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Improving dynamic and distributed congestion control in vehicular ad hoc networks

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ABSTRACT

To provide reliable communications in Vehicular Ad hoc Networks (VANets), it is vital to take into account Quality of Services (QoS). Delay and packet loss are two main QoS parameters considered by congestion control strategies. In this paper, a Multi-Objective Tabu Search (MOTabu) strategy is proposed to control congestion in VANets. The proposed strategy is dynamic and distributed; it consists of two components: congestion detection and congestion control. In the congestion detection component, congestion situation is detected by measuring the channel usage level. In congestion control component, a MOTabu algorithm is used to tune transmission range and rate for both safety and non-safety massages by minimizing delay and jitter. The performance of the proposed strategy is then evaluated with highway and urban scenarios using five performance metrics including the number of packet loss, packet loss ratio, number of retransmissions, average delay, and throughput. Simulation results show that MOTabu strategy significantly outperforms in comparison with other strategies like CSMA/CA, D-FPAV, CABS, and so on. Conducting congestion control using our strategy can help provide more reliable environments in VANets.

1. Introduction

Intelligent Transport Systems (ITSs) use Vehicular Ad hoc Networks (VANets) as wireless communications technology. Indeed, VANets are designed to provide a safe and efficient environment within transportation systems for reducing accidently dangers events for drivers, passengers and pedestrians in the roads. They are a new landscape of Mobile Ad-hoc Networks (MANets) that consider the vehicles as mobile nodes. VANets are equipped with two units that are called Road-Side Unit (RSU) and On-Board Unit (OBU). While the former is fixed on the roadside, the latter is carried on by vehicle. These units are used for carrying out wireless communications between vehicles (V2V communications) as well as between vehicles and roadside infrastructures (V2I communications) [1,2].

Dedicated Short Range Communication (DSRC) is a set of protocols and standards that are employed in VANets. Bandwidth utilization, which is one of main factors in DSRC, defines transmission range up to 1000 m and transmission rate ranging from 3 to 27 Mbps. DSRC employs Wireless Access in a Vehicular Environment (WAVE) to norm performance of V2V and V2I communications. WAVE is formed by IEEE802.11p and IEEE1609 standards in PHY and MAC layer, respectively. The above standards are applied for managing resources and network services for selecting channels, security, and so on.

VANets offer a large number of applications including safety applications (e.g., forward collision, traffic signal

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violation, and emergency brake lights) and service applications (e.g., traffic optimization, infotainment, and payment services). Safety applications utilize beacon and emergency messages that are transmitted by means of control channel, while service applications utilize non-safety massages transmitted over service channels [3,4]. VANets inherit the most behavior of MANets. However, they have different behaviors in comparison with MANets due to their special characteristics including high mobility of nodes, high rate of topology change, and high rate of node density. These unique characteristics in VANets raise new challenges related to data dissemination, scalability, security, and routing that lead to reduce performance of VANets [4,5].

To enhance performance of VANets, Quality of Services (QoS) strategies must be considered to guarantee reliability of safety and service applications. Packet loss and delay are two important parameters that can be used to quantify QoS and evaluate the performance of VANets. Congestion, which occurs due to the limitation of resources, leads to increase the number of packets loss and delay, and consequently to decrease the performance of VANets. Indeed, the channel bandwidth copes with congestion when the load of the network exceeds the capacity of the network nodes and links. Therefore, congestion control should be conducted for decreasing packet loss and delay to make a more reliable communication in VANets. Congestion control in VANets is a challenging task due to the special characteristics of the vehicular environment including sharing the wireless channel, frequently route break, dynamic topology, and so on. Thus, a dynamic and distributed strategy is required to handle congestion control [6–9].

Over the last decades, several strategies were proposed to address congestion problem in VANets. There are three main congestion control strategies for VANets: (1) controlling the transmission range that controls the range of transmission in channels, (2) controlling the transmission rate that controls the rate of packets transferring, and (3) scheduling messages in various channels based on their priorities [10]. Congestion control techniques can also be classified into end-to-end, and hop-by-hop techniques. The end-to-end techniques consider communication flows between senders and receivers, but they do not pay attention to intermediate nodes. The hop-by-hop techniques take into account the capacity of intermediate links [11]. However, using the existing strategies in practice revealed that there are a lot of problems associate with these congestion control strategies in VANets. Some of these problems include, but not limited to, high transmission delay, unfair resource usage, inefficient use of bandwidth, and communication overhead [8]. Therefore, a new strategy is needed to solve these problems, especially in emergency situations of VANets.

Tuning transmission range and rate to control congestion copes with computational overhead in VANets due to the large number of contributing parameters including size of messages, number of vehicles, number of lanes, vehicle velocity, and so on. Thus, the existing strategies conducting tuning transmission range and rate suffer from high delay and packet loss [10]. It will be shown that such a problem is NP-hard. Meta-heuristic techniques can be used to find near optimal solutions in a reasonable time for NP-hard problems [12].

In this paper, we propose a dynamic and distributed congestion control strategy to increase reliability of VANets. The remaining parts of this paper are structured as follow: Section 2 reviews the existing congestion control strategies in VANets. Section 3 proposes a congestion control strategy in VANets environments. Section 4 describes the Multi-Objective Tabu Search (MOTabu) algorithm for tuning transmission range and rate. Section 5 discusses the results obtained from applications of the proposed strategy in highway and urban scenarios.

2. Background and related works

Congestion control in modern wired/wireless communications plays an important role for providing reliable and fair environments. The main goals of a congestion control strategies are to obtain high bandwidth utilization, efficient fairness, high responsiveness, and fairly compatibility with protocols and standards. To increase efficiency of a congestion control, some metrics such as convergence speed, smoothness and responsiveness must be considered. The convergence speed is estimated by measuring the time spent to reach the equilibrium state. The smoothness, which depends on the size of fluctuation, is calculated using reflection of fluctuation intensity. Finally, the responsiveness is measured by Round Trip Time (RTT) to reach equilibrium [11].

The congestion control strategies are used to control channels loads and increase the performance of wireless channels. Generally, the congestion control strategies in VANets are classified into four categories: window-based, rate-based, single-rate, and multi-rate. Window-based category employs the congestion window in sender and receiver sides. The size of congestion window increases/decreases in states of with/without congestion. In rate-based category, transmission rate is adapted using some feedback-based algorithms. In single-rate category, the congestion is controlled using unicast protocols. Thus, sending rate must be adapted according to just one receiver. On the other hand, multi-rate category uses a layered multicast approach [11].

Torrent-Moreno et al. [13] proposed Distributed-Fair Power Adjustment for Vehicular environment (D-FPAV). This congestion control strategy dynamically controls transmission range of the safety messages (i.e., beacons and emergency messages). Beacon messages are periodically broadcasted between the vehicles that are composed of some information like speed, position, direction, and so on, while emergency messages are broadcasted when an event happens within VANets. In the congestion situation, D-FPAV shrinks the transmission range of the beacon messages. For reducing communication overhead, the value of transmission range is obtained based on the vehicle density. The main drawback of this strategy is that the probability of receiving beacons messages in far distance reduces by decreasing transmission range.

High beaconing frequency consumes a high amount of channel bandwidth when the number of vehicles increases. This problem causes to diminish the performance of safety messages in VANets environments due to the special characteristics of these networks. Djahel and Ghamri-Doudane [14] proposed a three-phases congestion control strategy which consists of prioritizing the messages, detecting congestion, and tuning beacon transmission rate and power. Prioritizing is carried out based on the content of messages and the number of hops that a message has to be traveled. In second phase, congestion can be detected using the average waiting time, the collision rate, and the beacon reception rate metrics. In the third phase, the beacon transmission rate and power are adjusted based on previous phases for efficiently usage of the channel bandwidth. The proposed congestion control strategy guarantees reliability and safety of VANets, but the delay of this strategy is high.

Baldessari et al. [15] introduced a congestion control strategy by adjusting transmission rate. The proposed strategy aims at fairly assigning resources to all network nodes. This strategy uses channel busy time metric for counting the number of vehicles in the surrounding area and estimating the local vehicle density. Transmission rate in this strategy is adjusted based on either the estimated vehicle density or the predefined threshold. The proposed strategy could not provide a safe and fair channel usage for all users because sharing of the channel bandwidth was not considered in the strategy.

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) strategy, which is used to access communication channels, was redefined by IEEE 802.11p/WAVE standard for VANets [16]. CSMA/CA is used as default congestion control strategy in VANets. This strategy employs the exponential back-off mechanism to control congestion. However, in VANets, exponential back-off mechanism for broadcasting the beacon messages is not efficient. This mechanism does not work adequately for high frequency of message generation, especially when beacon messages have a time-out, that lead to drop packets before transmission.

Most of the congestion control strategies in VANets only adjust transmission range and rate. However, congestion sometimes occurs due to the malfunctioning of CSMA in MAC layer under dense vehicular networks. Stanica et al. [17] investigated the impacts of physical carrier sense on the probability of beaconing reception in VANets. A congestion control strategy was then proposed by controlling the contention window, physical carrier sense, and transmission power. The results showed that the proposed strategy can enhance the performance and reduce the collision in VANets channels.

Huang et al. [18] developed A Vehicle Oriented Congestion Control Algorithm (AVOCA) for optimizing the network throughput. The developed algorithm can solve the existing problems of congestion control in transport layer. Congestion control conducting in transport layer may fail during continuous connectivity with the nodes located at coverage zone. AVOCA uses a performance threshold to control packet transmissions in transport layer. When the vehicle enters in a coverage zone, performance threshold increases. Then, congestion control parameters are reset and packet transmissions are initialed. In other hand, when the vehicle leaves the coverage zone, the performance threshold decreases. The decrease in performance threshold causes to terminate the packet transmission as well as freezing the congestion control parameters. Although AVOCA algorithm increases throughput and fairness usage of services, delay in AVOCA is relatively high (up to 60 ms).

High rate of beacon messages can lead to congestion in control channel, especially in dense networks. Bai et al. [19] developed Context Awareness Beacon Scheduling (CABS) to address this challenge in vehicular networks. CABS is a new distributed strategy for scheduling beacon messages. To dynamically schedule the beacon messages, CABS employs spatial context information in beacon such as position, speed, and direction. Then, time slot is assigned to the node by means of TDMA-like transmission. In the proposed strategy, the packet reception rate and channel access delay are improved, and congestion problem is solved using tuning of beacon frequency. However, CABS does not consider the interworking in MAC layer to adjust time slot for different transmissions.

Taherkhani and Pierre [20] proposed a Uni-Objective Tabu Search (UOTabu) strategy for controlling congestion in VANets. In the proposed strategy, after detecting the congestion situation via measuring the channel usage level, transmission range and rate are tuned by minimizing the delay function. This heuristic strategy just used short-term memory as tabu list for Tabu Search algorithm. In addition, UOTabu is a Uni-Objective Tabu Search algorithm and considered just delay as objective function. A comparison was conducted between UOTabu, D-FPAV [13], and CSMA/CA [16] strategies using a highway scenario. The comparison showed that the proposed strategy can reduce the delay, and number of packet loss, and increase the throughput, which results in improving the performance and reliability of VANets.

In the following, significant problems in applications of the introduced congestion control strategies in VANets are described. Some of the congestion control strategies conduct retransmissions of unnecessary packets, and drop undelivered packets to detect congestion [21]. However, applying such techniques in VANets is complicated and inefficient due to the special characteristics of VANets such as high mobility and topology change [8,14].

One of the main goals of VANets is to make a safe environment for drivers and pedestrians. In order to reach this goal, it is critical to broadcast the emergency messages with less possible delay in VANets [5]. However, this factor is not considered by the most of congestion control strategies.

In high vehicle density, high frequency of generation of beacon messages results in congestion over the control channels. Thus, the operations of safety applications are impaired due to the failure of receiving of beacon messages. Most of the introduced strategies reduce transmission rate of beacon messages during congestion situations. However, by reducing the frequency of generation of beacon messages, the applications face to staleness information. Thus, the applications required to get updated information cannot operate efficiently [22].

3. Problem statement and solving strategy

According to the previous section, congestion control based on tuning transmission range and/or transmission rate are very common in VANets. Tuning transmission range and rate are more challenging in VANets than in ad hoc networks due to high mobility of nodes, high rate of topology change, and high rate of node density. Moreover, tuning transmission range and rate in VANets is affected by various parameters such as vehicle velocity, vehicle density, and number of lanes and so on. Note that the number of effective parameters in VANets is more than in mobile ad hoc networks. Tuning transmission range and rate in the large scale networks copes with many challenges because by increasing the size of network, the number of effective parameters is also increased [23]. In this section, an efficient congestion control strategy is introduced for improving reliability and safety of VANets. For this purpose, tuning transmission range and rate in VANets is conducted by employing a Meta-heuristic algorithm.

To send safety messages to further distances, large transmission range is necessary. In other words, by increasing the transmission range, more vehicles located in transmission range can receive the safety messages. In other hand, large transmission range can lead to increase the number of packet collisions and channel contentions. A high transmission rate leads to more accuracy by updating information frequently. However, high transmission rate causes to saturation of channels and increasing message collision rate [19,23]. Therefore, a strategy should be proposed to determine optimal values of transmission range and rate for efficient operation of VANets. As mentioned in [24], the delay and jitter are much higher in VANets than ad hoc networks. Consequently, it is essential to minimize both the delay and jitter. In this research, therefore, finding the optimal values of transmission range and rate is conducted by minimizing delay and jitter for transferring messages. Finding optimum values of transmission range and rate to conduct congestion control in VANets is complex.

Finding the optimal values of transmission range and rate is a special case of the multidimensional Knapsack problem. The parameters in our optimization problem can be converted and adapted with the corresponding parameters in multidimensional Knapsack problem. The transmission range and transmission rate can be considered as the bags. The different values of transmission range and rate, which are determined based on DSRC standard, are like the worth of goods. Finally, minimizing delay and jitter are corresponding with maximizing the worth of goods in bags. Martello and Toth [25] proved that multidimensional Knapsack problem is an NP-hard problem. Thus, finding the optimal values of transmission range and rate is an NP-hard problem by reducing multidimensional Knapsack problem to finding optimal values of transmission range and rate problem [26]. Meta-heuristic techniques provide general solutions for coping with NP-hard problems. They are used for finding near-optimal solutions in the reasonable time [27]. Therefore, in this paper, Meta-heuristic techniques are used for tuning transmission range and rate for congestion control in VANet. Several parameters should be considered for optimizing channel usage in VANets including packet size, transmission rate, transmission range, vehicle velocity, vehicle density, and number of lanes. Due to the large number of parameters, finding the optimal transmission range and rate is complex. Meta-heuristic techniques can also handle such a high complexity by considering the reliability of applications in vehicular environments.

The main Meta-heuristic algorithms are Tabu Search, Simulated Annealing, Genetic Algorithm, Mimetic Algorithm, Ant Colony, and so on [12]. Tabu Search is one of the most common used Meta-heuristic algorithms which are designed to solve optimization problems. Tabu Search has simpler but more comprehensive concepts than the other Meta-heuristic algorithms. For optimization, the algorithm continues searching until a near optimal solution is obtained. The algorithm also avoids entrapping in local optimum [28].

Generally, congestion control solutions can be divided into two groups: closed-loop and open-loop. The closed-loop solutions control the congestion after it happens while the open-loop solutions avoid the congestion before it happens [29]. This research proposes a closed-loop congestion control strategy. The proposed strategy consists of two components including (1) congestion detection component, and (2) congestion control component.

Congestion detection can be carried out by employing measurement methods. These methods sense communication channels and measure parameters like number of messages queue, channel usage level, and channel occupancy time [30]. In this paper, the congestion detection component measures the channel usage level periodically to detect congestion situation. Then, the value of the channel usage level is compared with a predefined threshold. Zang et al. [31] calculated congestion threshold equal to 70% in wireless communication channels. Similarly, in this paper, the channel usage level threshold is also assumed 70%. Thus, if channel usage level exceeds the threshold, it is assumed that the communication channels face to congestion. After congestion detection, congestion control is carried out by second component of the proposed strategy.

In congestion control component, tuning transmission range and rate is conducted for controlling congestion. As it was mentioned before, tuning transmission range and rate is an NP-hard problem and Meta-heuristic techniques are an appropriate tool to solve these types of problems. Among different Meta-heuristic algorithms, Tabu Search algorithm is used in this paper since it provides a comprehensive and simple concept to handle complexity of congestion problem in VANets. Tabu Search is used to obtain the near optimal values of transmission range and rate whereas delay and jitter are minimized. Then, the optimal values of transmission range and rate are used for transferring data over communication channels. Fig. 1 depicts the flowchart of the proposed congestion control strategy. The proposed congestion control strategy is a dynamic and distributed strategy. It is dynamic because tuning transmission range and rate is conducted based on the current situation of the network. It is also distributed because

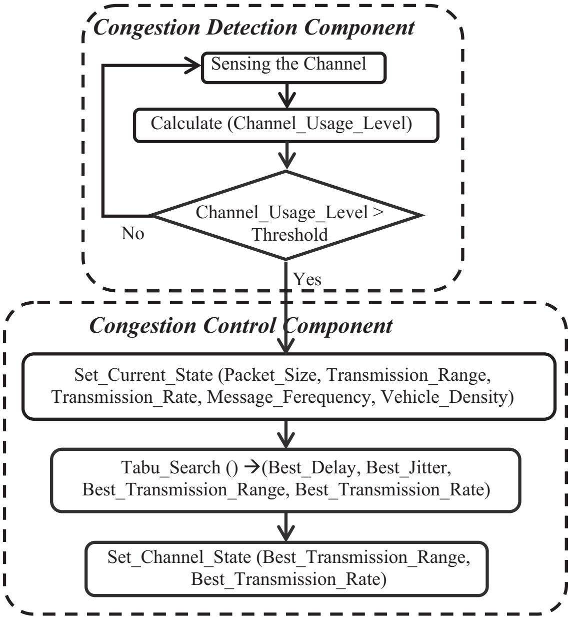

Fig. 1. Flowchart of the proposed congestion control strategy.

each node in VANets independently executes the proposed strategy, and obtains the optimal values of transmission range and rate.

4. The proposed tabu search algorithm

Tabu Search algorithm is one of the meta-heuristic techniques used to obtain near optimal solutions to difficult optimization problems. In this section, Tabu Search algorithm is described according to the following steps: encoding resolution based on the algorithm, generating initial solution, defining conditions for algorithm termination, and determining neighborhood solutions. Basically, a Tabu Search algorithm is composed by various elements including objective functions, initial solution, neighborhood set, candidate list, searching strategy, memory mechanisms, tabu list, and terminating rules. The performance of Tabu Search algorithm is affected by the length of the tabu list, the number of iterations to terminate the algorithm, objective functions, and so on [28,32]. These elements should be defined according to the features of congestion control problem in VANets for tuning transmission range and rate.

The main objective of a congestion control strategy is to minimize delay, jitter, packet loss, and number of retransmissions. However, in this paper for the purpose of making reliability and safe environment, only delay and jitter are considered whereas transferring the messages, specially emergency messages, is done in shorter time for making of safe environment in VANets. Thus, a multi-objective Tabu Search algorithm is developed while the objective functions of Tabu Search are delay and jitter.

Tabu Search generates various solutions to obtain near optimal solution. Each solution in the proposed Tabu Search algorithm is composed by transmission rate, transmission range, delay, and jitter. Delay and jitter are calculated using Eqs. (1)–(14) while current values of all required parameters (e.g. the packet size, vehicle density, number of lanes, and so on) are used.

Initial solution of Tabu Search algorithm can be defined using current state, previous state or random initialization methods [28,32]. In this paper, current state method is used to define initial solution. Thus, the initial solution in the proposed Tabu Search is composed by delay and jitter and current value of transmission range and rate.

Given initial solution, Tabu Search algorithm generates a collection of new solutions called neighborhood set [28,32]. To obtain neighborhood set, Tabu Search selects the values of transmission range and transmission rate between 10–1000 m, and 3–27 Mbps, respectively, based on DSRC standard [3,4]. The standard values for transmission rate are defined 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps [33–35]. The potential values for transmission range are 10, 50, 100, 126, 150, 210, 300, 350, 380, 450, 550, 650, 750, 850, 930, 971, and 1000 m [36]. Then, by finding feasible solutions in the neighborhood set, candidate solution list is developed. Candidate list is searched for selecting the best solution [28,32]. The best solution is the solution that has minimum values of delay and jitter.

In this paper, to obtain the new solutions, memory mechanisms (short-term, mid-term, and long-term) are applied. A short-term memory is used to avoid generating repeated solutions [28,32]. Short-term memory performs based on a list of forbidden solutions called "tabu list". A new solution, before to be selected as a best solution, is compared with the solutions in the tabu list. If the new solution exists in the tabu list, it should be neglected to avoid generating repeated solutions. When the best solution is selected, it is inserted into the end of tabu list. When the tabu list is full, the first solution is removed from the list. The size of tabu list in this strategy is set with 50. Briefly, the short term memory stores the best solutions founded recently.

Mid-term and long-term memory mechanisms are used for intensification and diversification of optimal solutions, respectively. Mid-term memory mechanism can help intensify the search within some specific areas of solution space. This specific area is determined using the recently best solutions from the tabu list. Indeed, the mid-term memory mechanism intensifies the search in the neighborhood of the best solutions. Finally, the long-term memory mechanism restarts the search process to create various solutions to avoid entrapping in the local minima. For this purpose, the new solutions should be selected far from the previous solutions within the tabu list that often needs to generate new initial solution.

The last element of Tabu Search algorithm is the terminating rules which can be defined based on different criteria including the number of iterations, the expectation time, and the performance criteria. In this paper, Tabu Search is terminated based on the number of iterations. Considering 136 possible combinations of transmission range and rate values, half of these combinations is set for number of iterations within proposed Tabu Search algorithm. The pseudo code of Tabu Search algorithm in each node is presented in Fig. 2.

```
Input:
Max size of TabuList
Number of Iteration
Diversification Counter
Output:
S_best (Best_Delay, Best_Jitter, Best_Transmission_Range, Best_Transmission_Rate)

1. S_0 ← genInitSolution() // current delay and jitter based on current situation of node
2. S_best ← S_0
3. Divers_count ← 0
4. insert TabuList(S_best)
5. i ← 0
6. while (i< Iteration) do
7.        N(s) ← Identify (Neighborhood set) // Changing the value of parameters between the
predefined boundaries with considering Mid-Term Memory
8.     T(s) ← Identify (TabuList) // Short-Term Memory
9.     CandidateList(s) ← N(s) – T(s)
10.    if empty ( CandidateList(s)) // Long-Term Memory
11.        Divers_Count++;
12.        if Divers_Count ==Diversification Counter // entrap in local minima
13.            Go to 1
14.        End if
15.    End if
16.    while (! empty ( CandidateList(s)) )
17.        if ( Delay(S_candidate ) < Delay_best AND Jitter(S_candidate ) < Jitter_best)
18.            S_best ← S_candidate
19.            Divers_Count ← 0;
20.            break;
21.        End if
22.    End while
  // Update-Tabu-List
23. if (LengthTabuList < MaxSizeTabuList)
24.        Add S_best to TabuList
25. else
26.        Delete the oldest item in TabuList
27.        Add S_best to TabuList
28. End while
29. Return( S_best)
```

Fig. 2. Pseudo code of Tabu Search algorithm in the proposed congestion control strategy.

As it was mention before, for tuning transmission rang and rate, a multi-objective Tabu Search is applied in which the delay and jitter function are considered as the objective functions. In the following, the delay and jitter functions are described.

Delay is a period of time under which a packet is delivered from source to destination. The delay is composed of the processing delay (D_{proc}), queuing delay (D_{queue}), transmitting delay (D_{trans}), and propagation delay (D_{prob}) [37]. The processing delay is the time needed for extracting header of packets and executing various algorithms (e.g., routing algorithms, congestion control algorithms, so on). The queuing delay is the waiting time of a packet in a queue before transferring. The transmitting and propagation delays are the required time for transferring, and propagation of the packet, respectively. Thus:

$$Delay = (D_{proc} + D_{queue} + D_{trans} + D_{prop})\left\lceil \frac{d}{TX} \right\rceil \tag{1}$$

where d is the distance between the sender and the receiver, and TX is transmission range. Thus, $\lceil \frac{d}{TX} \rceil$ is the number of hops between the sender and the receiver.The processing delay can be omitted in our computations. This is due to the fact that processing delay (nanosecond) is very smaller than other delay factors (millisecond). The queuing delay is calculated by formula (2):

$$D_{queue} = \frac{1}{\mu - \lambda} - \frac{1}{\mu} \cdot \frac{Q_L \rho^{Q_L}}{1 - \rho^{Q_L}} \tag{2}$$

where ρ is utilization which is equal to $\frac{\lambda}{\mu}$, where λ and μ are packet arrival rate and packet service rate, respectively. Q_L shows maximum queue length.

Transmission delay is calculated by (3):

$$D_{trans} = T_B + T_F + T_T \tag{3}$$

where T_B is back-off delay, T_F is freezing back-off delay, and T_T is successful transmission delay.

Back-off delay (T_B) is obtained using formula (4):

$$T_B = \begin{cases} \frac{W_{min}\cdot\eta}{2}\cdot(2^{N_{RT}}-1) & N_{RT}\leqslant m \\ \frac{\eta}{2}\cdot(W_{max}-W_{min}+W_{max}\cdot(N_{RT}-m)) & N_{RT}>m \end{cases} \quad (4)$$

where η shows the back-off time slot length which is equal to 20 μs in vehicular networks, W_{max} is the maximum contention window size equal to 1024 timeslots, W_{min} is the minimum contention window size equal to 32, m is the maximum number of back-off stage that is calculated by $W_{max} = 2^m W_{min}$, thus m is equal to 5 based on IEEE 802.11 standard. N_{RT} is the number of expected (re)transmissions upon success delivery which is calculated by (5):

$$N_{RT} = \sum_{s=1}^{7} sP_C^{s-1}(1-P_C) = \frac{1-8P_C^7+7P_C^8}{1-P_C} \quad (5)$$

where s is the number of back-off stages, the maximum s is equal to 7 based on IEEE 802.11 standard. P_C is also the collision probability calculated in exponential back-off mechanism of 802.11:

$$P_C = \frac{2W_{min}\cdot N_C}{(W_{min}+1)^2+2W_{min}\cdot N_C} \quad (6)$$

where N_C denotes the number of contenders within the transmission range.

Freezing back-off time occurs when the channel is busy. T_F is obtained using formula (7):

$$T_F = N_C + (N_C+1)\cdot\left(\frac{N_{RT}-1}{\sum_{t=2}^{N_C} t\cdot f(t)}\right)\cdot P_T \quad (7)$$

P_T is the time period for packet transmission including SIFS, DIFS, Data and ACK. t is a counter which tracks the number of contenders within the transmission range. $f(t)$ shows the number of retransmissions when the collision occurs:

$$f(t) = \binom{N_C}{t}\tau^t\cdot(1-\tau)^{N_C-t} = \left(\frac{N_C}{t!(N_C-t)}\right)\cdot\tau^t\cdot(1-\tau)^{N_C-t} \quad (8)$$

where τ is transmission probability that can be calculated based on formula (9):

$$\tau = \frac{2(1-p_0)}{w_0-1} \quad (9)$$

where w_0 is current back-off window size equal to $8V$, where V is the number of vehicles in the transmission range (V is constant during broadcasting), p_0 is the probability that there is no ready packet to transmit at the MAC layer in each vehicle:

$$p_0 = 1-\frac{\lambda}{\mu} \quad (10)$$

The success transmission delay is the time to transmit a packet successfully:

$$T_T = \frac{S}{TR} \quad (11)$$

where S and TR are the packet size and transmission rate, respectively.

Finally, the propagation delay is calculated by:

$$D_{prop} = \frac{d}{c} \quad (12)$$

where c is the light speed equal to 3×10^8 m/s.

The second objective function of Tabu Search is jitter function. The jitter function is usually expressed as the average of latency variance. In other words, the jitter is estimated iteratively based on the changes between inter arrival time of ith and $(i-1)$th packets:

$$J(i) = J(i-1) + \frac{|D(i-1,i)| - J(i-1)}{16} \quad (13)$$

where $J(i)$ is the jitter of ith packet, and $D(i-1,i)$ is the difference between transmission times of ith and $(i-1)$th packets:

$$\begin{aligned} D(i-1,i) &= (R_{i-1}-R_i)-(S_{i-1}-S_i) \\ &= (R_{i-1}-S_{i-1})-(R_i-S_i) \end{aligned} \quad (14)$$

where S_i, and R_i are the time stamp, and arrival time of ith packet, respectively. In (13), the second term is divided by 16 to reduce the influence of large random changes, and the noises effecting on estimating jitter [38].

Therefore, Tabu Search calculates delay and jitter using Eqs. (1)–(14). Then, optimal transmission range and rate are obtained by minimizing the value of delay and jitter.

5. Performance evaluation

5.1. Simulation parameters and scenarios

Mobility and network simulators are required to evaluate the performance of the proposed strategy. In this paper, the mobility simulator Simulation of Urban MObility (SUMO) was used for simulation of vehicular environments and vehicles movements [39,40]. SUMO generates a microscopic movement pattern of vehicles traffics and roads topologies. The network simulator NS2 (version NS2.35) was used for simulation of VANet. NS2 is one of the best network simulator which has been used and confirmed by many researchers [41]. Application of SUMO and NS2 for evaluating the proposed strategy helps overcome the limitations and complexities associated with implementing of the proposed strategy in real vehicular networks. The MObility model generator for VEhicular networks (MOVE) is used to connect the mobility simulator to the network simulator [42]. MOVE converts microscopic movement patterns from SUMO to acceptable scenarios of nodes movement for NS2. Therefore, using SUMO, MOVE and NS2, an environment very similar to VANets can be created to evaluate the performance of the proposed strategy to control congestion.

In this paper, two scenarios were considered: (i) a highway scenario (six lanes, three in each direction), and (ii) an urban scenario (Manhattan road pattern). These two scenarios led to two different levels of congestion. According to VANets standards, communications between vehicles, and also between vehicles and infrastructures units are established by IEEE 802.11p protocol. Moreover, data transmissions in MAC layer are carried out based on

CSMA/CA strategy. TwoRayGround and Nakagami propagation models were used for traffic propagation in highway and urban scenarios, respectively. Poisson distribution was used for data generations. The simulation time was set 200 s because the preliminary results showed that after 150 s the results become nearly steady. Table 1 shows the parameters used in the simulation of highway and urban scenarios.

5.2. Simulation results

To assess the performance of the proposed congestion control strategy, a comparison is conducted between the results obtained from the proposed MOTabu strategy and five existing congestion control strategies: CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu that have been reviewed in background and related works. Note that PRBC represents congestion control strategy introduced in [14]. For the purpose of comparison, five metrics are evaluated:

Average delay: This criterion shows the duration of time required to deliver a packet from the sender to the receiver.

Number of packets loss: The number of packets loss during simulation time is an appropriate criterion to estimate the network's performance.

Average throughput: Average throughput measures the average rate of messages successfully transmitted over the communication channels.

Packet loss ratio: This metric is calculated by dividing the number of packet losses by the number of packet transmissions for each receiver.

Number of retransmissions: This metric calculates the average number of retransmissions of packets during the simulation time.

In the following, the variations of these metrics with the number of vehicles and simulation time were investigated to compare the performance of the MOTabu with CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu strategies. Figs. 3–8 show the performance of the Congestion Control (CC) strategies in highway scenario, whereas Figs. 9–14 show the performance of the congestion control strategies in urban scenario.

First objective of the proposed congestion control strategy is to decrease packet loss. Fig. 3 depicts the variation of the number of packet loss/packet loss ratio with the

Table 1
Configuration parameters for simulation of highway or urban scenarios.

Parameters	Value
Total road length	2400 m[a], and 652 m × 752 m[b]
Number of lanes	6 (3 in each direction) [a], and 4 (2 in each direction) [b]
Number of vehicles	50, 80, 100, 120, 150, 200
Vehicles speed	80–120 km/h[a] and 0–40 km/h[b]
Transmission range	15–1000 m
Transmission rate	3–27 Mbps
Contention window size	15–1023
Bandwidth	10 MHz
Safety messages generation rate	10 packet/s
MAC type	802.11p
Propagation model	TwoRayGround[a], and Nakagami ($m = 3$)[b]
Simulation time	200 s
Simulation runs	20

[a] Highway scenario.
[b] Urban scenario.

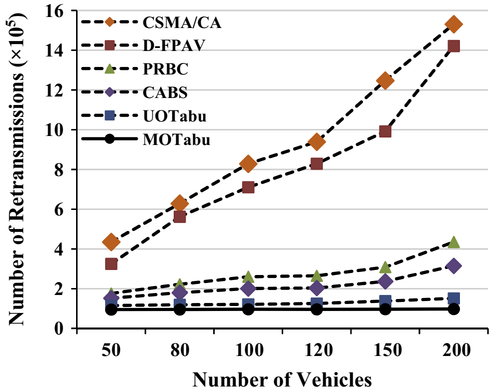

Fig. 4. Variation of the number of retransmissions with the number of vehicles in highway scenario.

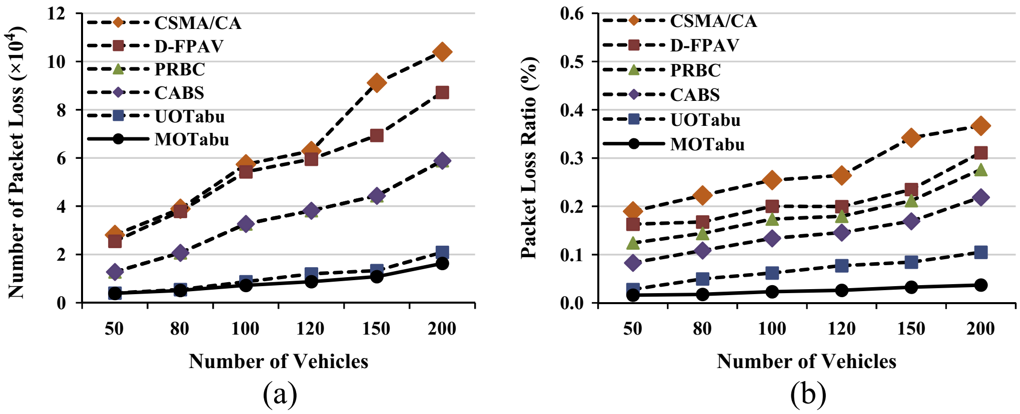

Fig. 3. Variation of (a) the number of packet loss, and (b) the ratio of packet loss with the number of vehicles in highway scenario.

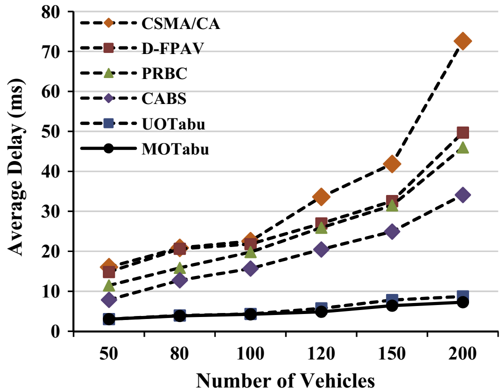

Fig. 5. Variation of average delay with the number of vehicles in highway scenario.

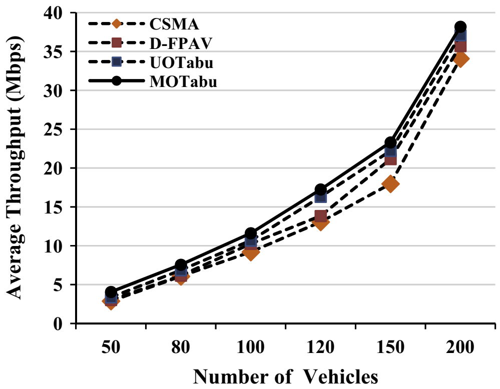

Fig. 6. Impact of the number of vehicles on throughput in highway scenario.

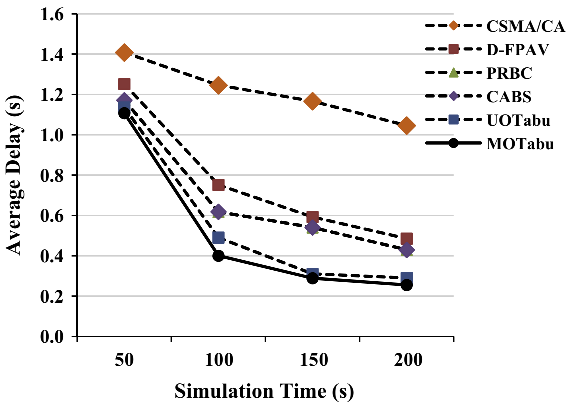

Fig. 7. Variation of the average delay with the simulation time in highway scenario.

number of vehicle for each congestion control strategies. Fig. 3(a) shows that the number of packet loss in Tabu Search congestion control strategies (i.e., MOTabu, and UOTabu) is less than the other strategies, regardless of the number of vehicles. Such as improvement was

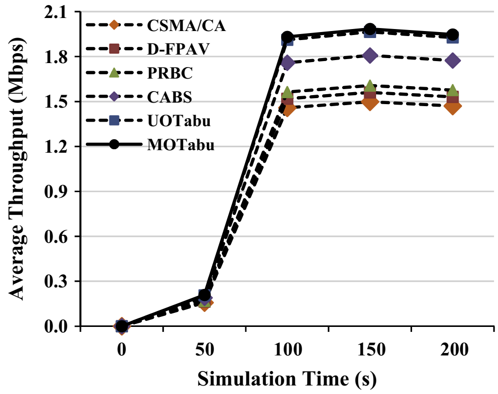

Fig. 8. Variation of the average throughput within the simulation time in highway scenario.

obtained because Tabu Search strategies tune the transmission range and rate for the all safety and non-safety messages. Note that, to control congestion, CSMA/CA varies back-off and contention window size, D-FPAV varies the beaconing range, PRBC adjusts the beaconing rate and power, and CABS schedules the beacon messages. Fig. 3(a) also shows that the performance of MOTabu strategy is better than UOTabu strategy. Here, it should be emphasized that congestion control in MOTabu strategy is carried out by minimizing both delay and jitter, while in UOTabu strategy only delay is considered. Thus, MOTabu strategy makes a discipline to transfer the packets between the vehicles. Moreover, MOTabu increases the performance of data transmissions by generating a synchronous data transferring that results from a short transmission time (delay) and a small latency variance (jitter).

In Fig. 3(b), the variations of the packet loss ratio with the number of vehicle are depicted for each congestion control strategy. Fig. 3(b) shows that in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu and MOTabu strategies, the packet loss ratio for the number of vehicles 50 is equal to 19%, 16.5%, 12%, 8%, 3%, and 1%, while for the number of vehicles 200, the packet loss ratio is equal to 38%, 32%, 27%, 21%, 10%, and 3%, respectively. The results show that by increasing the number of vehicles from 50 to 200, the packet loss ratio increases in all the strategies. However, increasing the number of vehicles increases the packet loss ratio 17%, 15.5%, 15%, 13%, 7%, and 2% in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu, respectively. It means increasing the number of vehicles does not have a significant impact on packet loss ratio when MOTabu strategy is used to control congestion. As a result, the proposed Tabu Search congestion control strategy can be considered as a scalable distributed strategy.

Briefly, the results shown in Fig. 3(a) and (b) prove that the proposed Tabu Search strategy can control the congestion in highways more efficiently than the other strategies. Decreasing the number of packet loss especially emergency massages can help provide a more reliable and safe environment in VANets.

Fig. 4 illustrates the variation of the number of retransmissions with the number of vehicles for each congestion control strategy. As the figure shows, the number of

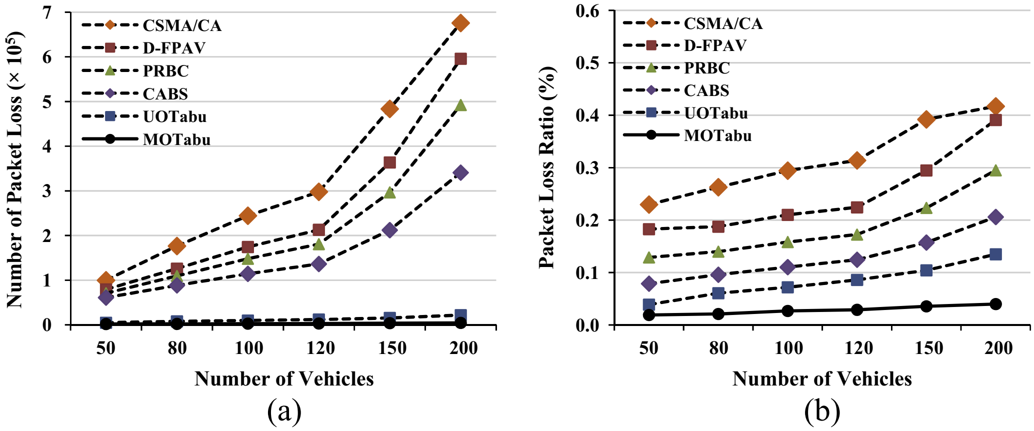

Fig. 9. Variation of (a) the number of packet loss, and (b) the ratio of packet loss with the number of vehicles in urban scenario.

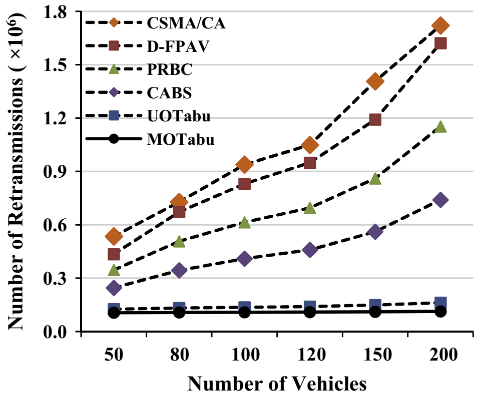

Fig. 10. Variation of the number of retransmissions with the number of vehicles in urban scenario.

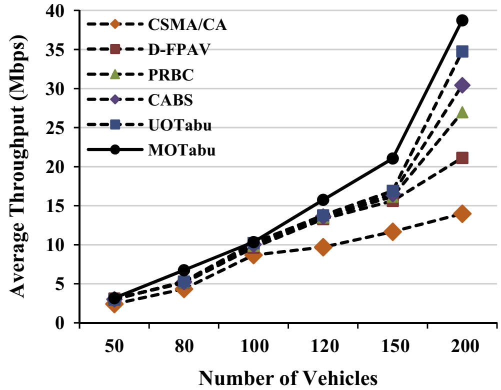

Fig. 12. Impact of the number of vehicles on throughput in urban scenario.

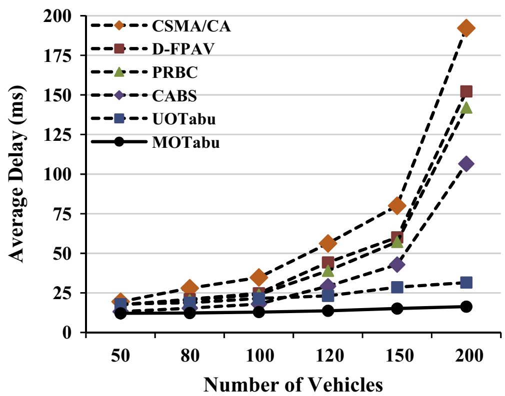

Fig. 11. Variation of delay with the number of vehicles in urban scenario.

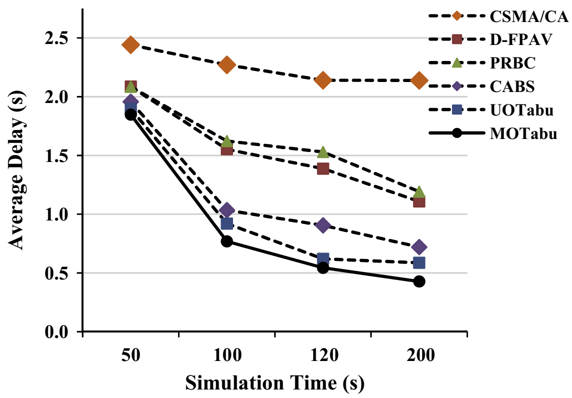

Fig. 13. Variation of the average delay with the simulation time in urban scenario.

retransmission for the number of vehicles 200 in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu and MOTabu strategies, is equal to 15.31×10^5, 14.21×10^5, 4.35×10^5, 3.15×10^5, 1.51×10^5, and 0.97×10^5, respectively. Thus, in Tabu Search strategies, especially MOTabu, the numbers of retransmissions are less than the other strategies. Note that the packets need to be retransmitted after the packet loss. Thus, reducing the packet loss (Fig. 3) results in the reduction of the number of packet retransmissions (Fig. 4). MOTabu strategy decreases the packet loss and

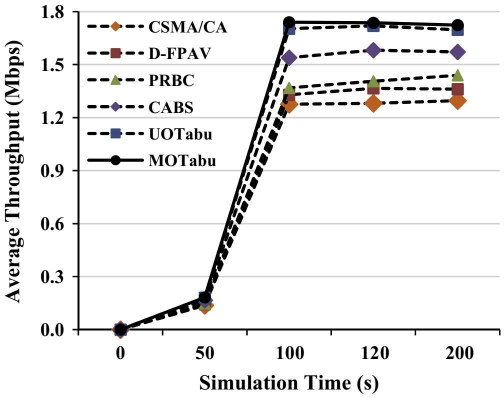

Fig. 14. Variations of the average throughput within the simulation time in urban scenario.

the number of retransmissions through tuning transmission range and rate for both safety and non-safety massages. Note that although non-safety massages compose the larger portion of massages, the other congestion control strategies do not consider the non-safety massages during the congestion control process.

The second objective of the congestion control strategy is to decrease delay. Fig. 5 depicts the variation of delay with the number of vehicles for each congestion control strategy. As the figure shows, when the number of vehicles increases from 50 to 200, the delay increase from 16.04, 14.82, 11.45, 7.84, 3.04, and 3.03 ms to 72.59, 49.68, 45.98, 34.11, 8.71, and 7.27 ms in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. The results show that the delay in Tabu Search strategies (MOTabu and UOTabu) is significantly less than the other strategies. It can be also seen that the delay in MOTabu is slightly less than the delay in UOTabu strategy. As it was mentioned before, in UOTabu, the delay is minimized for tuning transmission range and rate. However, in MOTabu, both the delay and jitter are minimized for tuning transmission range and rate. It should be emphasized that Tabu Search algorithm finds near optimal solution. The results show that using MOTabu strategy, an arranged messages transferring in reasonable time can be obtained.

The impacts of the number of vehicles on throughput were also studied to evaluate the performance of MOTabu Search strategy to control congestion in VANets. As Fig. 6 shows, throughput increases by increasing the number of vehicles because increasing the number of vehicles leads to increase the number of delivered packets. In this figure, two comparison strategies were removed to make a sparse and readable graph. The figure shows that, for the number of vehicles 200, throughput is equal to 34.09, 35.71, 37.09, and 38.19 Mbps in CSMA/CA, D-FPAV, UOTabu, and MOTabu strategies, respectively. MOTabu has slightly better performance than the others strategies because, as it was shown in the previous figures, using MOTabu strategy, channel collisions decreased and channel utilization improved.

In Figs. 3–6, the congestion control strategies were evaluated using the variations of the performance metrics (i.e., number of packet loss, packet loss ratio, number of retransmission, average delay, and throughput) with the number of vehicles. The evaluations revealed that MOTabu strategy outperforms the other congestion control strategies. MOTabu creates a discipline to transfer the packets by minimizing the delay and jitter leading to dynamically tuning transmission range and rate based on the current situation of the network. In the following, the variations of the delay and throughput with the simulation time are illustrated in Figs. 7 and 8 for more evaluation of the proposed strategy when the number of vehicles is 50.

Fig. 7 shows the variation of the average delay with the simulation time. In this figure, the average delay is investigated at four levels of simulation time: 50, 100, 150, and 200 s. Note that the delay at the simulation time zero is zero. The results show that by advancing the simulation time, the delay of delivering data packets to destinations is decreased for all the strategies, as it is expected. The delay at simulation time 200 s for CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu is 1.04, 0.48, 0.69, 0.42, 0.29, and 0.25 s. As it is expected, the lowest delay is obtained using MOTabu strategy at each simulation time. Moreover, the results show that within first 50 s (from simulation time 50–100 s), the average delay decreases 0.16, 0.52, 0.45, 0.55, 0.64, and 0.71 s using CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. It means MOTabu strategy can reduce the average delay more rapidly within the simulation time compare to the other strategies. In other word, although the delay is high at the beginning of the simulation due to more collisions occurrence in the transmissions, it rapidly decreases as long as the congestion is controlled by MOTabu.

In Fig. 8, the variations of the average throughput with the simulation time are shown for each congestion control strategy. The results show that the average throughput obtained from MOTabu strategy is larger than the other five strategies at any simulation time. In fact, controlling the congestion and decreasing the number of packet loss cause to increase the number of delivered packets over the simulation time, and consequently the throughput efficiency increases with passing the time.

In the following, urban scenario is investigated to evaluate the performance of the proposed congestion control strategy under a high level of congestion. In the urban scenario to consider existing obstacles in the urban environment (e.g. buildings, trees), Nakagami model is employed instead of TwoRayGround model for radio propagation. The Nakagami model is a suitable propagation model for simulating physical fading of mobile communication channels [23]. The other characteristics of urban scenario were shown in Table. 1. Figs. 9–14 depict the results obtained from the urban scenario.

Fig. 9 illustrates the variation of the number of packet loss/packet loss ratio with the number of vehicles for each congestion control strategies. The figure shows that the number of packet loss/packet loss ratio increases by increasing the number of vehicles regardless of the congestion control strategies. However, rate of changes in MOTabu strategy is much less than the other strategies. For example, in Fig. 9(a), the number of packet loss for number of vehicles 200 is 6.76, 6.49, 5.95, 4.58, 3.47, and

1.23 times more than the number of packet loss for number of vehicles 50, in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. Fig. 9(b) shows that the packet loss ratio obtained from MOTabu strategy is 10.5, 9.8, 7.4, 5.5, and 3.4 times less than CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu, respectively, for the number of vehicles 200. Such results show that MOTabu strategy can significantly reduce packet loss in urban scenario in regard to the other strategies.

Additionally, Figs. 10–12 show the impacts of the number of vehicles on the number of retransmissions, delay, and throughput for each congestion control strategy in the urban scenario, respectively. In MOTabu strategy, the number of packet loss/the packet loss ratio is less than the other strategies (Fig. 9). Such improvement lead to reduce the number of retransmissions (Fig. 10) and delay (Fig. 11), and to increase the throughput (Fig. 12) in MOTabu strategy in regard to CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu strategies. Note that the performance metrics in urban scenario has larger values than that in the highway scenario due to the miscellaneous environment of urban scenario.

Fig. 10 illustrates that the number of retransmissions obtained from MOTabu strategy, 94%, 93%, 90%, 84%, and 30% decreases in respect to CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu strategies, respectively, for the number of vehicles 200. By investigating the results shown in Fig. 11, it can be concluded that the average delay obtained from MOTabu for the number of vehicles 200 is at least 48% less than the other congestion control strategies. Fig. 12 shows that the average throughput for the number of vehicles 200 is equal to 13.97, 21.12, 26.96, 30.42, 34.75, and 38.73 Mbps in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. It means at least 10% improvements can be obtained for the throughput using MOTabu strategy to control congestion in VANETs.

Finally, Figs. 13 and 14 illustrate the variation of the average delay and throughput with the simulation time in various congestion control strategies in urban scenario when the number of vehicles is 50. Fig. 13 shows that after 150 s (from 50 to 200 s), 12.4%, 46.8%, 42.8%, 63.2%, 69%, and 76.8% reduction is observed in the average delay in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. Fig. 14 shows that the throughput at simulation time 200 s in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu is 1.29, 1.36, 1.43, 1.57, 1.69, and 1.72 Mbps. These results shown in Figs. 13 and 14 conclude that in urban scenario similar to highway scenario, MOTabu strategy decreases average delay rapidly and increases average throughput significantly rather than the other congestion control strategies. In the other words, MOTabu strategy outperforms the other strategies because MOTabu strategy dynamically tunes transmission range and rate for all kinds of messages (safety and non-safety) in congestion situations by minimizing the delay and jitter.

6. Summary and conclusion

In this paper, a MOTabu strategy was presented to control congestion in VANets. The proposed strategy was a closed-loop congestion control strategy that consists of congestion detection and congestion control components. Channel usage level was measured to detect congestion. The Multi-Objective Tabu Search was used to control congestion. The proposed strategy controlled congestion dynamically by tuning transmission range and rate for all kinds of messages (safety and non-safety), whereas delay and jitter were minimized. The proposed strategy was also distributed that means the strategy was executed in each vehicle. To reduce the complexity related to implementation of Tabu Search algorithm in the proposed strategy, some simplifying assumptions were made (e.g. assuming discrete values for transmission range and transmission rate; and also assuming constant value for the iteration number for Tabu Search algorithm).

Considering a highway and urban scenario, the performance of MOTabu was compared with five existing congestion control strategies including CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu. For comparison purposes, variations of performance metrics with the number of vehicles and simulation time were investigated. The comparison showed that the proposed strategy can control congestion more efficiently by tuning transmission range and rate. MOTabu strategy improved the number of packet loss, packet loss ratio, number of retransmissions, average delay, and average throughput. Consequently, the transmission range and rate were optimally increased or decreased while it takes into account minimizing delay and jitter by MOTabu. Control congestion using MOTabu strategy help create more reliable environments in VANets.

There are some limitations to implement the proposed strategies in real vehicular network. To implement this strategy, all the vehicles need to equip with an On-Board Unit (OBU) to do real time computations. The vehicles should be able to estimate channel usage level for detecting congestion situation. Also, the vehicles should be able to dynamically tune transmission range and rate. Moreover, the values of transmission range and rate need to be discretized due to the limitations of Tabu Search Algorithm. Finally, the vehicles should be equipped with GPS to determine speed, direction, and position of vehicles to estimate the delay and jitter.

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