Distributed Multichannel and Mobility-Aware Cluster-Based MAC Protocol for Vehicular Ad Hoc Networks

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***Abstract*—Since vehicular safety applications require periodic dissemination of status and emergency messages, contention-based medium-access-control (MAC) protocols such as IEEE 802.11p have problems in predictability, fairness, low throughput, latency, and high collision rate, particularly in high-density networks. Therefore, a distributed multichannel and mobility-aware cluster-based MAC (DMMAC) protocol is proposed. Through channel scheduling and an adaptive learning mechanism integrated within the fuzzy-logic inference system (FIS), vehicles organize themselves into more stable and nonoverlapped clusters. Each cluster will use a different subchannel from its neighbors in a distributed manner to eliminate the hidden terminal problem. Increasing the system's reliability, reducing the time delay for vehicular safety applications, and efficiently clustering vehicles in highly dynamic and dense networks in a distributed manner are the main contributions of the proposed MAC protocol. The reliability and connectivity of DMMAC are analyzed in terms of the average cluster size, the communication range within the cluster and between cluster heads (CHs), and the lifetime of a path. Simulation results show that the proposed protocol can support traffic safety and increase vehicular ad hoc networks' (VANETs) efficiency, reliability, and stability of the cluster topology by increasing the CH's lifetime and the dwell time of its members.**

***Index Terms*—Clustering, medium access control (MAC), mobility, reliability, vehicular ad hoc network (VANET).**

I. Introduction

RAPID advances in and cost reduction of wireless technologies have opened the door to utilizing these technologies in support of advanced vehicular safety applications. In particular, the new dedicated short-range communications (DSRC) or IEEE 802.11p [1] enables a new class of vehicular safety applications that will increase the overall safety, reliability, and efficiency of the current transportation system. In the field of intelligent transportation systems (ITSs), this technology will provide a wide spectrum of applications to avoid or to decrease the severity of road accidents.

In vehicular ad hoc networks' (VANETs) safety applications, vehicles have to be constantly aware of the events in their surrounding environment to prevent dangerous situations before they occur. Therefore, vehicles have to periodically exchange their status and emergency messages (beacons) every 100 ms [2]. Without efficient and reliable medium-access-control (MAC) protocol, such high beaconing may result in a large number of collisions, particularly in high-density networks, thereby causing serious degradation in the performance of VANETs' safety and nonsafety applications. To have a reliable and efficient MAC protocol that suits the high mobility of vehicles, the proposed MAC protocol should avoid transmission collisions between nodes (vehicles); hence, emergency messages will be forwarded in a real-time fashion. Moreover, the medium (wireless channel) has to be efficiently and fairly shared between vehicles.

Since the communication requirements of VANET safety applications are complex and demand high throughput, reliability, and bounded time delay concurrently, the design of their MAC protocol is a challenge, particularly in high-density networks. It is shown from previous studies that using time-division multiple access (TDMA) or self-organized TDMA (STDMA) is fair and has predictable delay. However, it needs strict synchronization and complete premapping of geographical locations to TDMA slots. On the other hand, using carrier sense multiple access (CSMA) is less complex, supports variable packet sizes, and requires no strict synchronization, but it has problems in unbounded time delay and consecutive packet drops. Therefore, clustering is used to limit channel contention, to provide fair channel access within the cluster, to increase the network capacity by the spatial reuse of network resources and to control effectively the network topology. The main challenge in clustering is the overhead that is introduced to elect the cluster head (CH) and to maintain the membership in a highly dynamic and fast changing topology. Optimization of the communication range and, hence, the cluster size, is also difficult, particularly in a highly dynamic environment such as VANETs. In [3] and [4], the relationships between the communication range and the

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TABLE I
CONTENTION PARAMETERS FOR IEEE802.11P CCH [5]

AC No.	Access Class	CWmin	CWmax	AIFSN
0	Background Traffic (BK)	15	1023	9
1	Best Effort (BE)	7	15	6
2	Voice (VO)	3	7	3
3	Video (VI)	3	7	2

network density, message sending rate, message size, data rate, and channel conditions were derived.

In this paper, a distributed multichannel and mobility-aware cluster-based MAC protocol (DMMAC) is proposed. It integrates orthogonal frequency-division multiple access (OFDMA) with the contention-based distributed coordination function (DCF) algorithm in IEEE 802.11p. CHs are elected based on their stability on the road and with minimal overhead since clustering information is embedded in vehicles' periodic status messages. The proposed MAC protocol is adaptable to drivers' behavior and has a learning mechanism to predict the future speeds and positions of all cluster members using the fuzzy-logic inference system (FIS). This makes the proposed protocol more efficient in maintaining the cluster topology and increases the lifetime of the elected CH and its members. In DMMAC, the OFDMA subcarriers of the IEEE 802.11p control channel (CCH) are divided into four sets. Each cluster can use only one set that is different from its neighbors to eliminate the hidden terminal problem. As a result, the system's reliability can be increased, and the time delay for safety messages can be decreased. Since each vehicle in the network has its own view of the network density and channel conditions, finding the optimal network parameters is difficult. Therefore, the main goal of the proposed DMMAC is to find the cluster size and, hence, the communication range, that maintains a high network stability and reliability, increases the lifetime of a path and, at the same time, decreases the time delay for an emergency message to reach its intended recipients. In DMMAC, it is assumed that vehicles are moving in a one-way multilane highway segment. Therefore, to eliminate the interference from the other side of the road, we assume that a different code or channel will be assigned to each side of the highway.

The rest of this paper is organized as follows. In Section II, we briefly review the related work. The proposed DMMAC protocol and its algorithms are introduced in Section III. In Section IV, the proposed DMMAC protocol is analyzed in terms of time delay, reliability, stability, and network convergence. Simulation results are presented in Section V, and the conclusion of this paper is provided in Section VI.

II. RELATED WORK

The IEEE community is working on the standardization of the DSRC or IEEE802.11p [1]. In this technology, there are four access classes (ACs) with different arbitration interframe space (AIFS) numbers to insure less waiting time for high-priority packets, as listed in Table I. This technology uses CSMA with collision avoidance in the licensed ITS 5.9-GHz (5.850–5.925 GHz) band in North America. The 75-MHz spectrum is divided into seven 10-MHz channels and a 5-MHz guard band. The CCH channel 178 will be used for safety-related applications and system control management. The other six channels are service channels (SCHs) dedicated for nonsafety and commercial applications. Vehicles will alternate between the CCH and one or more of the SCHs. The standard assumes that all vehicles will be synchronized to a common time through an external system, such as Global Positioning System, for the synchronization interval ($T_{\mathrm{SI}} = 100$ ms). At the beginning of this interval, vehicles will synchronize to the CCH for a period called CCH interval (CCI). The remaining time is called SCH interval (SCI), where vehicles synchronize to one of the SCHs, such that $T_{\mathrm{SI}} = T_{\mathrm{CCI}} + T_{\mathrm{SCI}}$.

Most of the vehicular safety applications being proposed in the literature rely on the IEEE 802.11p, which uses the DCF as its MAC protocol. Due to vehicles' high mobility, VANETs suffer from the rapid network topology change, unlimited redundancy due to small road's width compared with the range, frequent link ruptures, and variable vehicle density, which results in variable network connectivity. The authors in [3]–[10] have extensively studied the IEEE 802.11p protocol and showed that this protocol has problems in predictability, fairness, low throughput, and high collision rate, particularly in high-density networks. Moreover, the vehicles' high speed has huge impact on VANET throughput and the reliability of any proposed MAC protocol, as studied and analyzed in [11] and [12].

Due to these problems, many of the proposed solutions are based on TDMA. The authors in [9] proposed an STDMA MAC protocol. In [13], a multichannel TDMA MAC protocol is proposed to support efficient broadcast services in VANETs by using implicit acknowledgements. For each node, a fixed time slot of the CCH is assigned, which limits the number of vehicles that could be accommodated within the system. In [14], a distributed multichannel MAC protocol is proposed to increase mainly the throughput of the nonsafety applications. In this protocol, a limited number of nodes within the communication range are allowed to contend for the reservation of channel slots. This protocol does not need strict synchronization, which results in some nodes missing emergency information while they are out of the CCI. The authors in [15]–[17] proposed a space-division multiple-access schemes where the road is divided into small cells. For each cell, they assigned a time slot, a frequency band, or a code for the vehicles in that cell to use. In these schemes, most of the cells will be empty, particularly in low-density networks, and could suffer the location error problem.

Some token-ring protocols have been proposed for ITSs, such as [18], due to their bandwidth reservation efficiency and bounded time delay. The wireless token-ring protocol [18] is based on a single communication channel, which is not so efficient in utilizing channel resources. A multichannel token-ring protocol (MCTRP) for VANETs was proposed in [19]. Its main goal is to achieve low latency for safety messages and high throughput for nonsafety applications. In the MCTRP, vehicles with the same speed are grouped into rings. This protocol has high overhead since it heavily relies on a central node. Moreover, it invokes the central node election very frequently, which makes it more suitable for low-speed networks.

Many researchers, such as in [20]–[27], have proposed cluster-based multichannel MAC protocols to improve the performance and reliability of VANETs. The authors in [22] have proposed a clustering scheme where CHs have the main role of providing a TDMA schedule to their members. In [24], the authors proposed a clustering-based MAC multichannel protocol (CMCP) where each node is armed by two transceivers, which they assume that they can simultaneously operate on different channels. Inside the cluster, the CH organizes the channel access between member nodes by using TDMA using one of its transceivers with different CDMA code. Another transceiver is used to communicate with neighboring CHs by using the DCF of IEEE 802.11 on a different channel. This system has a very high cost and needs very strict synchronization between all nodes. Moreover, their CH selection criterion is based on time and size. The node that sends an invite-to-join message first and has more cluster members will be selected as the CH. This scheme results in high-frequency network topology change since vehicles move in and out of the cluster boundary very frequently. A mobility-based clustering scheme is proposed in [26]. They based their CH selection criterion on the Doppler shifts arising from the received hello packets. The authors in [27] have proposed a mobility-based clustering scheme, which is called APROVE, using an affinity propagation algorithm. In APROVE, vehicles send messages to one another describing the current affinity that one vehicle has for choosing another vehicle as its exemplar. Upon the network convergence, the CH is selected based on the vehicles' interdistances. The vehicle that has the minimum interdistance, i.e., the closest to its neighbors, will be selected as the CH. Although this scheme integrates mobility in its CH selection criteria, it needs very long time for a network to converge until all vehicles exchange their affinity messages. Moreover, the CH election process is frequently invoked when a predefined timer expires, which results in large overhead and low throughput.

III. Distributed Multichannel and Mobility-Aware Cluster-Based Medium-Access-Control Clustering Protocol

The proposed DMMAC protocol aims to make a large network with highly dynamic nodes to appear smaller and more stable. It is assumed that all vehicles have the same transmitting capability (three levels of power) since they have equal chance to be elected as CHs. Cluster members will use the same communication range R, i.e., the same transmitting power P_t, that has two values R_h and R_l depending on the network density. The details will be explained in Section IV-A. Vehicles will use the range $R = R_h$ when they enter the road for the first time or when they are not clustered (lone state). Otherwise, they will use the range $R \in \{R_l, R_h\}$ that is advertised by their CH. The CH has two communication ranges: the first range $R \in \{R_l, R_h\}$, which is dedicated to communicate with its cluster members; and the second range D_c, which is a function of the used range R, to communicate with its CH neighbors. The derivation of R_h, R_l, and D_c will be explained in Section IV-A.

In DMMAC, the CCH subcarriers are divided into four sets (c_1, c_2, c_3, c_4). The first three sets can be used by clusters where each CH has to select a different set from its neighboring CHs. The fourth set c_4 is a temporary set, which can be used only by a node that could not join a cluster. Once it joins a cluster, it releases c_4 and uses the same set as the new CH. While c_4 is a contention-based subchannel, the first three subchannels are schedule based, where vehicles follow the schedule advertised by the CH to access the wireless channel.

Type	ID	β_{WSF}	v	Pos	a	R	CHID	CHBK

Fig. 1. Status message format.

A. Clustering Algorithm and Its Parameters

The clustering algorithm is the most important component in the clustering-based MAC protocols. The faster the nodes are clustered around their elected CH and the less often they reelect a new CH, the more the network will be stable. In DMMAC, all vehicles have their own unique ID number and will synchronize to the CCH to exchange their status messages using AC_1, as in Table I. The status message contains information about the message type, vehicle's ID, weighted stabilization factor β_{WSF}, current speed v, current position Pos, acceleration a, communication range R, CH's ID (CHID), and the backup CH's ID (CHBK), as shown in Fig. 1. The acceleration will help to determine the vehicle's speed and position during the succeeding maintenance period T_f. The field type has four values: "0" is for cluster member's status message, "1" is for CH's first message and will be sent using AC_2, "2" is for CH's invitation message, and "3" is for CH's last message.

Each vehicle calculates its weighted stabilization factor β_{WSF} as in (1), which is a function of the change in its relative speed and direction compared with its neighbors for the time that it has been on the road. The higher the β_{WSF} factor, the higher the chance for this vehicle to be elected as a CH. Each vehicle will calculate its average relative speed as $\overline{v}_{d_j} = (1/(n-1)) \sum_{i=1}^{n-1} |v_j - v_i|$, where n is the number of vehicles within the jth vehicle's range including itself, and v_j is the jth vehicle's speed in meters per second. The jth vehicle calculates its stabilization factor β_{SF_j} at the end of every CCI as $\beta_{\mathrm{SF}_j} = \max\{1 - (\overline{v}_{d_j}/V_{\max}), 0\}$, where $V_{\max}$ is the maximum allowed speed on this road. If there are no other vehicles on the road, the vehicle compares its speed with $V_{\max}$ to calculate its β_{SF} factor. The value of β_{SF_j} is limited to the minimum value of 0, which could happen in a very rare situation when a vehicle is moving in almost zero speed, whereas all other vehicles are moving above the maximum speed $V_{\max}$. The jth vehicle calculates its new weighted stabilization factor $\beta_{\mathrm{WSF}_j}(n)$ from the new value of $\beta_{\mathrm{SF}_j}(n)$ and the previous value of $\beta_{\mathrm{WSF}_j}(n-1)$ as an exponential-weighted moving average, i.e.,

$$\beta_{\mathrm{WSF}_j}(n) = \zeta\, \beta_{\mathrm{SF}_j}(n) + (1-\zeta)\, \beta_{\mathrm{WSF}_j}(n-1) \qquad (1)$$

where $n = 1, 2, \ldots$ is an index to denote the time sequence, $\beta_{\mathrm{WSF}_j}(0) = 0$, and $0 \le \zeta \le 1$ is the smoothing factor and chosen here to be 0.5.

The vehicle's acceleration a, which helps to predict the vehicle's speed and position in the near future (after time T_f), depends on many factors, such as the distance between the vehicle and its front neighbor, the relative speed between them, the road conditions, and the driver's behavior. Most of the time,

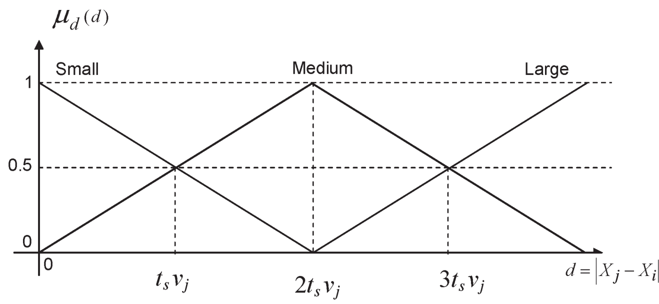

Fig. 2. Membership function of the interdistance d between two vehicles.

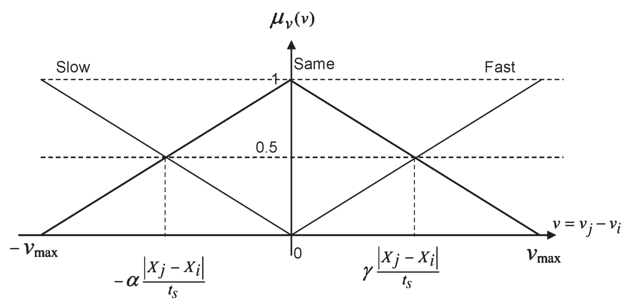

Fig. 3. Membership function of the relative speed v between two vehicles.

the drivers' behavior and how they estimate the interdistance and other factors are subjective and not predictable. Fuzzy logic is used to deal with this uncertainty in this paper. Fuzzy logic is a rule-based system that consists of IF–THEN rules that form the key components of the FIS [28]. Since FIS lacks the adaptability to deal with changing external environment, we incorporate a learning technique to predict the acceleration of vehicles based on the previous behavior of the driver.

The FIS system consists of a fuzzifier, a rule base, a reasoning mechanism, and a defuzzifier. The fuzzifier defines the membership functions used in the fuzzy rules. In this paper, the triangular fuzzifier is chosen to implement the FIS system. While the rule base contains a selection of the fuzzy rules, the reasoning mechanism performs the inference procedure upon those rules to derive a reasonable output. The defuzzifier is a method used to map the output fuzzy sets to a crisp output values. In this paper, the interdistance and the relative speed between two vehicles are used as input parameters to the FIS system and the vehicle's acceleration as its output.

The membership function of the distance between a vehicle and its immediate front neighbor is μ_d and can take any of the three values: *small, medium,* and *large,* as shown in Fig. 2. Parameter t_s is a design parameter that represents the safe following distance between two vehicles on the road, i.e., the time needed by the following vehicle with a speed of v_j to cross this interdistance d. The triangular function is selected here because we are only interested in the intersection points where the driver considers the distance to be either *small, medium,* or *large*. As in Fig. 2, the driver of vehicle j will consider the interdistance to be *small* if $d \in [0,\, t_s v_j]$, i.e., below the following safety distance. The driver will also consider the interdistance to be *large* if $d > 3t_s v_j$. Finally, the driver will consider the distance to be *medium* if $t_s v_j \le d \le 3t_s v_j$.

The membership function of the relative speed between two vehicles is μ_v and can take the three values: *slow, same,* and *fast,* as shown in Fig. 3. The triangular function is used since we are interested in the intersection points where the system will assume the speed to be either *fast, same*, or *slow,* compared with the front vehicle. If the relative speed $v = v_j - v_i$ between vehicle j and its front neighbor vehicle i is higher than what it should be to cross the interdistance between them in time t_s, the relative speed will have the value *fast*. On the other hand, v will be considered *slow* if it has the negative value of the first case, i.e., the front vehicle has higher speed than the following vehicle. Finally, if the relative speed is around the zero value, it will get the value *same*.

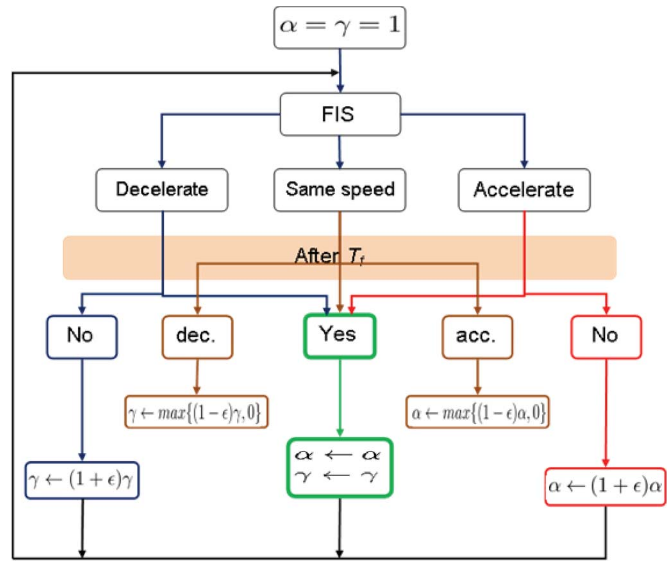

Fig. 4. Learning mechanism in DMMAC.

Parameters α and γ are used to make the system more adaptable to the driver's behavior on the road. Initially, their values are set to $\alpha = \gamma = 1$ and will be increased or decreased by a step of ϵ if the driver's decision to accelerate or decelerate did not match the predicted output values, as shown in Fig. 4. If the system predicts that the vehicle will accelerate but it did not, then $\alpha \Leftarrow (1+\epsilon)\alpha$. If the system predicts that the vehicle's speed will stay the same but it accelerates, then $\alpha \Leftarrow \max\{(1-\epsilon)\alpha, 0\}$. If it decelerates, then $\gamma \Leftarrow \max\{(1-\epsilon)\gamma, 0\}$. Finally, if the system predicts that the vehicle will decelerate but it did not, then $\gamma \Leftarrow (1+\epsilon)\gamma$. If the vehicle's acceleration matches with the predicted value, then the same values of α and γ are kept. By this, the values of α and γ will converge to certain values after a short period of time to capture the driver's behavior on the road. The learning mechanism is shown as Algorithm 1.

Algorithm 1 An adaptive learning mechanism in DMMAC.

Initial setup
$\alpha \leftarrow 1$ {/∗ set $\alpha = 1$ ∗/}
$\gamma \leftarrow 1$ {/∗ set $\gamma = 1$ ∗/}
$\epsilon \leftarrow 0.1$ {/∗ set $\epsilon = 0.1$ ∗/}
for $Every\ T_f\ seconds$ **do**
  $a_{\mathrm{FIS}} \leftarrow FIS \leftarrow a$ {/∗ at the beginning of T_f, predict the acceleration based on the FIS system ∗/}

$a_{\text{act}} \leftarrow measuredaccelaration$ {/∗ at the end of T_f, measure the actual acceleration ∗/}
if $a_{\text{FIS}} = 0$ **then**
  if $a_{\text{act}} = 1$ **then**
    $\alpha \Leftarrow \max\{(1-\epsilon)\alpha, 0\}$ {/∗ decrease α if vehicle accelerates instead of same speed ∗/}
  else
    if $a_{\text{act}} = -1$ **then**
      $\gamma \Leftarrow \max\{(1-\epsilon)\gamma, 0\}$ {/∗ decrease γ if vehicle decelerates instead of same speed ∗/}
    end if
  else
    $\alpha \leftarrow \alpha$ {/∗ keep the same values of α and γ ∗/}
    $\gamma \leftarrow \gamma$
  end if
else
  if $a_{\text{FIS}} = 1$ **then**
    if $a_{\text{act}} = 0, -1$ **then**
      $\alpha \Leftarrow (1+\epsilon)\alpha$ {/∗ if a vehicle should accelerate but it did not, increase α ∗/}
    else
      $\alpha \leftarrow \alpha$ {/∗ keep the same values of α and γ if the FIS decision matches real value∗/}
      $\gamma \leftarrow \gamma$
    end if
  else
    if $a_{\text{act}} = 0, 1$ **then**
      $\gamma \Leftarrow (1+\epsilon)\gamma$ {/∗ if a vehicle should decelerate but it did not, increase γ ∗/}
    else
      $\alpha \leftarrow \alpha$ {/∗ keep the same values of α and γ if the FIS decision matches real value∗/}
      $\gamma \leftarrow \gamma$
    end if
  end if
end if
end for

The output variable, namely the predicted acceleration, is μ_{acc}, which has the following fuzzy names: *accelerate, stay at the same speed*, and *decelerate*. We choose the crisp outputs 1, 0, and -1 m/s^2 for the values of μ_{acc}, respectively. This is called a center average defuzzifier, which produces a crisp output based on the weighted average of the output fuzzy sets. Table II shows the suggested fuzzy rule for the acceleration output. The output variable μ_{acc} is shown in Fig. 5 for $\alpha = \gamma = 1$ as a function of the relative speed and interdistance between two neighbor vehicles normalized by $V_{\max}$. As the values of α and γ change, the decision areas of the acceleration output will change accordingly. Fig. 6 shows the acceleration output when $\alpha = 1.5$ and $\gamma = 0.3$.

B. DMMAC Cluster Membership

In DMMAC, the vehicle first listens to the channel for a random length of time from the interval $[0, \text{CCI}]$ and checks if there are other vehicles on the network and does one of the following:

1) If there are no other vehicles or it does not lie within the range of a CH (lone state), it will set the fields CHID = CHBK = 0 in its status message and start transmitting it using the temporary subcarrier set c_4.
2) If it encounters other vehicles using the same temporary set c_4 without an elected CH, they will start forming a temporary cluster. The vehicle with the highest β_{WSF}

TABLE II
FUZZY RULE OF THE ACCELERATION

Rule	$\mu_d(d)$	$\mu_v(v)$	$\mu_{acc}(a)$
1	small	slow	same speed
2	small	same	decelerate
3	small	fast	decelerate
4	medium	slow	same speed
5	medium	same	accelerate
6	medium	fast	decelerate
7	large	slow	accelerate
8	large	same	accelerate
9	large	fast	same speed

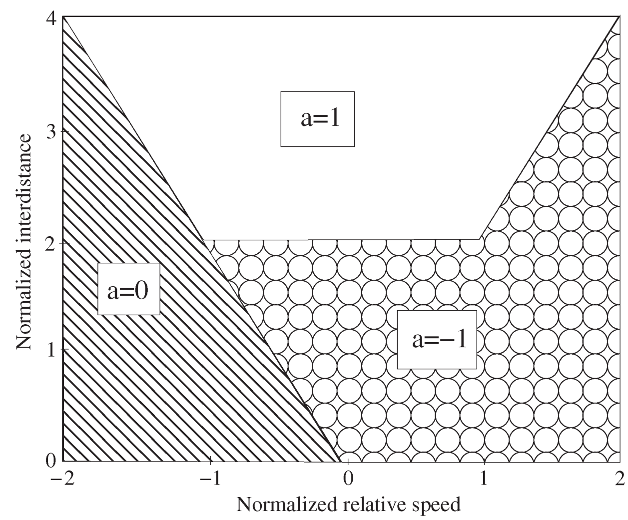

Fig. 5. Acceleration output for $\alpha = \gamma = 1$ as a function of the interdistance and relative speed normalized by the $v_{\max}$.

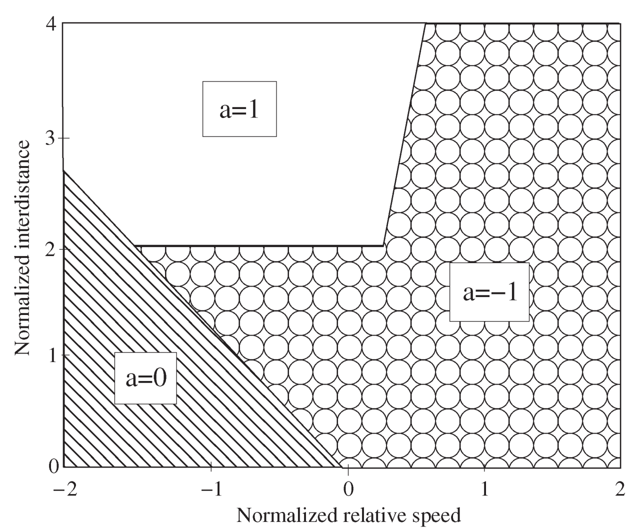

Fig. 6. Acceleration output for $\alpha = 1.5$ and $\gamma = 0.3$ as a function of the interdistance and relative speed normalized by the $v_{\max}$.

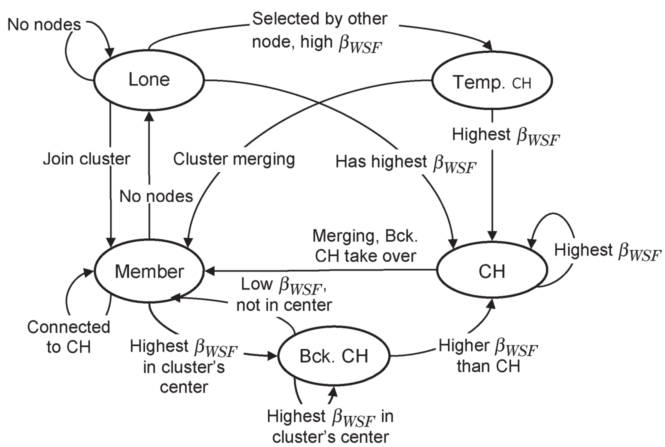

Fig. 7. DMMAC finite state machine.

will be elected as the CH, and if more than one vehicle have the same β_{WSF}, they will elect the vehicle with the highest ID. If the vehicle happened to be located within the range of two or more CHs, it will join the cluster with the closest CH to itself. Once a temporary cluster has been formed, the temporary CH will wait for the first chance to either become a main cluster itself or to merge with an adjacent cluster if it falls within half of its adjacent CH's range. On the other hand, it can change its state to a main cluster by selecting a subcarrier set that is not used by its adjacent clusters and tries its best to maintain the sequence of the subcarrier sets as c_1, c_2, and c_3. The core idea in DMMAC is to let each cluster to move iteratively its subcarrier set, following its immediate front cluster's set until network convergence occurs.

3) The vehicle will join a CH if it falls within its range. It will set its field CHID to the CH's ID and send its status message when it receives the CH's invitation message or the channel is being idle for time $T_w(d)$ as in (2), which is derived in Section III-D. This is the maximum time that a vehicle should wait before it can access the channel after one of its neighbors sends its message.
4) If the vehicle moves out of its CH's range, it will wait for a certain number of CCIs, which is three in this protocol, before it gives up the subcarrier set that it was using. The vehicle will look for a new or temporary cluster to join, as in step 1. Fig. 7 shows the finite state machine dictating the state of any DMMAC node.

C. CH Election and Reelection

In DMMAC, the algorithm of electing and reelecting the CH is fair and simple and with low communication and coordination among vehicles within the range. Once status messages are received, the vehicle with the highest β_{WSF} factor among all vehicles within its range will elect itself as a CH. It will set its CHID field to its own ID and select one of the main subcarrier sets (c_1, c_2, c_3) to send its status messages. All other vehicles within its range will join this cluster.

If there is another vehicle within this vehicle's range that has the highest β_{WSF} factor, it will assume the role of a temporary CH by setting its field backup CH's ID to the ID of that vehicle. This newly elected temporary CH will not participate in electing a new CH within its range and will wait either to merge with another cluster or to change its state to a main cluster.

To speed up the network convergence to a stable cluster topology, a vehicle that is not a CH within its own range and lies within the range of a temporary CH will join this cluster and will not participate in electing another temporary CH. The vehicle that lies within the range of two CHs will join the cluster with the closest CH to itself, giving the priority to the main cluster over the temporary cluster.

Once the CH is elected, the goal is to maintain the cluster topology as stable as possible by not initiating the election process very frequently. Therefore, the CH will calculate the expected positions of all of its members after time T_f, based on their advertised speeds and accelerations as $x(T_f) = x(0) + vT_f + (1/2)aT_f^2$, where $x(0)$ is the current position of a vehicle. The CH will maintain its status as a CH if all of its members are still within its range after time T_f. The CH will select a backup CH that has the highest β_{WSF} factor among all vehicles around the cluster's center other than itself. There are some cases when the CH speeds up or slows down such that some of its members that are located at the cluster boundary will be out of its range. If more than 10% of the cluster members become out of the current CH's range but are still within the backup CH's range, the current CH will hand the responsibility to the backup CH by setting its field $\mathrm{CHID} = \mathrm{CHBK}$ in its final message (Type 3). Otherwise, the current CH will maintain its status for the next interval. The backup CH, once it hears the third CH's message with its ID being set in the CHID field, will assume the role of the CH in the next CCI.

If the CH falls within two third of the neighbor CH's range, it will hand the responsibility to the backup CH if it exists. Otherwise, it will set the fields $\mathrm{CHID} = \mathrm{CHBK} = 0$ in its last message, announcing a merge with the neighbor CH. Other cluster members will either join the closest cluster or return back to the lone state.

D. CH's Role

The CH sends three additional messages that have the same format as the status message shown in Fig. 1, but with an additional data field that includes information about the schedule and the subchannel that vehicles should use in the succeeding CCI.

- First, at the beginning of every CCI, a consolidated message, with $\mathrm{type} = 1$, that has information about the neighboring clusters and all current cluster members using AC_2 parameters is sent. This insures a high priority for this message; hence, other vehicles can synchronize with the current CH. In this message, the cluster members' IDs are arranged from the behind to the front, and vehicles will follow this order to send their status messages. At the same time, each vehicle calculates its maximum waiting time $T_w(d)$ that it should wait for its turn to access the channel based on its distance d from its CH as

$$T_w(d) = T_A + \frac{T_A}{2}\left(1 + \frac{d}{R}\right) \tag{2}$$

where R is the used communication range (either R_h or R_l), $d \in [-R, R]$ is the distance from the CH where vehicles in front of the CH have positive distance and those behind it have negative distance, and $T_A = 6 \times 13$ μs is the AIFS for AC_1. A vehicle can send its status message when the vehicle ahead of it in the sequence finishes transmitting its message. Otherwise, it will send its message when its $T_w(d)$ expires. After every successful transmission, each node updates its $T_w(d)$ based on its distance from the last vehicle that successfully transmits the message. Vehicles that are at the front of the CH should wait until the CH takes its turn to send its status message $(\text{type} = 0)$. This is to eliminate the hidden terminal problem that could arise from the other side of the cluster.

- Second, after receiving all status messages from its cluster members, the CH sends a status message with $type = 2$, which is an invitation for new members to join the cluster by sending their status messages.
- Third, a consolidated message with $\text{type} = 3$ is sent, which contains information about all its members with enough power to reach a distance of D_c. This message is intended to reach the two neighboring CHs. The CH will send the final two messages after the channel has been idle for time $(2 + \psi) \times T_A$, where ψ is a random number uniformly distributed in [0, 1].

The CH decides which subcarrier set and what range R (R_h or R_l) that all of its members should use. In the remaining time of the CCI and after sending its final message, the CH will accept route requests from its members if they want to communicate with other vehicles on a different channel and outside the CCI.

If a vehicle has an emergency message, it will contend for the channel access using the minimum contention window specified for high-priority AC (AC_3), i.e., $CW_{\min} = 3$, and waiting time $T_w(d) = 2 \times 13$ μs to send this message for several times depending on the application. Once this message is received by the CH, it starts periodically transmitting the message using AC_3 parameters with enough power to reach a distance of D_c. All cluster members will refrain from using the channel during this time. When the next CH receives this message, it broadcasts the message with enough power to reach both the succeeding and the originating CHs. Once the originating CH hears its message back, it will stop broadcasting with high power but continues the broadcasting to all its members for several times depending on the application or until the emergency situation is cleared. The emergency message will continue to propagate in the direction of interest for a maximum number of hops depending on the application.

IV. Analysis

In DMMAC, vehicles send their status messages with less competition for accessing the channel and less vulnerable to the hidden terminal problem. This allows DMMAC to achieve an acceptable level of performance with respect to network convergence, stability, reliability, and time delay.

For the analysis of the DMMAC, the VANET model in [29] is used. This model is based on a one-way multilane highway segment that simplifies the network as a 1-D VANET, as shown in Fig. 8. In this model, vehicles are assumed to be distributed on the road as a Poisson process with average rate λ_v (in vehicles per meter) and follow the direction of the road with a speed uniformly distributed between $V_{\min}$ and $V_{\max}$. (For more information on this model, see [29].) In the following analysis, it is assumed that vehicles send their status messages $(\text{type} = 1$ and have the same length L bits) using the same transmission rate r_d (in megabits per second) and the same communication range R (in meters).

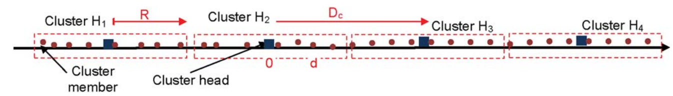

Fig. 8. Clustering model.

A. Network Convergence and Stability

In DMMAC, the cluster size is governed by the CH's communication range, which is a critical parameter in the stability of the network. Increasing the range will increase the cluster size; hence, more vehicles will contend for the channel use. At the same time, vehicles will have more space to move within the cluster with less probability to cross the cluster boundary.

Optimizing the communication range and, hence, the cluster size, is very difficult, particularly in a highly dynamic scenario. It has been shown in [4] and [29] how the vehicles' dynamic characteristic affects the network density and, hence, the reliability and throughput of VANETs' safety applications. Since each vehicle has its own view of the network density and channel conditions, finding the optimal network parameters is difficult. Therefore, range R has to be selected based on the vehicle density, status message size, and data rate such that all vehicles within the cluster have the chance to send their status messages within the CCI.

Assuming that the cluster can handle a maximum of K members, then the communication range R will have a CDF as

$$F_R(x) = \Pr(R \leq x) = \Pr\left(N(x) \geq \frac{K}{2}\right)$$
$$= 1 - \sum_{i=0}^{\frac{K}{2}-1} \frac{(\lambda_v x)^i}{i!} e^{-\lambda_v x} \quad (3)$$

where x is a dummy variable, and $N(x)$ is the Poisson process with parameter λ_v that represents the number of vehicles within distance x. By taking the first derivative of (3), it can be found that the probability density function (pdf) of the communication range has a gamma distribution as

$$f_R(x) = \frac{\lambda_v^{\frac{K}{2}} x^{\frac{K}{2}-1}}{\left(\frac{K}{2}-1\right)!} e^{-\lambda_v x}. \quad (4)$$

From (4), the mean value of the communication range can be found as $R = (K/2)(1/\lambda_v)$; therefore, the average cluster size is

$$K_{\text{avg}} = 2\lambda_v R. \quad (5)$$

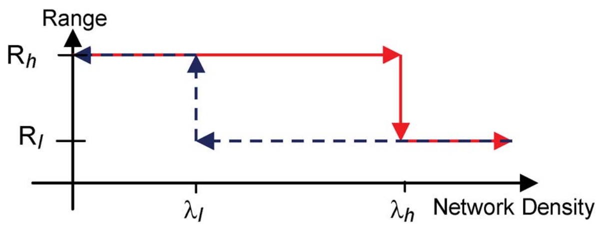

Fig. 9. Hysteresis mechanism in DMMAC.

As in (3), the CDF of the distance D_c between two adjacent CHs, which is the distance until the $K + 1$th arrival, can be derived as

$$F_{D_c}(x) = \Pr(D_c \le x) = \Pr(N(x) \ge K+1) = 1 - \sum_{i=0}^{K} \frac{(\lambda_v x)^i}{i!} e^{-\lambda_v x}. \quad (6)$$

By taking the first derivative of (6) with respect to x, the pdf of D_c is given by

$$f_{D_c}(x) = \frac{\lambda_v^{K+1} x^K}{K!} e^{-\lambda_v x}. \quad (7)$$

To make the probability of the CHs connectivity high, i.e., a CH finds a neighboring CH within distance D_c, we set $D_c = 2.5R$, where R is the range that is used and announced by the CH. This means that the CH will use communication range R to communicate with its members and a second level of power to reach a distance of $D_c = 2.5R$ to communicate with adjacent CHs.

To prevent the frequent changes in cluster size as vehicles move in and out of the cluster boundary, the CH in DMMAC will use the hysteresis mechanism shown in Fig. 9. Two threshold cluster sizes are defined: $K_h = 2\lambda_h R_h$ and $K_l = 2\lambda_l R_l$, where R_h is the range that all vehicles will use when they enter the road, λ_h is the maximum vehicle density that corresponds to R_h, R_l is the lowest range that can be used by all vehicles that is related to a jam scenario, and λ_l is the vehicle density that triggers the change from R_l to R_h. The CH can sense the network density by the number of received status messages within the CCI. K_h represents the maximum number of vehicles that can be accommodated within the cluster and have the chance to send their status messages. The CH will trigger a change in the used range from R_h to R_l when the density reaches λ_h and back to R_h when the density decreases to the threshold λ_l.

To find R_l and R_h, the upper bound of the average time T_{avg} until all cluster members managed to send their status messages is needed. It is assumed that all cluster members wait for time $T_w(d)$, as in (2), before they can access the channel (worst case scenario).

The CH sends its first message after time $T_{\text{cf}} = T_A + (L_{\text{cf}}/r_d) + \delta$, where L_{cf} is the CH's first message size in bits and δ is the propagation delay. After that, the first cluster member, which is located at distance x from the CH, will send its message after time $T_{\text{mf}}(x) = T_w(x) + (L/r_d) + \delta$. Since distance x is uniformly distributed over the interval $[-R, 0]$, the average time of T_{mf} is

$$[T_{\text{mf}}] = \int_{-R}^{0} T_{\text{mf}}(x) \frac{1}{R}\, d_x = \frac{5}{4} T_A + \frac{L}{r_d} + \delta. \quad (8)$$

The second vehicle to win the channel access is the closest neighbor to the first vehicle. If the distance between them is x, which has exponential distribution with mean $1/\lambda_v$, then its transmission time is $T_m(x) = T_w(x) + (L/r_d) + \delta$ with an average value, i.e.,

$$[T_m] = \int_{0}^{R} T_m(x) \lambda_v e^{-\lambda_v x}\, d_x = \frac{3}{2} T_A + \frac{L}{r_d} + \delta + \frac{T_A}{2R} \left[\frac{1}{\lambda_v} - (R + \frac{1}{\lambda_v}) e^{-\lambda_v R} \right]. \quad (9)$$

The CH will wait for time $(2 + \psi) \times T_A$ before it can send any of its invitation $\text{type} = 2$) and last $(\text{type} = 3)$ messages. Therefore, the average transmission time for its invitation message is $[T_{\text{in}}] = (5/2)T_A + (L/r_d) + \delta$. Assuming that the size of last message is L_{cl} bits, then its average transmission time is $[T_{\text{cl}}] = (5/2)T_A + (L_{\text{cl}}/r_d) + \delta$.

Since the average number of vehicles within the range is $2\lambda_v R$, the upper bound of T_{avg} can be found as

$$(T_{\text{avg}})_{\text{ub}} = T_{\text{cf}} + [T_{\text{mf}}] + (2\lambda_v R - 1)[T_m] + [T_{\text{in}}] + [T_{\text{cl}}]. \quad (10)$$

The lower bound of T_{avg} is when all cluster members send their status messages by following the sequence specified by the CH without waiting for time $T_w(d)$ to expire, i.e.,

$$(T_{\text{avg}})_{\text{lb}} = T_{\text{cf}} + (2\lambda_v R) \left[T_A + \frac{L}{r_d} + \delta \right] + [T_{\text{in}}] + [T_{\text{cl}}]. \quad (11)$$

To allow for all cluster members to send successfully their safety messages during the CCI, the following condition should be satisfied:

$$(T_{\text{avg}})_{\text{ub}} \le \varphi \times \text{CCI} \quad (12)$$

where $0 \le \varphi \le 1$ is a design parameter to spare some time from the CCI for other control messages.

From (10) and (12), λ_h and R_h that should be used to trigger the change in the cluster size, as discussed in Fig. 9, could be determined. Since the cluster has K vehicles in average, the size of the cluster's first message is $L_{\text{cf}} = 2K \times L$, and its last message is $L_{\text{cl}} = K \times L$. Moreover, as the range R increases, the term $e^{-\lambda_v R}$ in (9) approaches zero. Therefore, if a certain maximum range as R_h is used, then $\lambda_h = K/(2R_h)$ can be found by manipulating (10) and substituting the result in (12) as follows:

$$\lambda_h \le \frac{1}{2R_h} \frac{\varphi \times \text{CCI} - 5.75 T_A - \frac{2L}{r_d} - 3\delta}{\frac{3}{2} T_A + \frac{4L}{r_d} + \delta}. \quad (13)$$

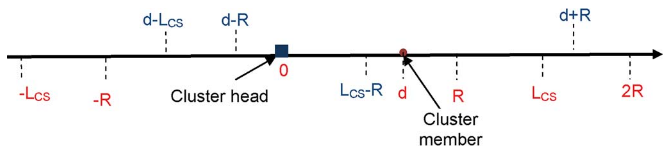

Fig. 10. Communication and carrier sense ranges of the CH and one cluster member.

Since R_l is governed by the jam scenario, where it is assumed that each vehicle occupies 10 m on average and the road has W lanes, then

$$R_l \leq \frac{10}{2W} \frac{\varphi \times \text{CCI} - 5.75T_A - \frac{2L}{r_d} - 3\delta}{\frac{3}{2}T_A + \frac{4L}{r_d} + \delta}. \tag{14}$$

On the other hand, λ_l is a design parameter that can be chosen as a fraction of λ_h, such that $\lambda_l < (R_l\lambda_h/R_h)$. If a smaller λ_l is selected, the less frequent the cluster size is changing. In the simulations, $\lambda_l = (R_l\lambda_h)/R_h$ is selected.

An enhanced version of DMMAC (eDMMAC) is when the number of cluster members reach K_h; the CH will not trigger the change in the communication range but select a certain set K_l of its members to only send their messages. The selection criteria is based on the stabilization factor and location. Vehicles with the lowest stabilization factor and/or located around the cluster boundary will have higher chances to be selected to send their status messages in the succeeding CCI. Vehicles should have at least one chance to send their messages every ten CCIs. The CH will arrange the selected vehicles in its first message from behind to the front, followed by the remaining cluster members that are not selected. Vehicles will follow this order to send their messages. A vehicle will defer from sending its message in the current CCI if it hears one of its front neighbors' messages. In this enhanced version, the CH will have to keep a table for the last ten CCIs to track which vehicles did send their messages. Although this version increases the processing time and the cluster overhead, it maintains a large cluster size compared with DMMAC. Therefore, eDMMAC will have higher CH time and cluster member dwell time compared with DMMAC, particularly in high-density scenarios, as will be shown in the simulations.

B. Clustering Reliability

To study the clustering reliability in DMMAC, which is the probability that a cluster member and a neighboring CH will transmit and receive the clustering information from the local CH successfully, the following parameters are defined: 1) $P = \sigma/\text{CCI}$, which is the probability that a vehicle (node) will send its status message in any time slot interval σ, assuming that cluster members contend for the channel use (worst case scenario); 2) the carrier sense range $L_{\text{CS}} = \rho R$, where $1 \leq \rho \leq 2$; hence, L_{CS} will range from R to $2R$; 3) the vulnerable period $T_v = \lceil (2T_{\text{data}} + \delta/\sigma) \rceil$, which is the time needed for the channel to be silent for a successful communication normalized over the slot time, where $T_{\text{data}} = L/r_d$ is the status message transmission time and $\delta = 1\ \mu$s is the propagation delay; and 4) the number of subcarrier sets or subchannels is $N = 4$.

Fig. 10 shows the CH's communication and carrier sense ranges. The probability P_s that a cluster member, which is located at distance d from the CH, will receive its CH's message can be derived in the following four cases.

The first case is when the local cluster uses a different subchannel from both neighboring clusters (from left and right), which happens with probability of $(N-1/N)^2$. In this case, with probability P_{s1}, the cluster member will receive its CH's message successfully when all local cluster members are silent during the same time slot that the CH is transmitting, i.e.,

$$\begin{aligned} P_{s1} &= \left(\frac{N-1}{N}\right)^2 \sum_{i=0}^{\infty} (1-P)^i \frac{(\lambda_v 2R)^i}{i!} e^{-\lambda_v 2R} \\ &= \left(\frac{N-1}{N}\right)^2 e^{-P\lambda_v 2R}. \end{aligned} \tag{15}$$

The second case is when the neighboring cluster on the left uses the same subchannel as the local cluster, whereas the neighboring cluster on the right uses a different one. This case happens with probability $(N-1/N^2)$. Therefore, with probability P_{s2}, the cluster member will successfully receive the message when all vehicles in the area $[-L_{\text{CS}}, R]$ did not use the channel in the same time slot as the local CH, i.e.,

$$\begin{aligned} P_{s2} &= \left(\frac{N-1}{N^2}\right) \sum_{i=0}^{\infty} (1-P)^i \frac{(\lambda_v(R+L_{\text{CS}}))^i}{i!} e^{-\lambda_v(R+L_{\text{CS}})} \\ &= \left(\frac{N-1}{N^2}\right) e^{-P\lambda_v R(1+\rho)}. \end{aligned} \tag{16}$$

The third case is when the neighboring cluster on the right uses the same subchannel as the local cluster, whereas the neighboring cluster on the left uses a different one. This case also happens with probability of $(N-1/N^2)$. The cluster member, in this case, will successfully receive the message with probability $P_{s3}(d)$ when all vehicles in the area $[-R, L_{\text{CS}}]$ did not use the channel in the same time slot, and vehicles in the hidden terminal area $[L_{\text{CS}}, d+L_{\text{CS}}]$ did not use the channel for the vulnerable period T_v, i.e.,

$$\begin{aligned} P_{s3}(d) &= \left(\frac{N-1}{N^2}\right) \\ &\quad \times \left[\sum_{i=0}^{\infty} (1-P)^i \frac{(\lambda_v(R+L_{\text{CS}}))^i}{i!} \cdot e^{-\lambda_v(R+L_{\text{CS}})}\right] \\ &\quad \times \left[\sum_{i=0}^{\infty} (1-P)^i \frac{(\lambda_v d)^i}{i!} e^{-\lambda_v d}\right]^{T_v} \\ &= \left(\frac{N-1}{N^2}\right) e^{-P\lambda_v R(1+\rho)} e^{-P\lambda_v d T_v}. \end{aligned} \tag{17}$$

By integrating over the range $d \in [0, R]$, the average value of $P_{s3}(d)$ can be derived as

$$P_{s3} = \left(\frac{N-1}{N^2 P\lambda_v R T_v}\right)\left(1 - e^{-P\lambda_v R T_v}\right) e^{-P\lambda_v R(1+\rho)}. \tag{18}$$

The last case is when both neighboring clusters use the same subchannel as the local cluster, and this happens with probability of $(1/N^2)$. Therefore, the probability that the cluster member will successfully receive the message when all vehicles in the area $[-L_{\mathrm{CS}}, L_{\mathrm{CS}}]$ did not use the channel in the same time slot and, at the same time, the vehicles in the hidden terminal area $[L_{\mathrm{CS}}, d + L_{\mathrm{CS}}]$ did not use the channel for the vulnerable period T_v is

$$P_{s4}(d) = \left(\frac{1}{N^2}\right)\left[\sum_{i=0}^{\infty}(1-P)^i \frac{(\lambda_v 2L_{\mathrm{CS}})^i}{i!} e^{-\lambda_v 2L_{\mathrm{CS}}}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i \frac{(\lambda_v d)^i}{i!} e^{-\lambda_v d}\right]^{T_v} = \left(\frac{1}{N^2}\right) e^{-P\lambda_v 2\rho R} e^{-P\lambda_v d T_v}. \tag{19}$$

By integrating over the range of $d \in [0, R]$, the average value of $P_{s4}(d)$ can be derived as

$$P_{s4} = \left(\frac{1}{N^2 P\lambda_v R T_v}\right)\left(1 - e^{-P\lambda_v R T_v}\right) e^{-P\lambda_v 2\rho R}. \tag{20}$$

From (15), (16), (18), and (20), probability P_s can be calculated as

$$P_s = \sum_{i=1}^{4} P_{s_i}. \tag{21}$$

To derive the probability P_c that the CH will successfully receive the status message from its member that is located at distance d, as shown in Fig. 10, the previous four cases are considered. In the first and last cases where both adjacent clusters use the same and different subchannels than the local cluster, respectively, the CH will receive its member's message with the same probabilities, as in (15) and (20), respectively.

The second case happens with probability $(N-1)/N^2$, when the neighboring cluster on the left uses the same subchannel as the local cluster, whereas the neighboring cluster on the right uses a different one. The CH will successfully receive the message when all vehicles in the area $[d - L_{\mathrm{CS}}, R]$ did not use the channel in the same time slot and, at the same time, the vehicles in the hidden terminal area $[-L_{\mathrm{CS}}, d - L_{\mathrm{CS}}]$ did not use the channel for the vulnerable period T_v as

$$P_{c2}(d) = \left(\frac{N-1}{N^2}\right)\left[\sum_{i=0}^{\infty}(1-P)^i \frac{(\lambda_v(R + L_{\mathrm{CS}} - d))^i}{i!} \cdot e^{-\lambda_v(R+L_{\mathrm{CS}}-d)}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i \frac{(\lambda_v d)^i}{i!} e^{-\lambda_v d}\right]^{T_v} = \left(\frac{N-1}{N^2}\right) e^{-P\lambda_v R(1+\rho)} e^{-P\lambda_v d(T_v-1)} \tag{22}$$

by integrating over the range of $d \in [0, R]$, the average value of $P_{c2}(d)$ can be derived as

$$P_{c2} = \frac{N-1}{N^2 P\lambda_v R(T_v-1)}\left(1 - e^{-P\lambda_v R(T_v-1)}\right) e^{-P\lambda_v R(1+\rho)}. \tag{23}$$

For the third case, which happens also with probability $(N-1)/N^2$, when the neighboring cluster on the right uses the same subchannel as the local cluster, whereas the neighboring cluster on the left uses a different one, with probability $P_{c3}(d)$, the CH will successfully receive the message when all vehicles in the area $[-R, d + L_{\mathrm{CS}}]$ did not use the channel in the same time slot, i.e.,

$$P_{c3}(d) = \left(\frac{N-1}{N^2}\right)\left[\sum_{i=0}^{\infty}(1-P)^i \frac{(\lambda_v(R + L_{\mathrm{CS}} + d))^i}{i!} \cdot e^{-\lambda_v(R+L_{\mathrm{CS}}+d)}\right] = \left(\frac{N-1}{N^2}\right) e^{-P\lambda_v R(1+\rho)} e^{-P\lambda_v d}. \tag{24}$$

By integrating over the range of $d \in [0, R]$, the average value of $P_{c3}(d)$ can be derived as

$$P_{c3} = \left(\frac{N-1}{N^2 P\lambda_v R}\right)\left(1 - e^{-P\lambda_v R}\right) e^{-P\lambda_v R(1+\rho)}. \tag{25}$$

From (15), (23), (25), and (20) P_c can be calculated as

$$P_c = P_{s1} + P_{c2} + P_{c3} + P_{s4}. \tag{26}$$

To find the probability that the CH of the neighboring cluster H_3 shown in Fig. 8 will receive the message from the CH of the local cluster H_2 successfully, the preceding four cases are considered. Moreover, the subchannel used by the neighboring cluster H_4 to the right of the receiving CH should be considered if it is the same or not as the receiving CH.

In the first case, when the neighboring clusters use different subchannels than the transmitting CH, the following two scenarios should be considered. First, with probability $(N-1/N)^3$, the neighboring cluster H_4 uses a different subchannel than cluster H_3. In this case, the probability that the receiving CH in H_3 will receive the message from the transmitting CH when all its members in H_2 do not use the channel in the same time slot and vehicles that are members of H_3 do not use the channel for the vulnerable period T_v is

$$P_{cc1} = \left(\frac{N-1}{N}\right)^3\left[\sum_{i=0}^{\infty}(1-P)^i \frac{(\lambda_v 2R)^i}{i!} e^{-\lambda_v 2R}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i \frac{(\lambda_v 2R)^i}{i!} e^{-\lambda_v 2R}\right]^{T_v} = \left(\frac{N-1}{N}\right)^3 e^{-P\lambda_v 2R(T_v+1)}. \tag{27}$$

The second scenario is when cluster H_4 uses the same subchannel as H_3, which happens with probability

$((N-1)^2/N^3)$. In this case, the probability that the CH in H_3 will receive the message successfully as in the previous case, except that the hidden terminal area is $[R, 2R+L_{\mathrm{CS}}]$, is

$$P_{cc2} = \frac{(N-1)^2}{N^3}\left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v 2R)^i}{i!}e^{-\lambda_v 2R}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(L_{\mathrm{CS}}+R))^i}{i!}e^{-\lambda_v(L_{\mathrm{CS}}+R)}\right]^{T_v} = \frac{(N-1)^2}{N^3}e^{-P\lambda_v R(2+T_v(\rho+1))}. \quad (28)$$

In the second case, with probability $((N-1)^2/N^3)$, the neighboring cluster H_4 uses a different subchannel than H_3. In this case, with probability P_{cc3}, the CH in H_3 will receive the message successfully when all vehicles in the area $[-L_{\mathrm{CS}}, R]$ did not use the channel during the same time slot and the hidden terminal area in this case $[R, 3R]$ is silent for the vulnerable period, i.e.,

$$P_{cc3} = \frac{(N-1)^2}{N^3} \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(R+L_{\mathrm{CS}}))^i}{i!}\cdot e^{-\lambda_v(R+L_{\mathrm{CS}})}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v 2R)^i}{i!}e^{-\lambda_v 2R}\right]^{T_v} = \frac{(N-1)^2}{N^3}e^{-P\lambda_v R(\rho+1+2T_v)}. \quad (29)$$

On the other hand, when H_4 is using the same subchannel as H_3, which happens with probability $(N-1/N^3)$, the hidden terminal area will be $[R, 2R+L_{\mathrm{CS}}]$. Therefore, the message will be received successfully with probability

$$P_{cc4} = \frac{N-1}{N^3}\left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(R+L_{\mathrm{CS}}))^i}{i!}e^{-\lambda_v(R+L_{\mathrm{CS}})}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(R+L_{\mathrm{CS}}))^i}{i!}e^{-\lambda_v(R+L_{\mathrm{CS}})}\right]^{T_v} = \frac{N-1}{N^3}e^{-P\lambda_v R(\rho+1)(T_v+1)}. \quad (30)$$

For the third case, consider first that cluster H_4 is using a different subchannel than H_3. This happens with probability $((N-1)^2/N^3$; therefore, the probability that the CH in H_3 will successfully receive the message when all vehicles within the area $[-R, L_{\mathrm{CS}}]$ are silent during the same time slot and the hidden terminal area $[L_{\mathrm{CS}}, 3R]$ is silent for the vulnerable period is given by

$$P_{cc5} = \left(\frac{(N-1)^2}{N^3}\right) \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(R+L_{\mathrm{CS}}))^i}{i!}e^{-\lambda_v(R+L_{\mathrm{CS}})}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(3R-L_{\mathrm{CS}}))^i}{i!}e^{-\lambda_v(3R-L_{\mathrm{CS}})}\right]^{T_v} = \frac{(N-1)^2}{N^3}e^{-P\lambda_v R(\rho+1+3T_v-\rho T_v)}. \quad (31)$$

On the other hand, when cluster H_4 uses the same subchannel as its neighbor H_3, which happens with probability $(N-1/N^3)$, the hidden terminal area will be, in this case, $[L_{\mathrm{CS}}, 2R+L_{\mathrm{CS}}]$. Therefore, the message will successfully be received with probability

$$P_{cc6} = \frac{N-1}{N^3}\left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(R+L_{\mathrm{CS}}))^i}{i!}e^{-\lambda_v(R+L_{\mathrm{CS}})}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v 2R)^i}{i!}e^{-\lambda_v 2R}\right]^{T_v} = \frac{N-1}{N^3}e^{-P\lambda_v R(\rho+1+2T_v)}. \quad (32)$$

For the last case, considering first that cluster H_4 is using a different subchannel than its neighbor H_3, which happens with probability $(N-1/N^3)$. The CH in H_3 will successfully receive the message when all vehicles in the area $[-L_{\mathrm{CS}}, L_{\mathrm{CS}}]$ are silent during the same time slot, and the hidden terminal area $[L_{\mathrm{CS}}, 3R]$ is silent for the vulnerable period with probability

$$P_{cc7} = \frac{N-1}{N^3}\left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v 2L_{\mathrm{CS}})^i}{i!}e^{-\lambda_v 2L_{\mathrm{CS}}}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v(3R-L_{\mathrm{CS}}))^i}{i!}e^{-\lambda_v(3R-L_{\mathrm{CS}})}\right]^{T_v} = \frac{N-1}{N^3}e^{-P\lambda_v R(2\rho+3T_v-\rho T_v)}. \quad (33)$$

On the other hand, when H_4 uses the same subchannel as its neighbor H_3, which happens with probability $(1/N^3)$, the hidden terminal area will be $[L_{\mathrm{CS}}, 2R+L_{\mathrm{CS}}]$. Therefore, the message will be received successfully with probability

$$P_{cc8} = \frac{1}{N^3}\left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v 2L_{\mathrm{CS}})^i}{i!}e^{-\lambda_v 2L_{\mathrm{CS}}}\right] \times \left[\sum_{i=0}^{\infty}(1-P)^i\frac{(\lambda_v 2R)^i}{i!}e^{-\lambda_v 2R}\right]^{T_v} = \frac{1}{N^3}e^{-P\lambda_v 2R(\rho+T_v)}. \quad (34)$$

Hence, the probability P_{cc} that the CH of H_3 will receive a message from the CH of its neighboring cluster H_2 successfully is

$$P_{\mathrm{cc}} = \sum_{i=1}^{8} P_{\mathrm{cc}_i}. \quad (35)$$

C. Time Delay

Here, the time delay for an emergency message to be sent from one vehicle in one cluster and reaches vehicles that are located at distance D (or $M = \lfloor (D/R) \rfloor$ clusters) from the emergency scene will be discussed.

In DMMAC, if a vehicle has an emergency message, it will contend for the channel access using AC_3 to send this message.

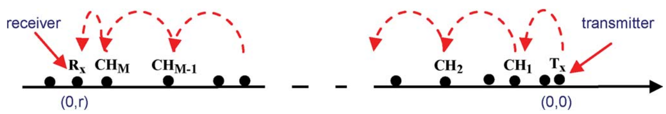

Fig. 11. Emergency message propagation model.

Once this message is received by the CH, it starts periodically transmitting this emergency message with enough power to reach a distance of D_c; all other cluster members will refrain from using the channel during this time. When the next CH receives this emergency message, it will broadcast the message with a range of D_c to reach both the next cluster and the originating CHs. Once the originating CH hears its message back from the neighboring CH, it will stop broadcasting the message with high power but continue the broadcasting to all of its members for several times depending on the application or until the emergency situation is cleared. The emergency message will continue to propagate in the direction of interest for a maximum number of hops M, depending on the application and the emergency situation, as shown in Fig. 11.

Since it is assumed that the message is of length L bits and its transmission time is T_{data}, then the average time delay T_{ed} for the emergency message to reach its intended distance of M clusters away is the sum of the time for the first CH to receive the message from its member, the time for the neighboring CHs to process and forward the message, and the time for the last CH to send the message to its members successfully. Therefore, T_{ed} can be calculated as

$$T_{\text{ed}} = \left(\frac{1}{P_c} + \frac{M}{P_{\text{cc}}} + \frac{1}{P_s}\right) T_{\text{data}} + MT_p \tag{36}$$

where T_p is the time needed by the CH to process and analyze the emergency message before propagating it to the succeeding cluster.

V. Model Validation and Simulation

To test the system's stability, reliability, and efficiency, the following metrics are defined: 1) The average CH time $\overline{\text{CHT}}$, which is the sum of all CHs times divided by the total number of CHs during the simulation period; 2) the average cluster size $\overline{\text{CS}}$, which is the total number of vehicles that became cluster members divided by the total number of formed clusters during the simulation time; 3) the system reliability $\Re$, which is the probability for a cluster member to send its status message during the CCI; 4) the average time delay for an emergency message to reach an intended distance of 2000 m; and 5) the average number of messages successfully received by either a CH, a cluster member, or a neighboring CH.

The simulation is developed based on the network simulator ns-2 [30] by using a realistic mobility model generated by MOVE [31], which is built on top of the microtraffic simulator SUMO [32]. The simulation scenario is based on one directional highway segment of 8000 m in length and four lanes. The vehicles' speed ranges from 80–120 km/h, which is typical for Ontario highways. The Nakagami-m propagation model with configuration parameters as in [33] is used. The proposed DMMAC is compared with the CMCP [24], APROVE [27], and the DCF of 802.11p since they are the most relevant to this paper. Each simulation typically simulates 1000 s. Table III lists the simulation parameters used unless a change is mentioned explicitly.

TABLE III
VALUE OF PARAMETERS USED IN SIMULATION

Parameter	Value
Modulation and Data rate	QPSK, r_d=6 Mbps
Message sizes L	64×8 Bits
Vehicle's speed	80-120Km/h
Communication range R=R_h	300m
Control Channel Interval CCI	100ms
Cluster maintenance time T_f	10s
Communication range between cluster heads D_c	2.5 R
Emergency message travel distance r	2000 meters
ρ	1.5
φ	1
ζ	0.5
Received power threshold R_{xTh}	3.162e-13
Slot time σ	13 μ s
Propagation delay δ	1 μ s

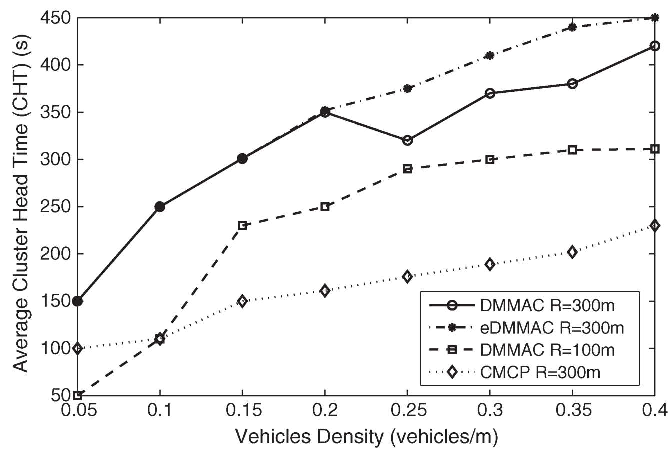

Fig. 12. Average CH time versus vehicle density.

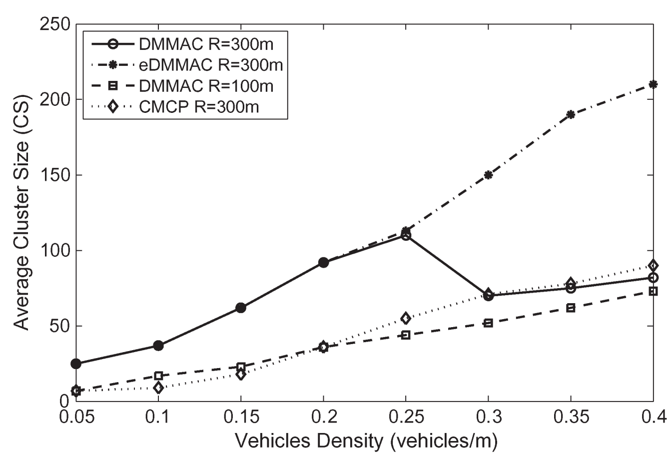

Fig. 13. Average cluster size versus vehicle density.

Figs. 12–14 show the impact of vehicle density on the cluster topology for various communication ranges. Fig. 12 shows that the CH's average lifetime increases by increasing the vehicle density. This is because the interdistance between vehicles are decreasing; hence, the relative speed between them is decreasing, resulting in high CH's stability factor. This verifies that the proposed clustering algorithm works well by allowing the CH

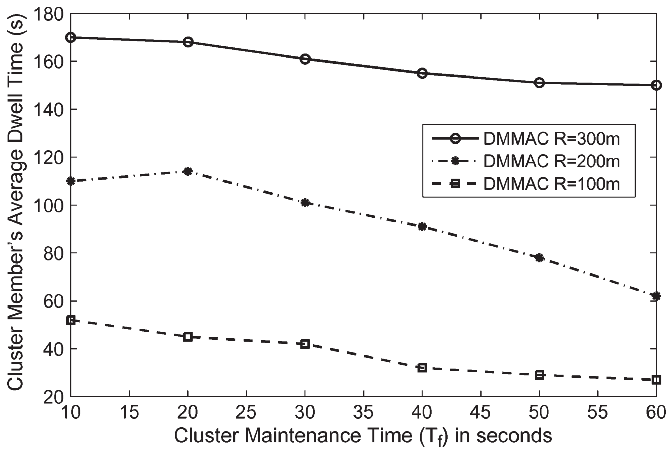

Fig. 14. Average cluster member's dwell time as a function of the cluster maintenance time T_f. $\lambda_v = 0.2$ vehicle/m.

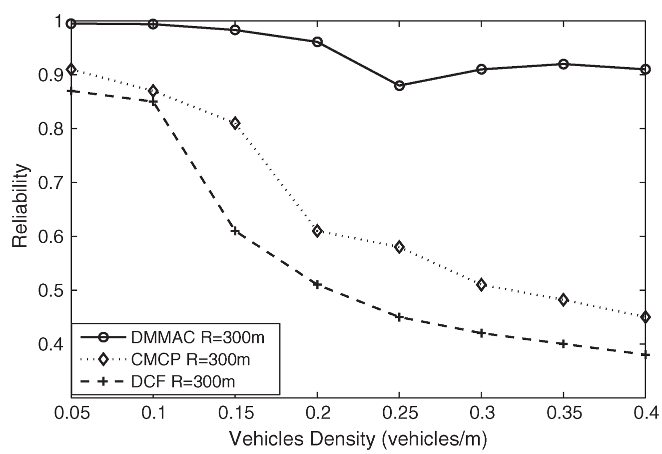

Fig. 15. Reliability versus vehicle density.

to reelect itself when all or most of its members are within its range after time T_f. Fig. 13 shows the increase in the average cluster size as the density increases. In DMMAC, the CH has a role to change the range when vehicle density reaches a threshold λ_h; hence, all its members have the chance to send their status messages. This is clear from the abrupt change in the cluster size when vehicle density reaches 0.25 vehicle/m for $R = 300$ m. It is obvious that the stability of the network topology will increase by increasing the communication range since there will be more space for vehicles to move within their CH's range. This explains why the eDMMAC has better performance than DMMAC, particularly when the vehicle density is high.

Fig. 14 shows the dwell time versus the cluster maintenance time T_f. As T_f increases, the accuracy of predicting the vehicle's future position and speed decreases. However, in DMMAC, this decrease is small since the CH elects a backup CH to maintain the network stability. It is also clear that increasing the range will increase the dwell time and, at the same time, will decrease the effect of using long maintenance time T_f since the probability of a vehicle to cross the cluster boundary will decrease.

Figs. 15–17 show the performance evaluation of DMMAC. Fig. 15 shows the probability that all cluster members managed to send their status messages during the CCI. Since the CH in

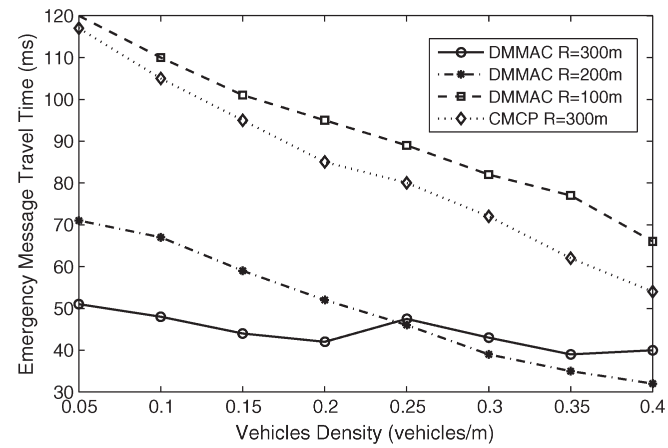

Fig. 16. Emergency message travel time versus vehicle density.

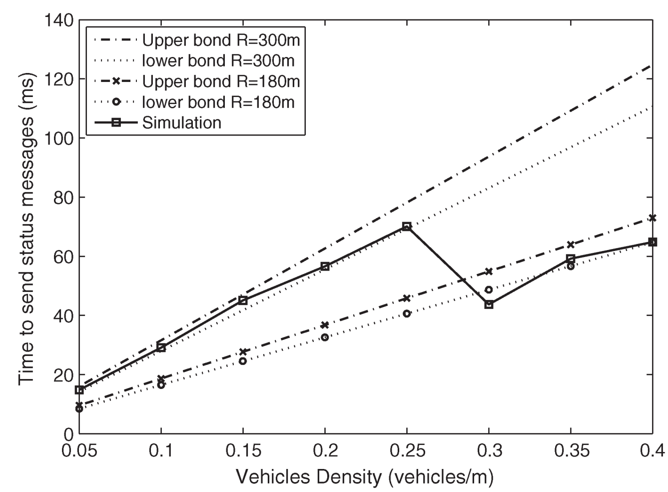

Fig. 17. Time duration for all cluster members to send their status messages versus vehicle density.

the proposed clustering algorithm advertises the sequence that all of its members should follow to send their status messages, the system's reliability is high, particularly in low-density networks. As the network density increases, the reliability slightly decreases since there is more possibility that new members will join the cluster. These new members are not included in the advertised sequence and have to compete for the channel use based on (2). This explains why the reliability drops when the range is changed as the density reaches 0.25 vehicle/m.

Fig. 16 shows the time taken by an emergency message sent by a vehicle to reach a distance of 2000 m for different communication ranges. It is shown that, as the range increases, the travel time decreases since the number of clusters that the message will hop through to reach its intended distance decreases. Moreover, the decrease in the vehicle density results in increasing the emergency message travel time since CHs may struggle to find a neighboring CH to carry the message forward.

Fig. 17 shows the time needed for all cluster members to send their status messages. The abrupt change is due to the change of the communication range from $R_h = 300$ m to $R_l = 180$ m triggered by the CH when the vehicle density reaches a certain value $\lambda_v = 0.25$, as explained before in the hysteresis mechanism. It is clear that this time is less than the theoretical

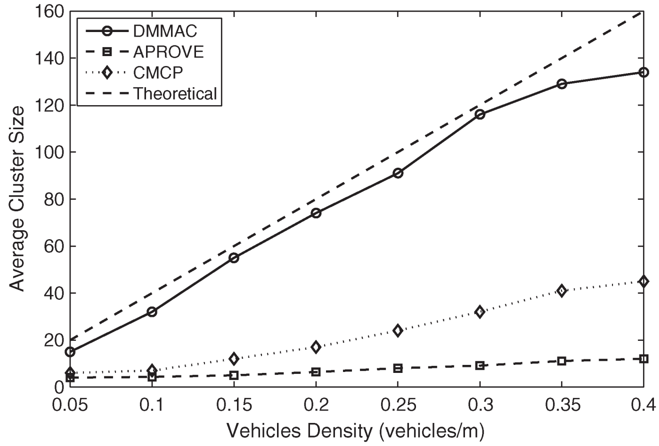

Fig. 18. Average cluster size versus vehicle density ($R = 200$ m).

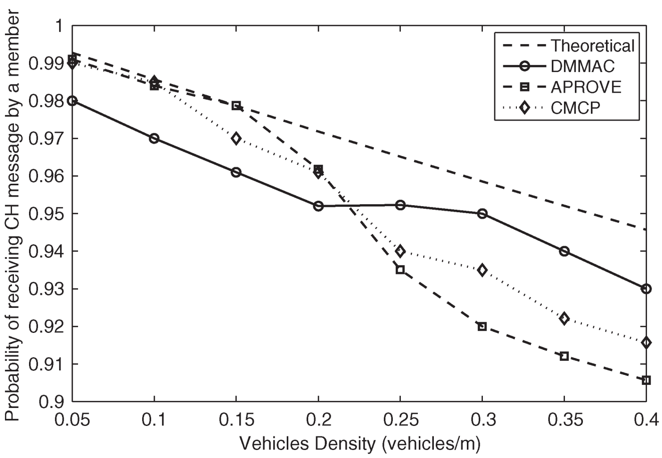

Fig. 19. Probability that a cluster member will receive a message from its CH successfully versus vehicle density ($R = 200$ m).

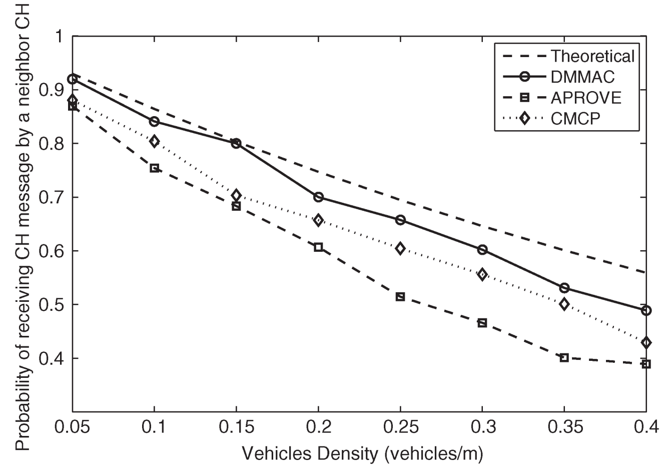

Fig. 20. Probability of successful transmission between neighboring CHs versus vehicle density ($R = 200$ m).

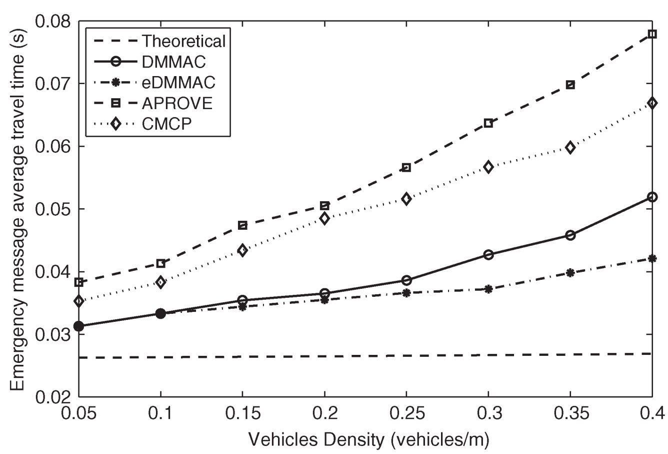

Fig. 21. Average travel time for an emergency message to reach an intended distance of 2000 m versus vehicle density ($R = 200$ m).

upper bound derived in (10). This proves that DMMAC algorithm is efficient in managing the cluster size to allow all of its members to send their status messages.

Fig. 18 shows the impact of traffic density on the cluster size and compare it with other multichannel protocols, such as CMCP [24] and APROVE [27], for $R = 200$ m. The traffic density λ_v can be increased by either decreasing the vehicles' average speed or increasing the number of vehicles on the road [29]. This figure shows that DMMAC protocol builds the largest cluster size compared with others. It is clear that the cluster size in DMMAC is also close to the theoretical results derived from (5). This is because DMMAC has a mechanism to balance the cluster by electing a CH, which is very close to the cluster center and is moving with the same speed as most of its members. These characteristics help to maintain a stable cluster topology.

Figs. 19 and 20 show the probability of receiving a message from a CH by its members and neighboring CHs, respectively, and compared with other protocols. It is obvious that the analytical results coincide with those obtained by simulation, particularly for the DMMAC protocol since it elects CHs based on their relative speeds and distances from their cluster members, whereas protocols such as CMCP [24] and APROVE [27] find difficulties to deliver their CHs' messages to cluster members, particularly in high-density networks. They perform better than DMMAC in low-density networks since they build smaller cluster size compared with DMMAC, as shown in Fig. 18. While in high-density networks, DMMAC has better performance since other protocols use more control messages to elect their CHs and do not maintain the elected CH in its cluster center such as in DMMAC.

Fig. 21 shows the average travel time for an emergency message to reach an intended distance of 2000 m versus vehicle density and compared with other protocols. It is clear that all protocols take more time than the theoretical values, particularly in high-density networks. This is because vehicles are forced to contend for the channel and not to use TDMA or other scheduling schemes.

Fig. 22 shows the cluster management overhead when the communication range is 100 m as a function of vehicle density for both the proposed DMMAC and CMCP protocols. It is obvious that, as the vehicle density increases, the overhead percentage decreases since more vehicles managed to send their status messages. In DMMAC, the overhead is much lower than that of CMCP since the CH in DMMAC has a role of selecting a backup CH that will take the responsibility of the cluster if it has a higher stability factor than the current CH. This increases the dwell time of the cluster members and the stability of the cluster topology.

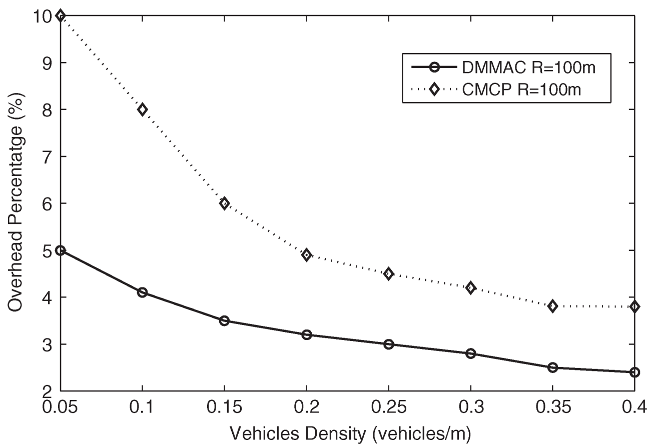

Fig. 22. Cluster management overhead versus vehicle density for range $R = 100$ m.

From all preceding figures, it can be seen that the performance of DMMAC exceeds the performance of both CMCP and APROVE. This is due to its learning capability and the feature of selecting a backup CH to take over the main CH's responsibilities when it has larger coverage. The algorithm of changing the communication range when the number of cluster members reaches a certain threshold helps to maintain a high reliability compared with CMCP and APROVE, particularly in high-density networks.

VI. Conclusion

In this paper, a novel clustering and mobility-based MAC protocol for VANETs has been proposed. CHs are elected and reelected in a distributed manner according to their relative speed and distance from their cluster members. The high stability of DMMAC results from its adaptability to drivers' behavior on the road and its learning process to predict the future speed and position of all cluster members using the FIS. In high-density scenarios, the CH in DMMAC has two options for increasing the network's reliability and stability. First, it can change the used communication range based on the sensed vehicle density to allow all of its members to send their status messages within the CCI. Second, it can select a certain set of vehicles that are more vulnerable to cross the cluster boundary to send their status messages. The created clusters exhibit long average CH lifetime and long average dwell time for its members. Status messages are exchanged within a cluster following a sequence that is advertised by the CH. Therefore, its reliability is the same as in TDMA schemes but without the hassle of reserving time slots and much more than fully contention-based schemes. Moreover, CHs have to select one of four subcarrier sets that is different from their neighbors to eliminate the hidden terminal problem. The reliability of DMMAC is analyzed. The cluster size, the probability of successfully receiving a message sent by a CH or a cluster member, and the average travel time for an emergency message to reach a certain distance are derived. From the comparison with some multichannel clustering protocols, it is clear that DMMAC has high stability, and its performance exceeds other protocols and can achieve a timely and reliable delivery of emergency messages to their intended recipients. The analytical results match those obtained via simulation.

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