For more evaluation of the proposed strategies, the variation of the average delay and throughput with simulation time are inves-

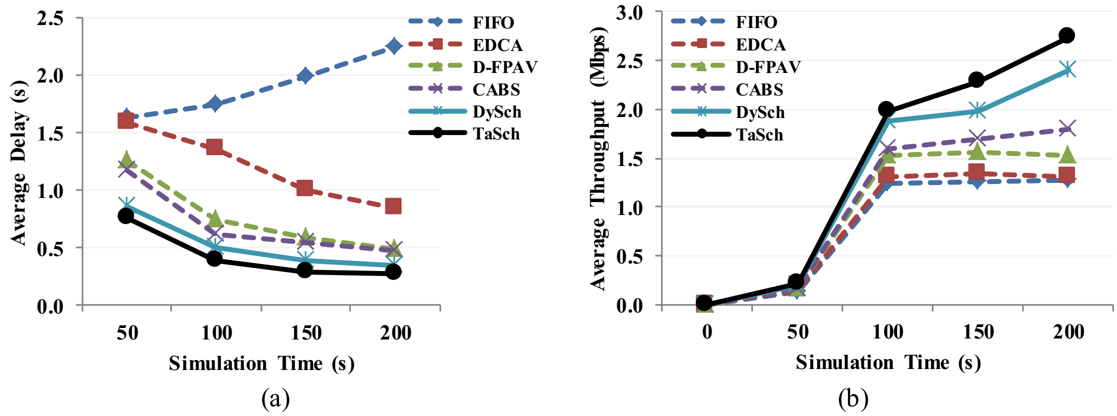

Fig. 11. Variation of (a) the average delay, and (b) the average throughput with simulation time in the highway scenario.

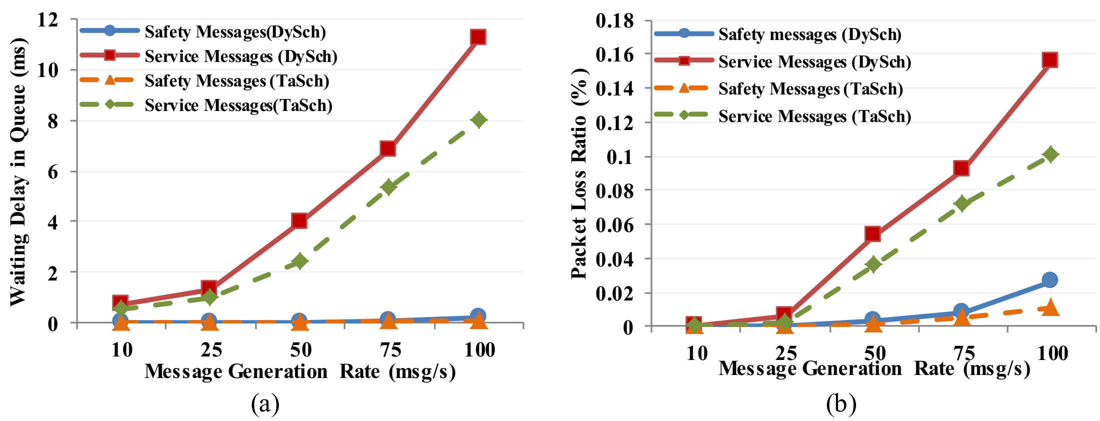

Fig. 12. Impact of the message generation rate on (a) waiting delay in queue, and (b) packet loss ratio in the highway scenario.

tigated in Fig. 11(a) and (b), respectively. Here, the number of vehicles is assumed to be 50. Fig. 11(a) illustrates that by advancing the simulation time, the average delay of the packet transmission decreases for all strategies, except FIFO. However, using TaSch and DySch strategies, the amount of reduction of average delay is higher than the other strategies. In Fig. 11(a), it can be also seen that the average delay using TaSch and DySch at simulation time 50 s is much lower than the other strategies. It means, using the proposed strategies, congestion is controlled before it occurs. Here, it should be emphasized that TaSch and DySch strategies are open-loop strategies.

Fig. 11(b) illustrates that TaSch and DySch can improve average throughput more than the other strategies during the simulation time. This figure shows that after 200 s the average throughput using FIFO, EDCA, D-FPAV, CABS, DySch and TaSch is improved to 1.27, 1.31, 1.53, 1.79, 2.39 and 2.73 Mbps, respectively. The average throughput obtained using DySch and TaSch is almost 2 times more than FIFO (basic scheduling strategy) or EDCA (default prioritizing strategy in VANets). Moreover, the results show that the rate of changes of average throughput calculated by DySch and TaSch strategies is positive. It means that the average throughput calculated by the proposed strategies may increase even after simulation time 200 s. Note that the rate of change of the average throughput obtained from the other strategies is almost zero after simulation time 100 s.

In Fig. 12, the impact of the message generation rate on average waiting delay in queue, and packet loss ratio is evaluated for safety and service messages while congestion control is conducted using DySch and TaSch. Fig. 12(a) illustrates that the average waiting delays in queue for safety messages are much lower than the average waiting delays in queue for service messages. This results show that DySch and TaSch transfer the safety messages without any significant waiting delay in queue by scheduling and prioritizing the messages that help provide a safe and reliable environment in VANet. A negligible delay for safety messages can be seen in Fig. 12(a) because the beacon messages generated periodically have to wait in control channel queue before transmitting. Similarly, Fig. 12(b) reveals that the packet loss ratio of safety messages is less than the packet loss rate ratios of service messages. Because the safety messages have higher priority for being transmitted compare to the service messages, their packet loss ratio is lower than the service messages.

In the following, an urban scenario is investigated to evaluate the performance of the proposed strategies in the vehicular environments with high level of congestion. For simulation of urban scenarios, Nakagami ($m = 3$) propagation model is used to simulate the obstacles (e.g. buildings and trees). The other parameters used for simulation of the urban scenario can be seen in Table 3. Figs. 13 to 17 illustrate the simulation results of urban scenario.

Figs. 13, 14 and 15 show the impact of the number of vehicles on the average delay, number of packet loss, and average throughput, respectively. In Fig. 13, the average delay increases with increasing the number of vehicles because as it is expected, when the number of vehicles increases, the number of collisions increases. However, here, similar to the highway scenario, the average delay resulted from the proposed strategies is less than the other strategies. When the number of vehicles increases from 50 to 200, the average delay increases from 26.69, 19.55, 17.40, 13.14, 12.48, and 10.10 to 206.10, 171.86, 152.22, 106.53, 33.91, and 17.44 milliseconds for FIFO, EDCA, D-FPAV, CABS, DySch and TaSch,

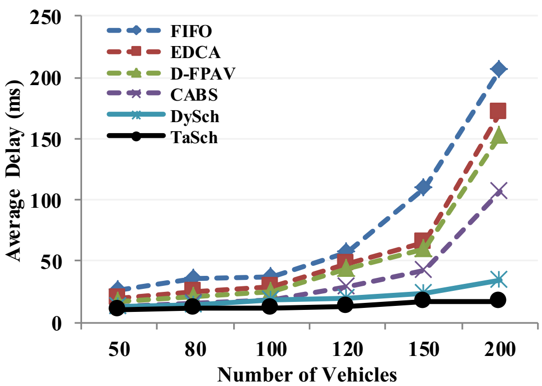

Fig. 13. Variation of the average delay with number of vehicles in the urban scenario.

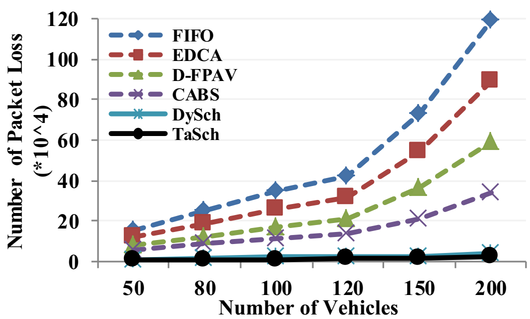

Fig. 14. Impact of the number of vehicles on number of packet loss in the urban scenario.

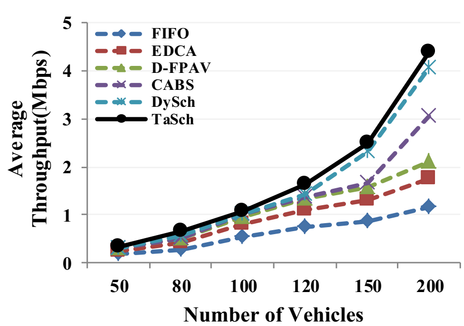

Fig. 15. Variation of the average throughput with number of vehicles in the urban scenario.

respectively. The results show that by increasing the number of vehicles, the average delay does not increase significantly using DySch and TaSch. Therefore, the proposed strategies are scalable congestion control strategies. It is also important to note that the average delay resulted from TaSch is less than DySch. As it was mentioned before, in TaSch strategy, delay is the objective function that is minimized to control the congestion.

Fig. 14 shows that for the number of vehicles 200, the number of packet loss obtained from FIFO, EDCA, D-FPAV and CABS strategy are 31, 24, 16 and 9 times higher than DySch strategy, respectively. Also, the figure shows that TaSch strategy reduces the number of packet loss more than DySch strategy; the number of packet loss obtained from TaSch strategy is almost 1.4 times less than DySch strategy. In Fig. 15, the average throughput obtained from DySch and TaSch are more than the other strategies due to control the congestion and decrease delay and collisions. Such results show that the performance of the proposed strategies (especially TaSch) to control congestion is better than the other strategies.

The variations of average delay and throughput with simulation time in the urban scenario are shown in Fig. 16 whereas the number of vehicles is assumed to be 50. In the urban scenario, similar to the highway scenario, using TaSch strategy leads to the lowest average delay and the highest average throughput during the simulation time. Fig. 16(a) shows that, at simulation time 50, the average delay is equal to 3.45, 2.76, 2.07, 1.95, 1.33, and 1.04 seconds for FIFO, EDCA, D-FPAV, CABS, DySch, and TaSch, respectively. These results show that even at the beginning of simulations, the average delay computed by DySch and TaSch is less than the other strategies. The reason for this observation is that the proposed strategies control congestion before the congestion actually happens (open-loop strategies).

Fig. 16(b) illustrates that the average throughput after 200 seconds of simulation increases to 0.73, 0.92, 1.35, 1.57, 1.77 and 1.99 Mbps for FIFO, EDCA, D-FPAV, CABS, DySch, and TaSch, respectively. As it was expected, the proposed strategies outperform the other strategies. In contrast of the highway scenario shown in Fig. 11(b), the results show that the rate of change of the average throughput calculated by DySch, and TaSch strategies is reaching to the zero for simulations time larger than 100 s. It means that, in this scenario, the average throughput cannot increase significantly after simulation time 100 s due to high level of congestion in the scenario.

Fig. 17 reveals the impact of message generation rate on waiting delay in queue, and packet loss ratio of safety and service messages for DySch and TaSch strategies in the urban scenario. The results show that the waiting delay in queue and packet loss ratio for safety messages is much less than the service messages. To control congestion, DySch and TaSch strategies schedule the messages while safety messages are prioritized for being sent. It should be also noted that the results obtained from urban and highway scenario are different because of the higher level of congestion and different characteristics of vehicular environment in the urban scenario.

Finally, for evaluating performance of proposed strategies with varying the packet queue size metric, Fig. 18 shows the variation of and packet loss ratio waiting delay in queues with packet queue size in highway scenario. As Fig. 18(a) shows the packet loss ratio decreases with increasing the packet queue size because the number of packet losses decreases due to increasing the space for queuing the packets. However, the Fig. 18(b) shows that the waiting delay in queues for DySch is less than the waiting delay in queue for TaSch when the packet queue size is more than 50. This figure illustrates that DySch outperforms TaSch when the size of queue is more than 50. These results obtain because, with increasing the size of queue, the complexity of search process using Tabu Search algorithm in TaSch strategy increases to obtain the optimal solution for scheduling the messages in the queues. Although with increasing the packet queue size, the packet loss ratio resulted from TaSch strategy is less than DySch strategy, the waiting delay in queue resulted from TaSch is more than DySch. Therefore, in large packet queue size, DySch strategy has higher potential compared to heuristically scheduling algorithm to perform better and decrease the waiting delay in queues.

5. Summary and conclusion

In this paper, we proposed two novel open-loop congestion control strategies including DySch and TaSch strategies. The proposed strategies operated through two units: 1) priority assignment unit, and 2) message scheduling unit. In priority assignment unit, first, static and dynamic factors were calculated based on the content of messages, and situation of vehicles, respectively. Then, a priority was assigned to each message based on static and

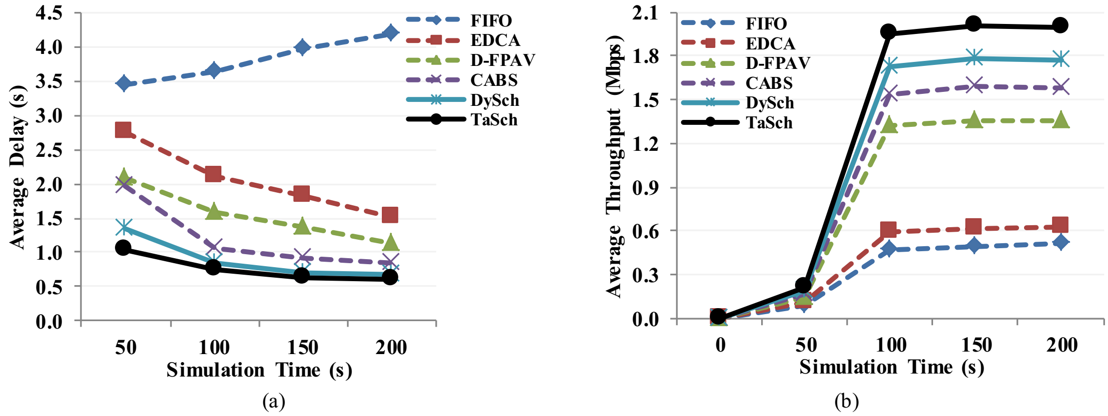

Fig. 16. Variation of (a) the average delay, and (b) average throughput with simulation time in the urban scenario.

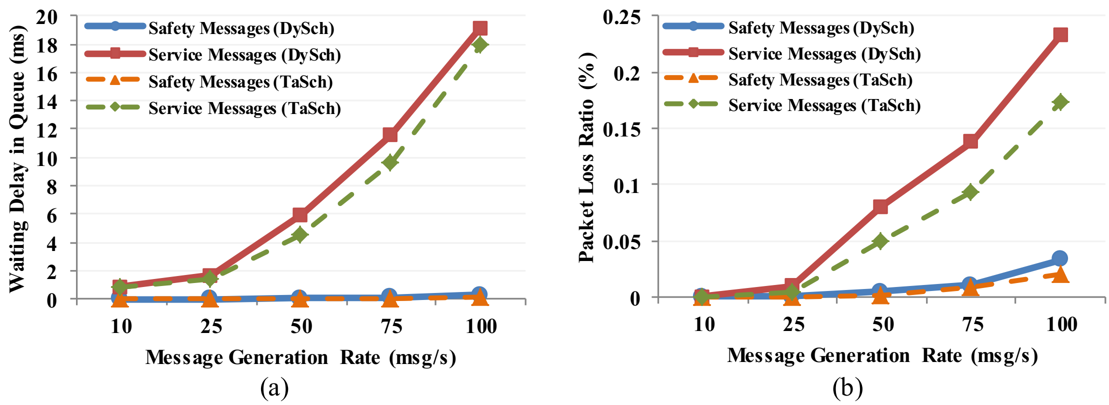

Fig. 17. Impact of the message generation rate on (a) waiting delay in queue, and (b) packet loss ratio in the urban scenario.

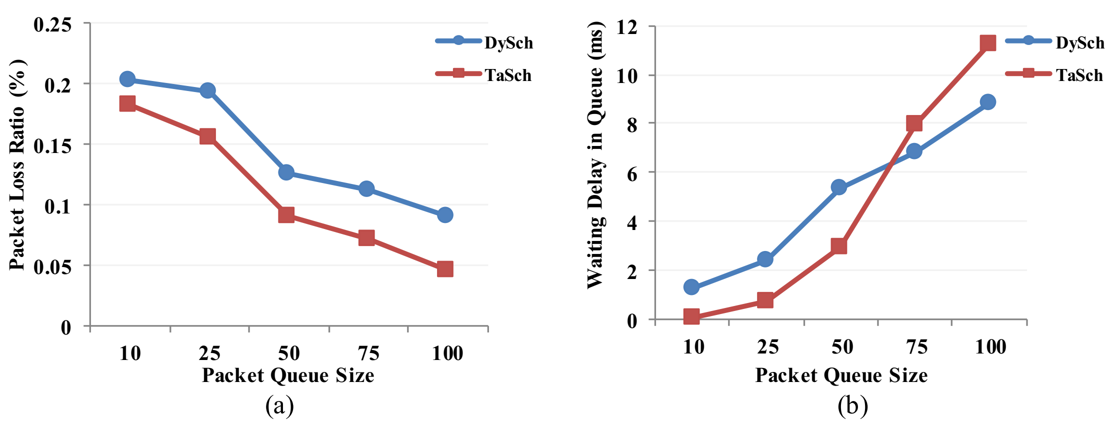

Fig. 18. Variation of (a) waiting delay in queue, and (b) packet loss ratio with packet queue size in the highway scenario.

dynamic factors, and size of the message. In message scheduling unit, first, the messages were transferred to control and service channel queues based on the calculated static factors (static scheduling). Then, the packets in each queue were rescheduled for transferring to the channels (dynamic scheduling). Dynamic scheduling was performed differently in DySch and TaSch strategies. In DySch strategy, dynamic scheduling was carried out based on the priority of messages. However, in TaSch strategy, dynamic scheduling was conducted by minimizing the delay and jitter, and considering the priorities of messages. Both DySch and TaSch strategies were distributed strategies. It means each vehicle independently prioritized and scheduled all the generated/received messages by executing the proposed strategies.

The performance of DySch and TaSch strategies was evaluated and compared with other strategies in highway and urban scenarios whereas the average delay, number of packet loss, average throughput, waiting delay in queue, and packet loss ratio were used. The results of comparisons showed that the proposed strategies outperformed the other strategies. Application of DySch and TaSch strategies improved the performance of VANets by increasing the average throughput, and reducing the average delay, and number of packet loss. Comparisons between the proposed strategies also revealed that the improvements obtained from TaSch were greater than that of DySch strategy. TaSch strategy considered the delay, jitter, and priorities of messages while DySch strategy only considered the priority of messages. The results showed that the applications of the both strategies led to the lower waiting delay in queue, and packet loss ratio for safety messages rather than the service messages. Therefore, more safe and reliable environments can be provided in VANets using TaSch and DySch strategies.

Appendix

Here, the delay and jitter formulas used as the objective function of Tabu Search algorithm are illustrated [1,27,44]. The notifications of these formulas are shown in Table 4.

$$Delay = (D_{proc} + D_{queue} + D_{trans} + D_{prop})\frac{d}{TX}$$

$$D_{queue} = \frac{1}{\mu - \lambda} - \frac{1}{\lambda}.\frac{Q_L \rho^{Q_L}}{1 - \rho^{Q_L}}$$

$$\rho = \frac{\lambda}{\mu}$$

$$D_{trans} = T_B + T_F + T_T$$

$$T_B = \begin{cases} \frac{W_{min}.\eta}{2}.\left(2^{N_{RT}} - 1\right) & N_{RT} \le m \\ \frac{\eta}{2}.(W_{max} - W_{min} + W_{max}.(N_{RT} - m)) & N_{RT} > m \end{cases}$$

$$N_{RT} = \sum_{s=1}^{7} s{P_C}^{s-1}(1 - P_C) = \frac{1 - 8{P_C}^7 + 7{P_C}^8}{1 - P_C}$$

$$P_C = \frac{2W_{min}.N_C}{(W_{min} + 1)^2 + 2W_{min}.N_C}$$

$$T_F = N_C + (N_C + 1).\left(\frac{N_{RT} - 1}{\sum_{t=2}^{N_C} t.f(t)}\right).P_T$$

$$f(t) = \binom{N_C}{t}\tau^t.(1 - \tau)^{N_C - t} = \left(\frac{N_C}{t!(N_C - t)!}\right).\tau^t.(1 - \tau)^{N_C - t}$$

$$\tau = \frac{2(1 - p_0)}{w_0 - 1}$$

$$p_0 = 1 - \frac{\lambda}{\mu}$$

$$T_T = \frac{S}{TR}$$

$$D_{prop} = \frac{d}{c}$$

$$J(i) = J(i-1) + \frac{|D(i-1,i)| - J(i-1)}{16}$$

$$D(i-1,i) = (R_{i-1} - R_i) - (S_{i-1} - S_i) = (R_{i-1} - S_{i-1}) - (R_i - S_i)$$

Table 4
Notifications for calculating the delay and jitter.

Notation	Description
D_{trans}	Transmission delay
D_{queue}	Queuing delay
D_{prop}	Propagation delay
D_{proc}	Processing delay
ρ	Utilization
μ	Packetservice rate
λ	Packet arrival rate
T_B	Timer back-off delay
T_F	Back-off timer freeze delay
T_T	Successful transmission delay
N_{RT}	Number of (re)transmissions upon success delivery
P_C	Collision probability
W_{min}	Minimum contention window size = 32
W_{max}	Maximum contention window size = 1024
m	Maximum number of back-off stage ($W_{max} = 2^m W_{min}$, $m = 5$ in IEEE 802.11)
η	Back-off time slot length(= 20 μs)
$f(t)$	Number of retransmissions when the collision occurs
τ	Transmission probability
p_0	Probability that there are no packet ready to transmit at the MAC layer in each vehicle
w_0	Current back-off window size that is always a constant for broadcast
S	Packet size
TR	Transmission rate
TX	Transmission range
c	Light velocity = 3×10^8 m/s
P_T	Time period for a packet transmission including SIFS, DIFS, Data and ACK
V	Number of vehicles
Q_L	Maximum queue length
N_C	Number of contenders within the transmission range
s	Number of back-off stages
D	Distance between sender and receiver
$J(i)$	jitter of ith packet
$D(i-1,i)$	the difference between transmission times of ith and $(i-1)$th packets
S_i	the time stamp of ith packet
R_i	the arrival time of ith packet

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