

Multihop-Cluster-Based IEEE 802.11p and LTE Hybrid Architecture for VANET Safety Message Dissemination

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Abstract—Several vehicular ad hoc network (VANET) studies have focused on communication methods based on IEEE 802.11p, which forms the standard for wireless access for vehicular environments. In networks employing IEEE 802.11p only, the broadcast storm and disconnected network problems at high and low vehicle densities, respectively, degrade the delay and delivery ratio of safety message dissemination. Recently, as an alternative to the IEEE 802.11p-based VANET, the usage of cellular technologies has been investigated due to their low latency and wide-range communication. However, a pure cellular-based VANET communication is not feasible due to the high cost of communication between the vehicles and the base stations and the high number of handoff occurrences at the base station, considering the high mobility of the vehicles. This paper proposes a hybrid architecture, namely, VMaSC-LTE, combining IEEE 802.11p-based multihop clustering and the fourth-generation (4G) cellular system, i.e., Long-Term Evolution (LTE), with the goal of achieving a high data packet delivery ratio (DPDR) and low delay while keeping the usage of the cellular architecture at a minimum level. In VMaSC-LTE, vehicles are clustered based on a novel approach named Vehicular Multihop algorithm for Stable Clustering (VMaSC). The features of VMaSC are cluster head (CH) selection using the relative mobility metric calculated as the average relative speed with respect to the neighboring vehicles, cluster connection with minimum overhead by introducing a direct connection to the neighbor that is already a head or a member of a cluster instead of connecting to the CH in multiple hops, disseminating cluster member information within periodic hello packets, reactive clustering to maintain the cluster structure without excessive consumption of network resources, and efficient size- and hop-limited cluster merging mechanism based on the exchange of cluster information among CHs. These features decrease the number of CHs while increasing their stability, therefore minimizing the usage of the cellular architecture. From the clustered topology, elected CHs operate as dual-interface nodes with the functionality of the IEEE

802.11p and LTE interface to link the VANET to the LTE network. Using various key metrics of interest, including DPDR, delay, control overhead, and clustering stability, we demonstrate the superior performance of the proposed architecture compared with both previously proposed hybrid architectures and alternative routing mechanisms, including flooding and cluster-based routing via extensive simulations in ns-3 with the vehicle mobility input from the Simulation of Urban Mobility. The proposed architecture also allows achieving higher required reliability of the application quantified by the DPDR at the cost of higher LTE usage measured by the number of CHs in the network.

Index Terms—Clustering, IEEE 802.11p, Long-Term Evolution (LTE), message dissemination, safety application, vehicular ad hoc networks (VANETs).

I. INTRODUCTION

THE VEHICULAR ad hoc network (VANET) is expected to significantly improve the safety of transportation systems by providing timely and efficient data dissemination about events such as accidents, road conditions, and traffic jams beyond the driver's knowledge [3]. Driver behavior, constraints on mobility, and high speeds create unique characteristics, such as rapid but somewhat predictable topology changes, uneven network density, and frequent fragmentation for VANETs. Meeting the strict delay and packet delivery requirements of safety applications in such a dynamic network determines the feasibility of the deployment of such applications. Table I shows the specifications of various VANET safety applications extracted from [4] and [5]: The update rate refers to the packet generation rate of the nodes; the maximum dissemination distance is defined as the distance within which the safety message needs to be disseminated; maximum delay is the maximum tolerable delay for safety message dissemination. The packet delivery ratio of the safety application, which is defined as the ratio of the nodes that successfully receive packets within the maximum dissemination distance, on the other hand, mostly ranges from 90% to 100%, depending on the application type and network scenario, although it is not explicitly provided in the safety application specifications.

Up to now, several VANET studies have focused on communication methods based on IEEE 802.11p, which forms the standard for Wireless Access for Vehicular Environments. IEEE 802.11p provides data rates ranging from 6 to 27 Mb/s at a short radio transmission distance, i.e., around 300 m. Disseminating safety information over a large area requires an intelligent multihop broadcast mechanism handling two major problems: broadcast storm [6] and disconnected network [7].

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TABLE I
VANET SAFETY APPLICATION REQUIREMENTS

Service	Update Rate	Maximum Dissemination Distance	Maximum Delay
Safety Recall Notice	-	400 m	5 s
Vehicle Diagnostics and Maintenance	10Hz	500 m	5 s
Wrong Way Driver Warning	10Hz	500 m	1 s
Emergency Vehicle Signal Preemption	1Hz	1000 m	1 s
Approaching Emergency Vehicle Warning	-	1000 m	1 s

TABLE II
RELATED WORK ON HYBRID ARCHITECTURES IN VANETS

Reference	Cellular Technology	Clustering	Radius	Application	Mobility Traces	Performance Criteria
[27]	UMTS	No	-	Control info dissemination	TraNS[28] and SUMO[29]	Packet delivery ratio, Packet drop, Delay
[30]	LTE	Yes	One-Hop	Cluster management	VanetMobiSim [31]	Packet loss, Overhead, Goodput, Cluster lifetime
[32]	UMTS	Yes	One-Hop	Message dissemination	-	Packet delivery ratio, Overhead, Packet loss
[33]	UMTS	Yes	One-Hop	Message dissemination	-	Packet delivery ratio, Overhead, Packet loss, Delay
[34]	LTE	Yes	One-Hop	Message dissemination	-	Packet delivery ratio, Packet error rate, Delay
[35]	UMTS	No	-	Connection to cellular backbone	MOVE [36]	Packet delivery ratio, Delay, Duplication ratio

The broadcast storm problem occurs at high vehicle traffic density, where the packet delay and the number of collisions at the medium-access-control layer dramatically increase as the number of vehicles attempting to transmit simultaneously increases. Probabilistic flooding [6] and clustering [8]–[20] are commonly used to address the broadcast storm problem. On the other hand, the disconnected network problem occurs at low vehicle traffic density, where the number of nodes is not sufficient to disseminate the information to all the vehicles in a certain region. Store–carry–forward, where the vehicles in the opposite lane are used for message dissemination, is commonly utilized to address the disconnected network problem [7], [21]. The solutions addressing both broadcast storm and disconnected network problems, however, have been shown to provide network delays varying from a few seconds to several minutes and the percentage of the vehicles successfully receiving the packets going down to 60% [22].

Recently, as an alternative to the IEEE 802.11p-based VANET, the usage of cellular technologies has been investigated. The key enabler of such usage is the standardization of the advanced content broadcast/multicast services by the Third-Generation Partnership Project (3GPP), which provides efficient message dissemination to many users over a geographical area at fine granularity. The use of the third-generation mobile cellular system, which is called the Universal Mobile Communication System (UMTS), in the safety application of vehicles has already been experimented in Project Cooperative Cars (CoCars) [23]. The traffic hazardous warning message has been shown to be disseminated in less than 1 s. The fourth-generation cellular system, which is called Long-Term Evolution (LTE), is an evolution of UMTS increasing capacity and speed using a different radio interface together with core network improvements. The LTE specification provides downlink peak rates of 300 Mb/s, uplink peak rates of 75 Mb/s, transfer latency of less than 5 ms, and transmission range up

to 100 km in the radio access network (RAN). Despite the high rate coupled with wide-range communication, however, a pure LTE-based architecture is not feasible for vehicular communication due to the high cost of LTE communication between the vehicles and the base stations, a high number of handoff occurrences at the base station considering the high mobility of vehicles, and overload of the base station by the broadcast of a high number of vehicles at high vehicle traffic density [24]–[26].

Hybrid architectures have been recently proposed to exploit both the low cost of IEEE 802.11p and the wide-range low-latency communication of the cellular technologies, as summarized in Table II. Some of these works [27], [30], [35] focus on the usage of the hybrid architecture for more efficient clustering: Lequerica *et al.* in [27] demonstrate the usage of the cellular communication signaling in the hybrid architecture, Remy *et al.* in [30] exploit the usage of the centralized architecture of the cellular communication to reduce the clustering overhead, and Benslimane *et al.* in [35] propose a new protocol based on the selection of a route with the longest lifetime to connect to the wired network for services such as driver information systems and Internet access. On the other hand, the authors in [32]–[34] propose cluster-based hybrid architecture for message dissemination. In this hybrid architecture, the cluster members (CMs) communicate with the cluster head (CH) by using IEEE 802.11p, and the CHs communicate with the base station by using cellular technologies. The goal is to minimize the number of CHs communicating with the cellular network. Decreasing the number of clusters reduces the cost of using cellular infrastructure by lowering both the amount of communication with the base stations and the frequency of handoff occurrences at the base station. Efficient clustering, however, should not only minimize the number of CHs but maintain the stability of the cluster-based topology with minimum overhead as well. None of the proposed

hybrid architectures, nevertheless, perform any stability analysis. Moreover, Taleb and Benslimane in [32] do not consider the delay performance of the message dissemination in the network. Although Benslimane *et al.* in [33] and Sivaraj *et al.* in [34] provide the delay performance of the hybrid architecture, they do not include the effect of multihop clustering on the number of CHs and clustering stability. Furthermore, none of the previous hybrid architectures compare their performance to that of IEEE 802.11p-based alternative routing mechanisms, such as flooding and cluster-based routing.

In the literature, VANET clustering has been performed with different purposes, such as load balancing, quality-of-service support, and information dissemination in high-density vehicular networks [38]. Stable clustering with a minimum number of CHs and minimum overhead requires efficient cluster joining, maintenance, and merging mechanisms together with an efficient clustering metric, considering the high mobility of vehicles. Clustering metrics used in the VANET literature include direction [8], [11]–[13], packet delay variation [10], location difference [9], [14], [16], [20], speed difference [18], and combination of location and speed differences [15], [17], [19]. Although a metric combining the location and speed of the neighboring vehicles is a better measure of their link duration compared with a metric considering their speed only, all vehicles may not have localization capability. Calculating packet delay variation, on the other hand, requires very accurate synchronization among the vehicles with low-level time stamping of the packets due to the random access protocol used by IEEE 802.11p. Moreover, cluster joining in both one-hop and multihop VANETs is direct to the CH. However, joining the cluster through a CM and informing the CH later via periodic hello packets can decrease clustering connection time and overhead significantly. Such efficient mechanisms have been proposed in mobile ad hoc networks, which, however, usually assume stationarity of the nodes during clustering [39]. In addition, cluster maintenance is achieved through either periodic reclustering [8]–[10], [12], [16], [17], where the clustering procedure is periodically executed, or reactive clustering [14], [15], [18], where clustering is triggered only when the CH has lost connection to all its members or the CM cannot reach its cluster. Reactive clustering is more efficient since the reclustering procedure is activated only when the cluster structure is destroyed without excessive periodic packet transmission overhead. Furthermore, the previously proposed cluster merging mechanisms are activated either when the distance between two neighboring CHs is less than a certain threshold [12], [15], [18] or when the CHs remain connected for a time duration greater than a predetermined value [19], [20]. However, cluster merging can result in very-large-size merged clusters, where the CH becomes a bottleneck due to the high number of packets of its CMs and a large number of hops, which increases the delay of packet transmissions. To solve the cluster-head bottleneck and large-delay problems, cluster merging should limit both the size and the number of hops in the resulting merged cluster. Moreover, the previously proposed multihop clustering algorithms only focus on providing clustering stability through metrics such as CH duration, CM duration, and CH change but do not analyze the performance of their proposed algorithm

in message dissemination in terms of metrics such as packet delivery ratio and delay (see Table III).

In this paper, we propose a hybrid architecture, namely, VMaSC-LTE, combining IEEE 802.11p-based multihop clustering and LTE, with the goal of achieving high data packet delivery ratio (DPDR) and low delay while keeping the usage of the cellular infrastructure at a minimum level via minimizing the number of CHs and maximizing clustering stability. The original contributions of this paper are listed as follows.

- We propose a multihop-cluster-based IEEE 802.11p-LTE hybrid architecture for the first time in the literature. The features of the multihop clustering algorithm used in this hybrid architecture, which is called VMaSC, are CH selection using the relative mobility metric calculated as the average relative speed with respect to the neighboring vehicles, cluster connection with minimum overhead by introducing a direct connection to the neighbor that is already a head or a member of a cluster instead of connecting to the CH in multiple hops, disseminating CM information within periodic hello packets, reactive clustering to maintain the cluster structure without excessive consumption of network resources, and efficient size- and hop-limited cluster merging mechanism based on the exchange of cluster information among CHs. Combining all of these features in a multihop-cluster-based hybrid architecture, using minimum overhead cluster connection, and size- and hop-limited cluster merging mechanism are unique characteristics of VMaSC.
- We perform an extensive analysis of the performance of the multihop-cluster-based IEEE 802.11p-LTE hybrid architecture over a wide range of performance metrics, including DPDR, delay, control overhead, and clustering stability, in comparison to both previously proposed hybrid architectures and alternative routing mechanisms, including flooding and cluster-based routing over a large-scale highway, using a realistic vehicle mobility model for the first time in the literature.
- We illustrate the tradeoff between the reliability of the application measured by the DPDR and the cost of the LTE usage determined by the number of CHs in the network for the first time in the literature.

The rest of this paper is organized as follows. Section II describes the system model. Section III presents the proposed multihop clustering scheme. Section IV delineates the data-forwarding approach in the IEEE 802.11p-LTE hybrid architecture. The comparison of the proposed hybrid architecture to the previously proposed hybrid architectures and alternative routing mechanisms is given in Section V. Finally, concluding remarks and future work are given in Section VI.

II. SYSTEM MODEL

The envisioned IEEE 802.11p-LTE hybrid architecture is shown in Fig. 1. The vehicles form a multihop clustered topology in each direction of the road. The vehicles within the transmission range of a CH, which is denoted by R and shown by a dotted line around the CH in the figure, become a CM

TABLE III
RELATED WORK ON VANET CLUSTERING

Reference	Hop Distance	Clustering Metric	Cluster Joining	Cluster Update	Cluster Merge	Mobility Traces	Performance Criteria
[8]	One-Hop	Direction	Directly to CH	Periodic	-	-	Packet delivery ratio, Clustering overhead
[9]	One-Hop	Location Difference	Directly to CH	Periodic	-	-	Packet delivery ratio
[11]	One-Hop	Direction	Directly to CH	-	-	Car following model	Packet reduction in transmission, Collision rate
[12]	One-Hop	Direction	Directly to CH	Periodic	Location Threshold	Car following model	Head duration, Head relative speed
[13]	One-Hop	Direction	Directly to CH	-	-	Car following model	Head change
[14]	One-Hop	Location Difference	Directly to CH	Reactive	-	Reference region group mobility model [37]	Head duration, Head change
[15]	One-Hop	Location Difference, Speed Difference	Directly to CH	Reactive	Location Threshold	Car following model	Cluster lifetime, Number of clusters
[16]	One-Hop	Location Difference	Directly to CH	Periodic	-	-	Head duration, Member duration, Connectivity
[18]	One-Hop	Speed Difference	Directly to CH	Reactive	Location Threshold	-	Head Change, Throughput
[19]	One-Hop	Location Difference, Speed Difference	Directly to CH	-	Merge Timer	MOVE [36]	Head duration, Member Duration, Head change, Number of clusters
[20]	One-Hop	Location Difference	Directly to CH	-	Merge Timer	SUMO [29]	Cluster Life Time
[10]	Multi-Hop	Delay Variation	Directly to CH	Periodic	-	Free way and Manhattan model	Head duration, Member duration, Head change
[17]	Multi-Hop	Location Difference, Speed Difference	Directly to CH	Periodic	-	VanetMobiSim [31]	Number of clusters, Clustering overhead

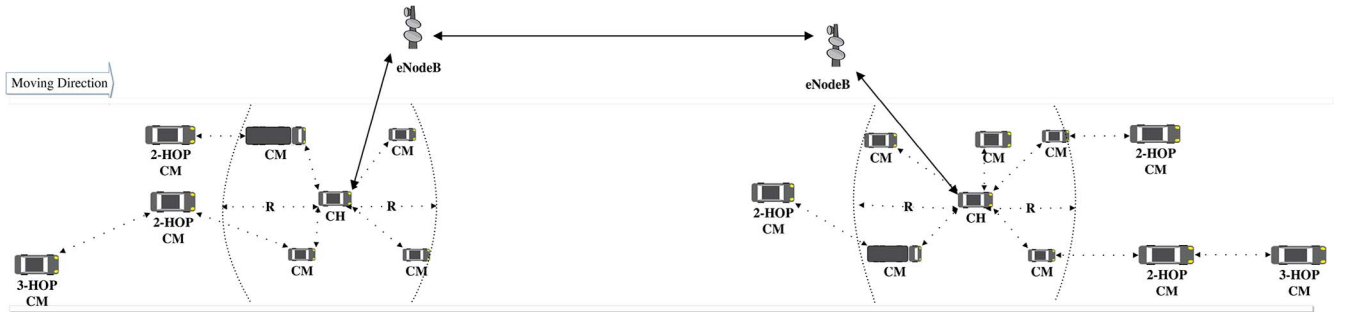


Fig. 1. IEEE 802.11p-LTE hybrid architecture.

and directly communicate with their corresponding CH. The vehicles that are multihops away from the CH become multihop CMs and transfer data packets to the CM to which they are connected to reach their corresponding CH.

The vehicle information base (*VIB*) of a vehicle consists of a repository storing the information of the vehicle and its neighboring vehicles within a predetermined maximum number of hops, which is denoted by *MAX_HOP*. *VIB* is used in determining the members and heads of the clusters in the network.

The vehicles possess two communication interfaces: IEEE 802.11p and LTE. CMs can only communicate with the members of the cluster they belong to via IEEE 802.11p, whereas CH communicates with both CMs via IEEE 802.11p and eNodeB via LTE.

The LTE infrastructure is responsible for disseminating the generated data within a VANET inside a geographical region. The LTE part of the system consists of a RAN, where each cell is managed by an eNodeB and the evolved packet core (EPC), which consists of a server gateway (SGW) and packet data network gateways (PGWs) [40]. eNodeB is a complex base station that handles radio communications with multiple devices in the cell and carries out radio resource management and handover decisions. SGW provides the functionality of routing and forwarding data packets to neighboring eNodeBs, whereas PGW is responsible for setting the transfer paths of vehicle data packets, quality-of-service control, and authentication. eNodeBs are connected to EPC over a wired network. EPC has global information of the location of eNodeBs. When a CH sends the data packet to the eNodeB it is connected to

over a radio network, the packet is sent to the EPC over the wired network. The EPC then determines all the eNodeBs that cover an area within the safety dissemination region of the data packet and sends the packet to them. When an eNodeB receives a data packet for dissemination, the packet is multicast to all the CHs that are within the coverage of eNodeB.

The objective of the proposed hybrid architecture is to efficiently forward data packets over a certain geographical region with small delay and high percentage of vehicles successfully receiving packets while minimizing the number of CHs and maximizing the clustering stability to minimize the overhead on the vehicles and eNodeB.

III. VEHICULAR MULTI-HOP ALGORITHM FOR STABLE CLUSTERING (VMaSC)

The features of the proposed multihop clustering algorithm VMaSC are as follows.

- 1) It provides stable CH selection by the use of the relative mobility metric calculated as the average relative speed with respect to the neighboring vehicles in a multihop clustered vehicular network.
- 2) It provides cluster connection with minimum overhead by introducing a direct connection to the neighbor that is already a head or a member of a cluster, instead of connecting to the CH in multiple hops, and disseminating CM information within periodic hello packets.
- 3) It provides reactive clustering to maintain the cluster structure without excessive packet transmission overhead.
- 4) It provides minimum intercluster interference by minimizing the overlap of clusters in space through prioritizing the connections to existing clusters and introducing efficient size- and hop-aware cluster-merging mechanisms based on the exchange of cluster information among the CHs.

A preliminary version of VMaSC and its integration with data aggregation appeared previously in [1] and [2], respectively.

Fig. 1 shows a sample multihop clustered network topology. Next, we describe the states of the vehicles, *VIB* generation and update, cluster state transitions, cluster formation, cluster merging, and intercluster interference. The notation used is presented in Table IV.

A. States of Vehicles

Each vehicle operates under one of the following five states at any given time.

- INITIAL (*IN*) is the starting state of the vehicle.
- STATE ELECTION (*SE*) is the state of the vehicle in which the vehicle makes a decision about the next state based on the information in *VIB*.
- CLUSTER HEAD (*CH*) is the state of the vehicle in which the vehicle is declared to be a cluster head.
- ISOLATED CLUSTER HEAD (*ISO – CH*) is the state to which the vehicle makes a transition when it cannot

TABLE IV
NOTATION

Notation	Description
<i>IN</i>	Initial State
<i>SE</i>	State Election
<i>CH</i>	Cluster Head
<i>ISO – CH</i>	Isolated Cluster Head
<i>CM</i>	Cluster Member
<i>VIB</i>	Vehicle Information Base
<i>VIB_TIMER</i>	VIB Timer
<i>IN_TIMER</i>	Initial State Timer
<i>SE_TIMER</i>	State Election State Timer
<i>CH_TIMER</i>	Cluster Head State Timer
<i>CM_TIMER</i>	Cluster Member State Timer
<i>JOIN_TIMER</i>	Join Response Packet Timer
<i>MERGE_TIMER</i>	Merge Timer
<i>V_{state}</i>	Vehicle's Current State
<i>AVGREL_SPEED_i</i>	Average Relative Speed of Vehicle <i>i</i>
<i>MEMBER_{CH}</i>	CH's Connected Member Counter
<i>MEMBER_{CM}</i>	CM's Connected Member Counter
<i>MAXMEMBER_CH</i>	Max. Member CH can serve
<i>MAXMEMBER_CM</i>	Max. Member CM can serve
<i>MAX_HOP</i>	Max. Hop Between CH and CM
<i>HOP_{CM}</i>	Number of hops between CM and CH
<i>CH_ADV</i>	CH's Advertisement Packet
<i>JOIN_REQ</i>	Join Request Packet
<i>JOIN_RESP</i>	Join Response Packet
<i>CH_ADV</i>	Cluster Head Advertisement Message
<i>HELLO_PACKET</i>	Periodic Hello Packet
<i>DATA_PACKET</i>	Data Packet
<i>CLUSTER_INFO</i>	Cluster Information Packet
<i>TRY_CONNECT_i</i>	Try Connect Flag for Vehicle <i>i</i>
<i>MERGE_REQ</i>	CH's Merge Request
<i>MERGE_RESP</i>	CH's Merge Response
<i>ID_{DATA}</i>	Data Packet Generator Identifier
<i>SEQ_{DATA}</i>	Data Packet Sequence Number
<i>PARENT_i</i>	Vehicle through which vehicle <i>i</i> is connected to the cluster
<i>CHILDREN_i</i>	Vehicles that use vehicle <i>i</i> to connect to the CH

connect to any existing cluster and when there is no potential neighboring vehicle that can connect to it.

- CLUSTER MEMBER (*CM*) is the state of the vehicle in which the vehicle is attached to an existing cluster.

B. *VIB* Generation and Update

VIB at each node includes the information of the vehicle itself and its neighboring vehicles within *MAX_HOP* hops. The vehicle information includes its direction, its velocity, its current clustering state, the number of hops to the CH if it is a CM, the ID of the vehicle through which the node is connected to the CH, its clustering metric, and the source ID and sequence number of the data packets that are recently generated.

VIB is updated upon any change in the vehicle's own information or reception of a periodic *HELLO_PACKET* from any of the neighbors within *MAX_HOP* hops. *HELLO_PACKET* includes the vehicle information for its direction, its velocity, its current clustering state, the

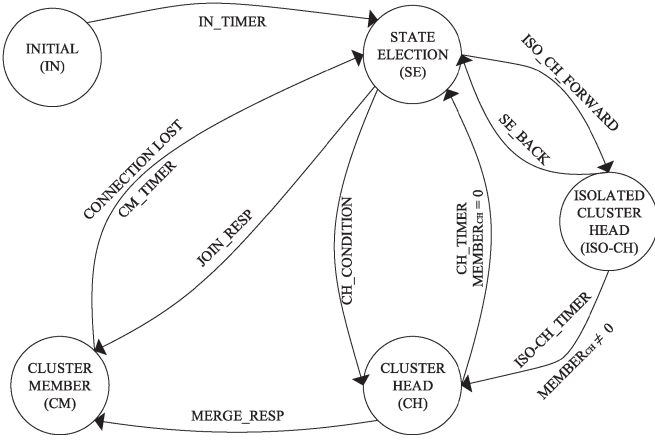


Fig. 2. VMA SC state transition diagram.

number of hops to the CH if it is a CM, and the ID of the vehicle through which the node is connected to the cluster. *HELLO_PACKET* is retransmitted to the neighbors within *MAX_HOP* hops. The entries of *VIB* are deleted if not updated for a certain time, which is denoted by *VIB_TIMER*.

The clustering metric denoted by $AVGREL_SPEED_i$ for vehicle i is calculated as

$$AVGREL_SPEED_i = \frac{\sum_{j=1}^{N(i)} |S_i - S_{i_j}|}{N(i)} \quad (1)$$

where $N(i)$ is the number of same-direction neighbors within *MAX_HOP* hops for vehicle i , i_j is the ID of the j th neighboring node of vehicle i , and S_i is the speed of vehicle i . The lower the average relative speed, the less mobile is the vehicle compared with its neighbors. Therefore, the vehicle with the lowest average relative speed is elected as the CH.

C. Cluster State Transitions

Fig. 2 shows the possible state transitions of a vehicle. The vehicle starts in state *IN* and stays in this state for a duration denoted by *IN_TIMER*. The periodic exchange of *HELLO_PACKET* in this state helps the vehicle build its own *VIB*. The vehicle then transitions to state *SE*, in which it makes the decision about its next state, as described in Algorithm 1 in Section III-D.

A vehicle transitions from state *SE* to state *CM* if it receives a *JOIN_RESP* from a CH or a CM. Receiving a *JOIN_RESP* shows the success of the join request. A vehicle transitions from state *SE* to *CH* if *CH_CONDITION* is satisfied. *CH_CONDITION* refers to the condition where the vehicle cannot connect to any neighboring CH or CM, there is at least one neighboring vehicle in state *SE*, and the vehicle has minimum average relative speed among all the neighboring vehicles in state *SE*. The vehicle in state *SE* transitions to state *ISO-CH* if the *ISO_CH_FORWARD* condition is met. *ISO_CH_FORWARD* refers to the condition where the vehicle cannot connect to any neighboring CH or CM and there is no neighboring vehicle in state *SE*. The vehicle in state *ISO-CH* similarly behaves as that in state *CH*. A separate *ISO-CH* state is included to differentiate the CHs with no

CMs since the condition to switch from *CH* to *SE* is the lack of a CM connected to CH. If the number of the members of *CH* denoted by *MEMBER_CH* is zero for the duration *CH_TIMER*, the CH changes its state to *SE* to decrease the number of clusters in the network by connecting to another cluster. The vehicle in state *ISO-CH* transitions to state *CH* if a CM is connected after *ISO_CH_TIMER* and to state *SE* when the node is no longer isolated, meeting the *SE_BACK* condition. *SE_BACK* refers to the condition of discovering a node in either the *CM* or the *CH* state that does not exist in the *VIB*. If none of the transitions can be made in state *SE*, then the vehicle stays in *SE* for a duration denoted by *SE_TIMER* and reruns Algorithm 1.

A vehicle changes state from *CH* to *CM* if it receives a *MERGE_RESP* from another CH, demonstrating the success of cluster merging, as explained in detail in Section III-E. The vehicle transitions from state *CM* to *SE* if it has lost connection to the neighboring node through which it is connected to the cluster named *PARENT*. If the CM vehicle does not receive any packet from its *PARENT* for duration *CM_TIMER*, it assumes to have lost the connection.

D. Cluster Formation

As shown in detail in Algorithm 1, a vehicle in the *SE* state first tries to connect to the existing clusters to minimize the number of CHs. The vehicle gives priority to the neighboring CHs over the neighboring CMs for connection to decrease the delay of the data packets transmitted to the CH over a smaller number of hops.

The vehicle first scans the neighboring CHs in the order of increasing average relative mobility. If the number of members of the CH is less than the maximum number of members allowed and the vehicle has not tried connecting to that CH before with *TRY_CONNECT* set to false, it sends a *JOIN_REQ* packet (lines 1–4). If it receives *JOIN_RESP* from the corresponding CH within a given amount of time denoted by *JOIN_TIMER*, the vehicle transitions to state *CM* and exits the *SE* algorithm (lines 5–7). Otherwise, the vehicle sets the *TRY_CONNECT_CH* flag to *true* in order not to try connecting to that CH again (line 9). *TRY_CONNECT* flags of vehicles are initially set to false.

If none of the neighboring vehicles are a CH or the vehicle cannot connect to any of the neighboring CHs, then the vehicle tries to connect to a CH in multiple hops through a CM (lines 10–19). The order in which the CMs are scanned is determined based on the average relative mobility. Similar to the connection to CH, if the number of members of the CM is less than the maximum number of members allowed and the vehicle has not tried connecting to that CM before with *TRY_CONNECT* set to false (lines 10–12), and the vehicle is within *MAX_HOP* hops away from the corresponding CH (line 13), the vehicle sends the *JOIN_REQ* packet to this CM (line 14). Depending on the reception of *JOIN_RESP*, the vehicle then either transfers to state *CM* or sets the *TRY_CONNECT* flag of the *CM* to *true* (lines 15–19). If the vehicle receives multiple *JOIN_RESP*s, then it prefers

Algorithm 1: State Election (SE) Algorithm

```

1 forall the  $CH \in VIB$  do
2   if  $TRY\_CONNECT_{CH} == false$  then
3     if  $MEMBER_{CH} < MAXMEMBER_{CH}$ 
4       then
5         Send  $JOIN\_REQ$ ;
6         if  $JOIN\_RESP$  received then
7            $V_{state} = CM$ ;
8           Exit;
9         else
10           $TRY\_CONNECT_{CH} = true$ ;
11 forall the  $CM \in VIB$  do
12   if  $TRY\_CONNECT_{CM} == false$  then
13     if  $MEMBER_{CM} < MAXMEMBER_{CM}$ 
14       then
15         if  $HOP_{CM} < MAX\_HOP$  then
16           Send  $JOIN\_REQ$ ;
17           if  $JOIN\_RESP$  received then
18              $V_{state} = CM$ ;
19             Exit;
20           else
21              $TRY\_CONNECT_{CM} = true$ ;
22 if Not exists  $SE \in VIB$  then
23    $V_{state} = ISO - CH$ ;
24   Exit;
25 else if  $AVGREL\_SPEED_{curr} =$ 
26    $\min_{SE \in VIB}(AVGREL\_SPEED_{SE})$  then
27    $V_{state} = CH$ ;
28   Broadcast  $CH\_ADV$ ;
29   Exit;
```

CH over CM and the vehicle with the smallest average relative mobility among multiple CHs and CMs.

If the vehicle cannot connect to any CH or CM, the vehicle checks the neighboring vehicles in the SE state. If there is no such vehicle, it transitions to state $ISO - CH$ (lines 20–22). If there are vehicles in the SE state in its VIB and the vehicle has the smallest average relative speed, it makes a transition to the CH state and broadcasts the CH_ADV packet (lines 23–26). Otherwise, the vehicle stays in state SE for SE_TIMER duration and reruns Algorithm 1.

E. Cluster Merging

Since the vehicles do not send the $JOIN_REQ$ messages to the CH in multiple hops, the CH learns about the vehicles within its cluster via $HELLO_PACKET$. The CH keeps the information about its cluster, including the ID and $PARENT$ node of its CMs and its cluster direction within a data structure named $CLUSTER_INFO$.

When two CHs become neighbors, they first check whether they stay neighbors for a certain time period denoted by $MERGE_TIMER$. The value of $MERGE_TIMER$ should be chosen to balance the tradeoff between cluster stability

and number of clusters in the network: As $MERGE_TIMER$ increases, the cluster stability increases at the cost of increase in the number of clusters. If the CHs stay neighbors for $MERGE_TIMER$, they share their $CLUSTER_INFO$ and their average relative speed with each other. Both CHs then check the feasibility of the merged cluster formed when the CH with higher average relative speed gives up its CH role and connects to the CH with lower average relative speed. A feasible merged cluster requires that both clusters have the same cluster direction; the number of members of the CH and CMs in the merged cluster be less than $MAXMEMBER_{CH}$ and $MAXMEMBER_{CM}$, respectively; and the number of hops in the merged cluster be less than MAX_HOP . Limiting the maximum number of vehicles and the number of hops in the merged cluster eliminates CH bottleneck and longer hierarchical routes, respectively. If the merged cluster is determined to be feasible, then the CH with higher average relative speed sends $MERGE_REQ$ to the less mobile CH. If this CH receives $MERGE_RESP$, it gives up its CH role and informs its CMs about the merge operation. Otherwise, the CHs continue to function as CHs. If the vehicle receives multiple $MERGE_RESP$ s, then it prefers the CH with the smallest average relative mobility.

F. Intercluster Interference

Intercluster interference occurs when the clusters overlap in space. Intercluster interference leads to higher medium contention and inefficient flooding. VMaSC minimizes overlapping clusters via two methods. 1) The vehicles in the SE state try to join an existing cluster first before declaring themselves as CH or $ISO - CH$. 2) The CHs that are within the transmission range of each other merge their clusters if the resulting merged cluster is considered feasible. Moreover, the data packets of the CMs are unicast to their $PARENT$ to decrease the medium contention and increase the efficiency of the flooding. Furthermore, the packets of each cluster are only broadcast within that cluster identified with a unique ID, avoiding unnecessary flooding among multiple clusters.

G. Theoretical Analysis of VMaSC Clustering

Here, we provide the theoretical analysis of the relative speed metric used in VMaSC clustering.

Let us assume that two neighboring vehicles 1 and 2 have average speed values v_1 and v_2 and average acceleration values a_1 and a_2 , respectively. Assume that these vehicles move on a 1-D road, and they communicate with each other only if they are within the transmission range of each other called r_t . Let the location of vehicles 1 and 2 on the road in the moving direction be l_1 and l_2 with difference denoted by r_{12} equal to $l_1 - l_2$. r_{12} is a random variable that takes values within the $[-r_t, r_t]$ interval. The intervehicle distance has been shown to have an exponential distribution at low vehicle density and a lognormal distribution at high vehicle density [7]. In this case, it should also be conditioned on the fact that its value is in the $[-r_t, r_t]$ range. We represent the distribution of r_{12} by $P(r_{12})$ without making any assumption on its distribution,

except that it is limited to the $[-r_t, r_t]$ range and symmetric around 0. Since the vehicles exchange their speed information with each other, we assume that v_1 and v_2 are predetermined. The average acceleration values of the vehicles a_1 and a_2 , however, are assumed to be random variables. Most theoretical analyses related to clustering in the literature assume no vehicle acceleration, i.e., $a_1 = a_2 = 0$ [41]–[43]. The Freeway mobility model, on the other hand, assumes that a_1 and a_2 are independent random variables with uniform distribution in the interval $[-a, a]$, where a is determined by the maximum acceleration and deceleration of the vehicles, while also enforcing the minimum and maximum speed values for the vehicles and the minimum safety distance between any two vehicles, generating a possibly nonzero correlation on the values of the accelerations a_1 and a_2 , whereas the Reference Point Group Mobility Model determines the speed of each vehicle by randomly deviating from the speed of a vehicle in their group as a function of a predetermined speed and angle deviation ratio [44], [45]. To encompass all these different mobility models while preserving the tractability of the analysis, we assume that the distribution of the difference between a_1 and a_2 , δ_{12} , which is denoted by $f(\delta_{12})$, is symmetric around 0 and a decreasing function of δ_{12} for $\delta_{12} > 0$.

Let us first condition on the values of a_1 and a_2 . At any time T , if $r_{12} + (v_1 - v_2)T + (a_1 - a_2)T^2/2$ is less than r_t in magnitude, the two vehicles can communicate with each other. To have a more stable link among the CMs, at any given time T , we need to maximize the probability that the vehicles can communicate with each other, which is given by

$$P(-r_t < r_{12} + (v_1 - v_2)T + (a_1 - a_2)T^2/2 < r_t) \\ = \int_{-r_t}^{r_t} P(-r_t - r_{12} < (v_1 - v_2)T + (a_1 - a_2)T^2/2 \\ < r_t - r_{12} | r_{12} = \tau) P(\tau) d\tau \quad (2)$$

where $P(-r_t - r_{12} < (v_1 - v_2)T + (a_1 - a_2)T^2/2 < r_t - r_{12} | r_{12} = \tau)$ takes a value of 1 or 0, depending on the values of $\tau, v_1 - v_2, a_1 - a_2, r_t$, and T parameters. By using the symmetry of the distribution $P(r_{12})$ around 0, this probability can be simplified as

$$\int_{-r_t}^{r_t - |(v_1 - v_2)T + (a_1 - a_2)T^2/2|} P(\tau) d\tau. \quad (3)$$

If $a_1 = a_2$, then to maximize this connection probability, we need to minimize the relative speed of the vehicles given by $|v_1 - v_2|$. On the other hand, if $a_1 \neq a_2$, the probability that the two vehicles are in the communication range of each other is given by

$$\int_{-\infty}^{\infty} P(-r_t < r_{12} + (v_1 - v_2)T + \delta_{12}T^2/2 < r_t) f(\delta_{12}) d\delta_{12} \\ = \int_{-\infty}^{\infty} \int_{-r_t}^{r_t - |(v_1 - v_2)T + \delta_{12}T^2/2|} P(\tau) f(\delta_{12}) d\tau d\delta_{12}. \quad (4)$$

By using the symmetry of the distribution $f(\delta_{12})$ around 0, this probability can be simplified as

$$\int_0^{\infty} \left(\int_{-r_t}^{r_t - |(v_1 - v_2)T + \delta_{12}T^2/2|} P(\tau) d\tau + \int_{-r_t}^{r_t - |(v_1 - v_2)T - \delta_{12}T^2/2|} P(\tau) d\tau \right) f(\delta_{12}) d\delta_{12}. \quad (5)$$

By using the fact that both $|(v_1 - v_2)T + \delta_{12}T^2/2|$ and $|(v_1 - v_2)T - \delta_{12}T^2/2|$ are lower bounded by $|(v_1 - v_2)T| - |\delta_{12}T^2/2|$ and upper bounded by $|(v_1 - v_2)T| + |\delta_{12}T^2/2|$, the probability that the two vehicles are in the communication range of each other is lower bounded by

$$2 \int_0^{\infty} \int_{-r_t}^{r_t - |(v_1 - v_2)T| - \delta_{12}T^2/2} P(\tau) f(\delta_{12}) d\tau d\delta_{12} \quad (6)$$

and upper bounded by

$$2 \int_0^{\infty} \int_{-r_t}^{r_t - |(v_1 - v_2)T| + \delta_{12}T^2/2} P(\tau) f(\delta_{12}) d\tau d\delta_{12}. \quad (7)$$

To maximize both the lower bound and the upper bound of this probability, we need to again minimize the relative speed of the vehicles $|v_1 - v_2|$.

IV. DATA DISSEMINATION IN HYBRID ARCHITECTURE

The goal of the proposed multihop-cluster-based IEEE 802.11p-LTE hybrid architecture is to disseminate the data generated in the network to all the vehicles within a geographical area with small delay and high DPDR. LTE is used in this architecture to provide the connectivity of the nodes even when the IEEE 802.11p-based network is disconnected within the dissemination distance and improve the delay and reliability performance of the transmissions when the IEEE 802.11p-based network has high node density, leading to high medium-access contention.

Data forwarding at a vehicle depends on its clustering state. If its clustering state is *SE*, the vehicle broadcasts *DATA_PACKET* so that it reaches a member of a cluster in the network. If the clustering state of the vehicle generating or receiving a *DATA_PACKET* is *CM* (*CH*), the vehicle runs Algorithm 2 (Algorithm 3). The data flow is as follows.

- 1) unicast from CM to its CH (if the vehicle is a CM);
- 2) broadcast from CH to all its members and to the eNodeB;
- 3) unicast from eNodeB to EPC;
- 4) multicast from EPC to the neighboring eNodeBs covering a part of the geographical area targeted for the dissemination of the *DATA_PACKET*;
- 5) multicast from eNodeBs to the CHs within their coverage;
- 6) broadcast from the CHs to all its members.

As provided in Algorithm 2, if the CM generates or receives a *DATA_PACKET*, then it checks its *VIB* to determine whether the packet has already been received (lines 2–3). If the CM receives the packet for the first time, then it checks the source of the packet. If it is coming from its parent vehicle (*PARENT_{curr}*) in the cluster, then it multicasts the packet to all its children *CHILDREN_{curr}* (lines 4–5). Otherwise, the packet is from either one of its children or another vehicle that is in the *SE* state. The vehicle then unicasts the packet to its parent vehicle for the dissemination of the packet to the corresponding CH (lines 6–7) and updates its *VIB* for the packet (line 8).

Likewise, as provided in Algorithm 3, if the CH generates or receives a *DATA_PACKET* for the first time, it checks the source of the packet (lines 1–3). If the packet is coming from eNodeB, the CH broadcasts *DATA_PACKET* to all the members of its cluster (lines 4–5). Otherwise, the packet comes from itself, one of its children or another vehicle in the *SE* state. In that case, it broadcasts the packet to the members of its cluster, creates an *LTE_DATA_PACKET* containing the data of the received packet, forwards the *LTE_DATA_PACKET* to the eNodeB (lines 6–8), and updates its *VIB* for the packet (line 9).

Upon reception of the *LTE_DATA_PACKET* from a CH, the eNodeB multicasts the packet to all the CHs within its coverage and forwards it to the EPC via a wired network. The EPC then determines all the eNodeBs that cover an area within the dissemination region of the corresponding packet. The eNodeBs that receive an *LTE_DATA_PACKET* from the EPC then multicast it to all the CHs under their coverage, which again disseminate the data to their CMs.

Algorithm 2: IEEE 802.11p-LTE CM Algorithm

```

1 On DATA_PACKET generation or receipt;
2 Extract IDDATA and SEQDATA;
3 if (IDDATA, SEQDATA)  $\notin$  VIB then
4   if DATA_PACKET is from PARENTcurr then
5     Multicast DATA_PACKET to
       CHILDRENcurr;
6   else
7     Unicast DATA_PACKET to PARENTcurr;
8 Update VIB;

```

Algorithm 3: IEEE 802.11p-LTE CH Algorithm

```

1 On DATA_PACKET generation or receipt;
2 Extract IDDATA and SEQDATA;
3 if (IDDATA, SEQDATA)  $\notin$  VIB then
4   if DATA_PACKET is from eNodeB then
5     Broadcast DATA_PACKET into cluster;
6   else
7     Broadcast DATA_PACKET into cluster;
8     Put data in LTE_DATA_PACKET and
       forward it to eNodeB;
9 Update VIB;

```

V. PERFORMANCE EVALUATION

The goal of the simulations is to compare the performance of the proposed multihop-cluster-based IEEE 802.11p-LTE hybrid architecture to the previously proposed VANET multihop clustering algorithms NHop [10] and MDMAC [17], the hybrid architectures built with the usage of these clustering algorithms NHop and MDMAC, and flooding-based message dissemination.

The simulations are performed in the Network Simulator ns3 (Release 3.17) [46] with the realistic mobility of the vehicles generated by Simulation of Urban Mobility (SUMO) [29]. The software for the implementation of VMaSC and VMaSC-LTE is available in [48]. SUMO, which is generated by the German Aerospace Center, is an open-source, space-continuous, and discrete-time traffic simulator that is capable of modeling the behavior of individual drivers. The acceleration and overtaking decision of the vehicles is determined by using the distance to the leading vehicle, traveling speed, dimension of vehicles, and profile of acceleration–deceleration.

The road topology consists of a two-lane and two-way road of length 5 km. The vehicles are injected into the road according to a Poisson process with a rate equal to two vehicles per second. The total simulation time is 355 s. The clustering process starts at the 55th second when all the vehicles have entered the road. All of the performance metrics are evaluated for the remaining 300 s. Two classes of vehicles with different maximum speed ranges are used in the simulation to create a realistic scenario with different types of vehicles on the road, such as passenger cars, buses, and trucks. The first vehicle class has a maximum speed of 10 m/s, whereas the maximum speed of the second vehicle class is considered as a variable ranging from 10 to 35 m/s. Considering the injection of the vehicles into the road and their maximum speed constraint, the average number of the neighbors of the vehicles ranges from 10 to 18 at different times for different scenarios.

Tables V and VI list the simulation parameters of the VANET and LTE networks, respectively. The maximum number of hops within a cluster is chosen in the range [1,3] since the number of hops above three reduces the clustering stability considerably due to the increase in the number of *HELLO_PACKET*s disseminated within the maximum number of hops, increase in the number of retransmitted packets lost due to higher contention, and increase in the number of connections lost among the CMs due to higher packet collisions. The YANS channel model [47] used throughout the simulation is based on first deciding whether a packet can be received at the beginning of the packet transmission considering the physical layer and the signal-to-interference-plus-noise ratio (SINR) level and then determining the successful reception of the packet probabilistically at the end of the packet transmission by calculating the packet error rate as a function of the SINR level, modulation type, transmission rate, and error-correcting code.

We first compare the stability of the proposed clustering algorithm VMaSC with the previously proposed multihop VANET clustering algorithms. We then examine the delay and DPDR performance of the proposed hybrid architecture compared with both previously proposed cluster-based hybrid architectures and

TABLE V
ns-3 SIMULATION PARAMETERS FOR VANET

Parameters	Value
Simulation Time	300 s
Maximum Velocity	10 - 35 m/s
MAX_HOP	1, 2, 3
Number of Vehicles	100
Transmission Range	200 m
MAC Layer	DCF, CSMA/CA
Channel Model	YANS [47]
$MAXMEMBER_{CH}$	5
$MAXMEMBER_{CM}$	1
$HELLO_PACKET$ period	200 ms
$HELLO_PACKET$ size	64 bytes
$DATA_PACKET$ period	1 s
$DATA_PACKET$ size	1024 bytes
VIB_TIMER	1 s
IN_TIMER	2 s
SE_TIMER	2 s
CH_TIMER	2 s
CM_TIMER	2 s
$JOIN_TIMER$	2 s
$MERGE_TIMER$	2 s
MAX_HOP	1, 2, 3

TABLE VI
ns-3 SIMULATION PARAMETERS FOR LTE

Parameters	Value
$eNodeB$ Scheduler Type	RrFfMacScheduler
$eNodeB$ Coverage	7 km
Pathloss Model	Friis Propagation Model

alternative mechanisms, including flooding and pure VANET cluster-based data forwarding.

A. VANET Clustering

Here, VMaSC is compared with multihop-clustering algorithms NHop [10] and MDMAC [17], the characteristics of which are summarized in Table III. The performance metrics used for comparison are CH duration, CM duration, CH change rate, clustering overhead, and number of vehicles in the SE state.

1) *CH Duration*: CH duration is defined as the time period from when a vehicle changes state to CH to when a vehicle transitions from state CH to state SE or CM .

Fig. 3 shows the average CH duration of the clustering algorithms as a function of maximum vehicle velocities for different maximum numbers of hops, whereas Fig. 6(a) shows the cumulative distribution function (cdf) of the CH duration of VMaSC for different maximum numbers of hops and different maximum vehicle velocities. The average CH duration of VMaSC is higher than that of NHop and MDMAC under all conditions, which is mainly due to the efficient cluster maintenance mechanism based on reactive reclustering in VMaSC. Moreover, increasing the maximum number of hops allowed

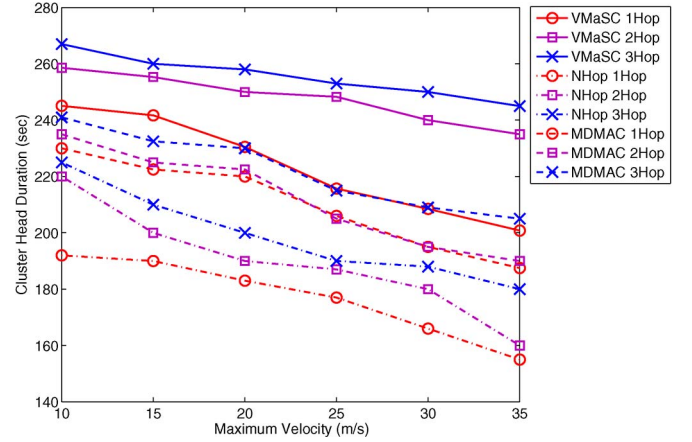


Fig. 3. Average CH duration of the clustering algorithms as a function of maximum vehicle velocities for different maximum numbers of hops.

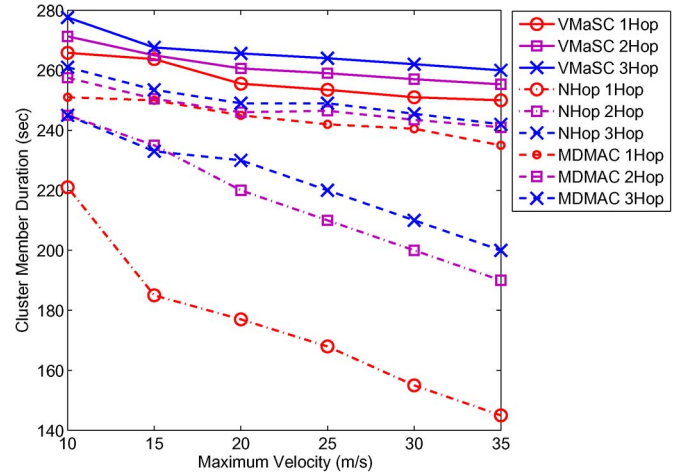


Fig. 4. Average CM duration of the clustering algorithms as a function of maximum vehicle velocities for different maximum numbers of hops.

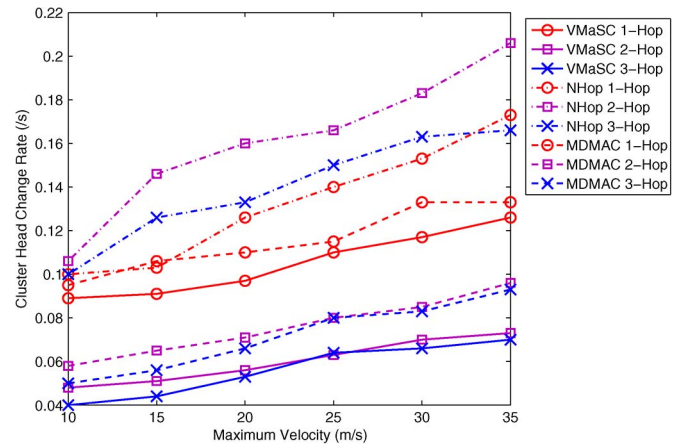


Fig. 5. CH change rate of the clustering algorithms as a function of maximum vehicle velocities for different maximum numbers of hops.

within each cluster increases the average CH duration and, hence, clustering stability. The main reason is that the CH has a higher chance of finding a member to serve as the number of hops increases. Moreover, vehicles collect more information on surrounding vehicles at higher hops, which eventually

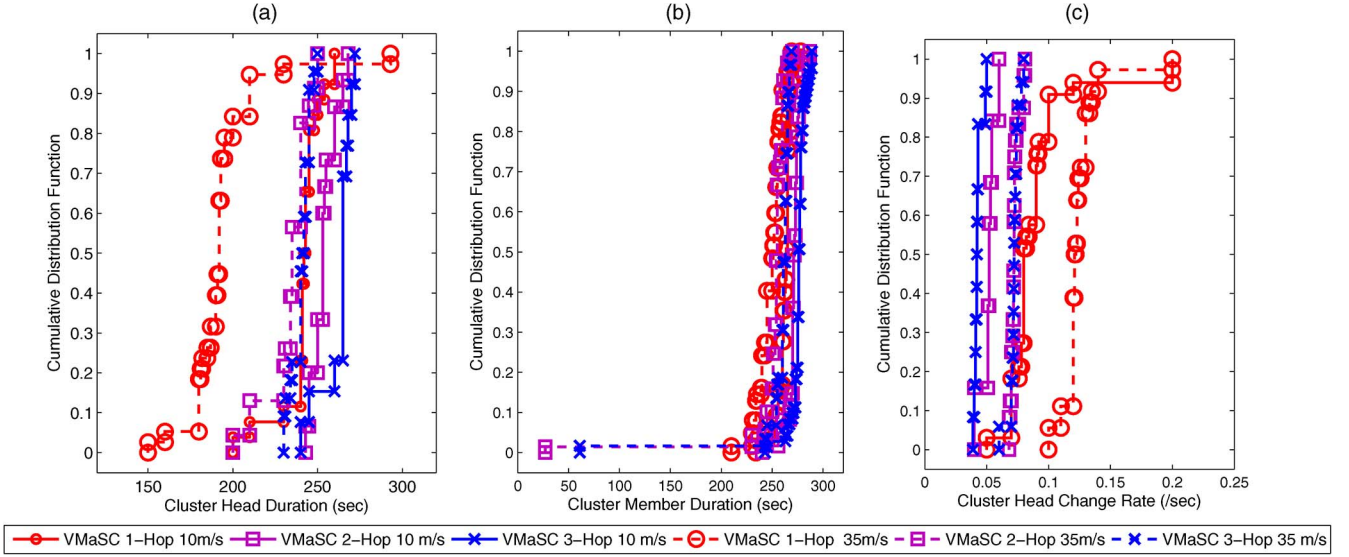


Fig. 6. CDF of (a) CH duration, (b) CM duration, and (c) CH change rate of VMaSC for different maximum numbers of hops and vehicle velocities.

contributes to better assignment of the roles *CH* and *CM* to the vehicles. Furthermore, the average CH duration, in general, decreases as the vehicle velocity increases since higher vehicle velocity results in higher dynamicity of the network topology. The cdf of the CH duration, on the other hand, shows that the variation around the average CH duration of VMaSC is small, demonstrating its stability.

2) *CM Duration*: CM duration is defined as the time interval from joining an existing cluster as a member in the *CM* state to leaving the connected cluster by transitioning to the *SE* state.

Fig. 4 shows the average CM duration of the clustering algorithms as a function of maximum vehicle velocities for different maximum numbers of hops, whereas Fig. 6(b) shows the cdf of the CM duration of VMaSC for different maximum numbers of hops and different maximum vehicle velocities. Similar to the CH duration, the average CM duration of VMaSC is higher than that of NHop and MDMAC under all conditions, which, again, is mainly due to the efficient cluster maintenance mechanism as well as the low-overhead and low-delay cluster-joining mechanism of VMaSC. The CM duration increases as the maximum number of hops increases since collecting more information on surrounding vehicles at a higher number of hops enables the selection of better CH for connection. The cdf of the CM duration, on the other hand, shows that the variation around the average value of the CM duration of VMaSC is minimal, similar to that of the CH duration.

3) *CH Change Rate*: CH change rate is defined as the number of state transitions from *CH* to another state per unit time.

Fig. 5 shows the CH change rate of the clustering algorithms as a function of maximum vehicle velocities for different maximum numbers of hops, whereas Fig. 6(c) shows the cdf of the CH change rate of VMaSC for different maximum numbers of hops and different maximum vehicle velocities. The CH change rate of VMaSC is lower than that of NHop and MDMAC in all cases, which again proves the higher stability attained by VMaSC. VMaSC reduces the CH change

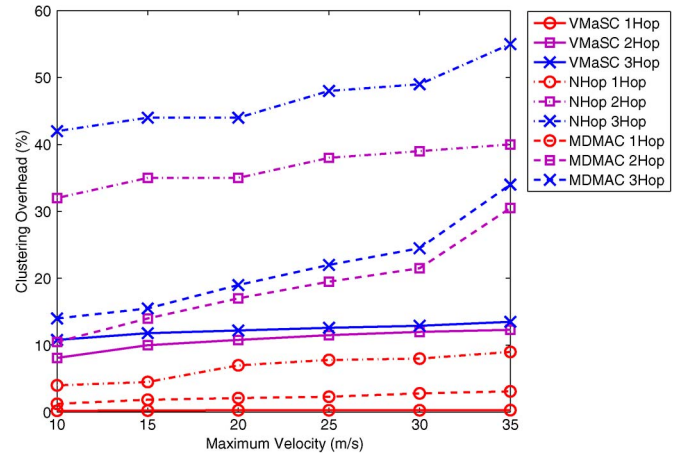


Fig. 7. Clustering overhead of the clustering algorithms for different maximum numbers of hops as a function of maximum vehicle velocities.

rate by leaving the *CH* state only when there is no member to serve, whereas NHop and MDMAC use periodic clustering maintenance, which causes unnecessary CH change in the network. Moreover, VMaSC avoids unnecessary state transitions from *CH* to *CM* by ensuring the connectivity of two clusters for *MERGE_TIMER* before merging them. Furthermore, similar to CH and member duration, increasing the number of hops allowed in the clusters decreases the CH change rate and, thus, increases the stability of VMaSC. The cdf of the CH change rate, on the other hand, shows that the variation around the average CH change rate of VMaSC is again small, demonstrating its stability.

4) *Clustering Overhead*: Clustering overhead is defined as the ratio of the total number of clustering related packets to the total number of packets generated in the VANET.

Fig. 7 shows the clustering overhead of the algorithms as a function of maximum vehicle velocities for different maximum numbers of hops. The clustering overhead of VMaSC is smaller than that of NHop and MDMAC. The first reason is

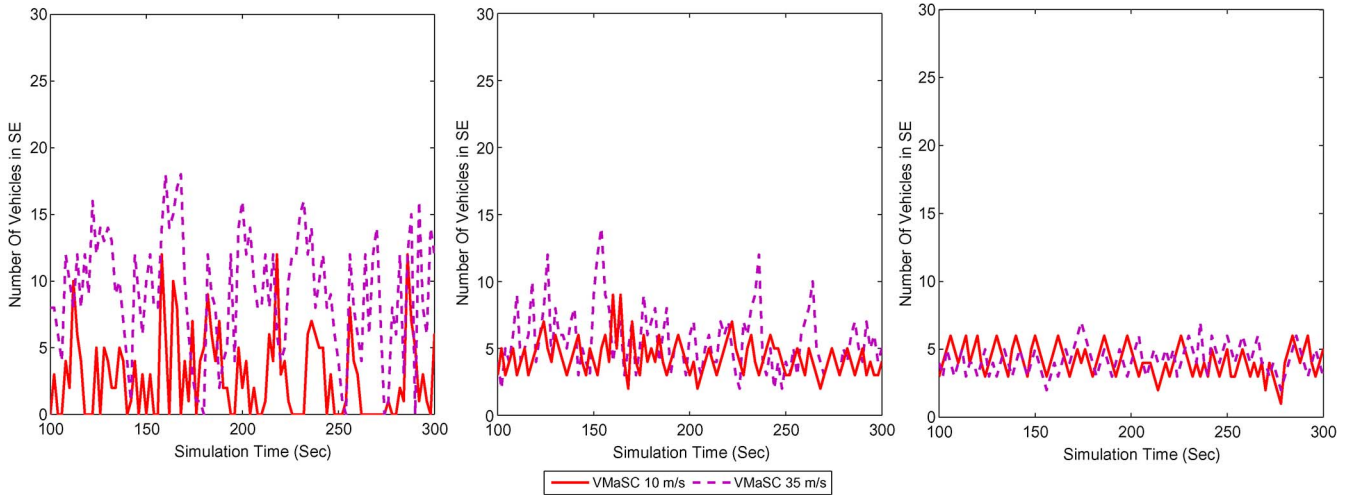


Fig. 8. Number of vehicles in the *SE* state for (a) one-hop, (b) two-hop, and (c) three-hop VMaSC clustering.

better cluster stability of VMaSC with higher cluster head and member duration. Another reason is the efficient mechanism for connection to the cluster through the neighboring CM instead of connecting to the CH in multiple hops. The VMaSC also eliminates the overhead of periodic active clustering by timer-based cluster maintenance. Moreover, as the maximum velocity of the vehicles increases, the increase in the clustering overhead of NHop and MDMAC is steeper than that of VMaSC, which illustrates the stability of VMaSC in highly dynamic networks. Furthermore, the clustering overhead of the protocols increases as the maximum number of hops increases since the *HELLO_PACKET*'s are rebroadcast over multiple hops to the neighbors within *MAX_HOP*.

5) *Number of Vehicles in the SE State*: Fig. 8 shows the number of vehicles in the *SE* state of VMaSC as a function of simulation time for different maximum numbers of hops and different maximum vehicle velocities. The number of nodes in the *SE* state is larger at higher vehicle velocities when the maximum number of hops is small. This is expected since the connections in the network break with higher probability as the relative vehicle velocities increase. The difference between the number of nodes in the *SE* state at higher and lower vehicle velocities and the variation in the number of nodes in the *SE* state over time, however, decreases as the number of hops increases. The reasons for this decrease are 1) the suitability of a larger set of neighboring vehicles at a higher maximum number of hops, allowing better cluster selection for CMs, and 2) the suitability of a larger number of CMs, decreasing the probability of losing all members and transitioning to the *SE* state for CHs.

B. VANET-LTE Hybrid Architectures

The performance of the proposed VANET-LTE hybrid architecture, namely, VMaSC-LTE, is compared with that of flooding; pure VANET cluster-based data-forwarding mechanisms, including VMaSC, NHop, and MDMAC, where the CHs relay information over the IEEE 802.11p network instead of eNodeBs; hybrid architectures NHop-LTE and MDMAC-LTE

that integrate the VANET clustering algorithms NHop and MDMAC with LTE; and a recently proposed hybrid architecture named CMGM-LTE. CMGM-LTE is the adaptation of the clustering-based multimetric adaptive gateway management mechanism (CMGM) proposed for UMTS [33] to LTE. CMGM-LTE uses a clustering metric defined as a function of the received signal strength from base stations, direction of movement, and intervehicular distance, and a periodic-cluster-update-based maintenance mechanism with no any cluster merging.

The performance metrics are DPDR, delay, and the cost of using LTE infrastructure.

1) *DPDR*: This metric is defined as the ratio of the number of vehicles successfully receiving data packets to the total number of vehicles within the target geographical area for the dissemination of the data packet. The average is taken over all the data packets sent by the vehicles in the simulation.

Fig. 9 shows the DPDR of different algorithms at different maximum velocities for one-, two-, and three-hop-based clustering mechanisms. The DPDR of VMaSC-LTE is above all the other algorithms in all cases. The reasons for the superior DPDR performance of VMaSC-LTE over the other hybrid architectures, namely, CMGM-LTE and MDMAC-LTE, are better clustering stability, minimal clustering overhead, and minimal overlap among clusters. Higher clustering stability results in stable connections among CMs and a smaller number of nodes in the *SE* state. Minimal clustering overhead and minimal overlap among clusters, on the other hand, decrease the medium-access contention, thus increasing the success probability of the transmissions. The reason for the superior performance of the clustering-based hybrid architectures over pure clustering-based data forwarding and pure flooding, on the other hand, is the efficiency of LTE-based communication among clusters in hybrid architectures. Hybrid architecture decreases the number of transmissions in the IEEE 802.11p-based network by providing LTE-based intercluster communication, which, in turn, decreases the medium-access contention. Moreover, the DPDR of VMaSC-LTE does not considerably change when the maximum velocity increases,

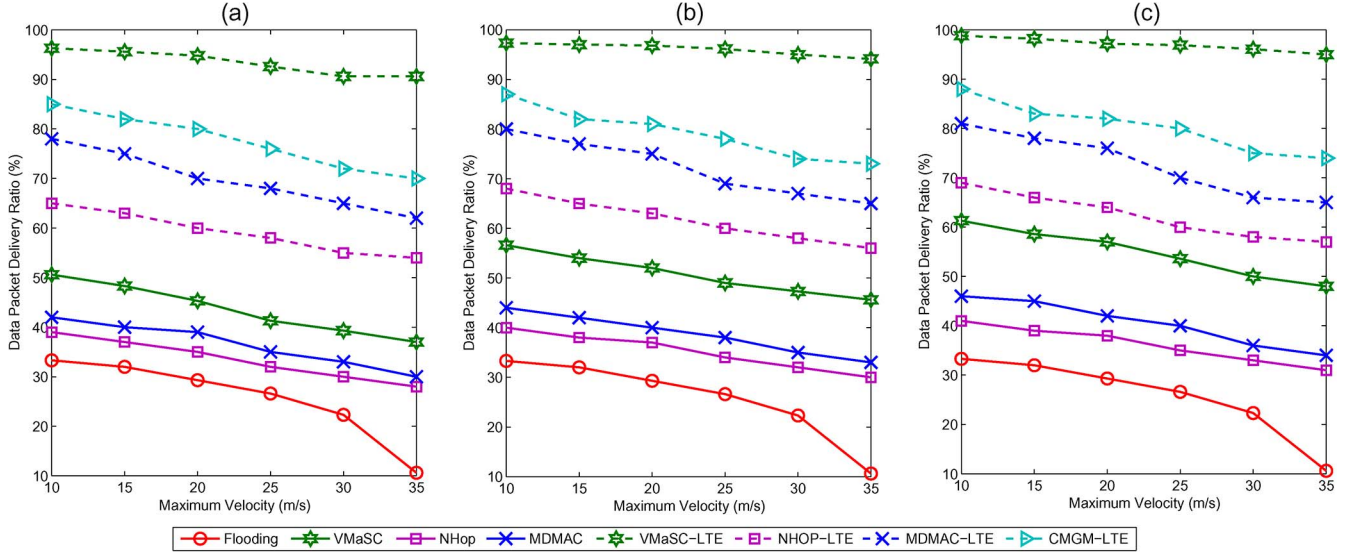


Fig. 9. DPDR of data dissemination algorithms at different maximum velocities for (a) one-hop-, (b) two-hop-, and (c) three-hop-based clustering.

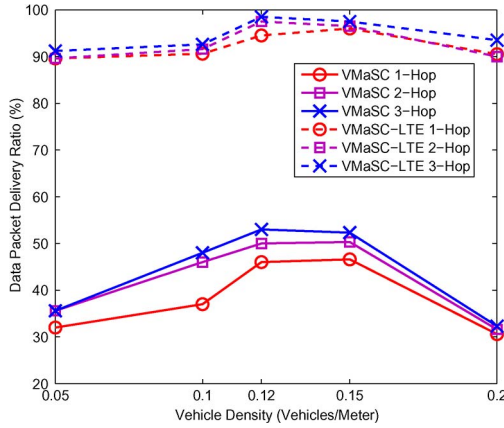


Fig. 10. DPDR of VMaSC and VMaSC-LTE at different vehicle densities.

demonstrating the robustness of the clustering algorithm to the increasing dynamicity of the network. Furthermore, the DPDR of VMaSC-LTE slightly improves as the maximum number of hops increases, which, again, is due to higher clustering stability, as demonstrated in Section V-A.

Fig. 10 shows the DPDR of VMaSC and VMaSC-LTE at different vehicle densities. The performance of pure cluster-based data-forwarding mechanism VMaSC is poor at low and high vehicle densities due to the disconnected network and broadcast storm problems, respectively. We observe that LTE-based hybrid architecture VMaSC-LTE improves the performance greatly, providing a high DPDR that is stable at all vehicle traffic densities.

2) *Delay*: The delay metric is defined as the average latency of the data packets that travel from their source to the vehicles within the target geographical area of dissemination. The average is taken over both the packets and the destinations. On the other hand, the maximum delay metric is defined as the maximum latency of the data packets that travel from their source to the vehicles within the target geographical area of dissemination.

Figs. 11 and 12 show the average and maximum delay of different algorithms at different maximum velocities for one-, two-, and three-hop-based clustering mechanisms, respectively. When we consider these results together with Fig. 9, we observe that there is a tradeoff between DPDR and delay for flooding and pure cluster-based algorithms: Flooding provides lower delay than cluster-based algorithms, whereas cluster-based algorithms achieve a higher DPDR than flooding. LTE-based hybrid architectures, on the other hand, achieve both low delay and high DPDR at the cost of using the infrastructure. Among the hybrid architectures, VMaSC-LTE achieves the lowest delay. Furthermore, the DPDR and delay analysis at different numbers of maximum hops allowed within clusters shows that increasing the maximum number of hops increases the DPDR at the cost of slight increase in the delay.

3) *LTE Cost*: The LTE cost metric indicates the cost of using LTE infrastructure to improve the data delivery performance of the hybrid architecture and is measured by the number of CHs in the network. The number of CHs depends on both the number of hops used in the clustering algorithm and the constraint on the maximum number of members that CH and CM can admit, which is denoted by $MEMBER_{CH}$ and $MEMBER_{CM}$, respectively. We assume that the value of $MEMBER_{CH}$ varies from 1 to 10; however, the value of $MEMBER_{CM}$ is kept constant at 1 in the simulation.

Table VII shows the number of clusters, i.e., number of CHs, for different $MEMBER_{CH}$ and number of hops values. As $MEMBER_{CH}$ increases, the number of clusters, in general, decreases. The number of clusters, however, may increase back when the number of hops and $MEMBER_{CH}$ are high, e.g., $MEMBER_{CH} = 10$ at a two-hop scenario, due to the higher clustering overhead at the CHs, higher contention around CHs, and larger number of CMs affected when a link within the cluster breaks. When both the number of hops and $MEMBER_{CH}$ are high in a cluster, the number of vehicles connected or sending a request for connection to the CH is higher. Moreover, the number of packets traveling to the CH is larger. Therefore,

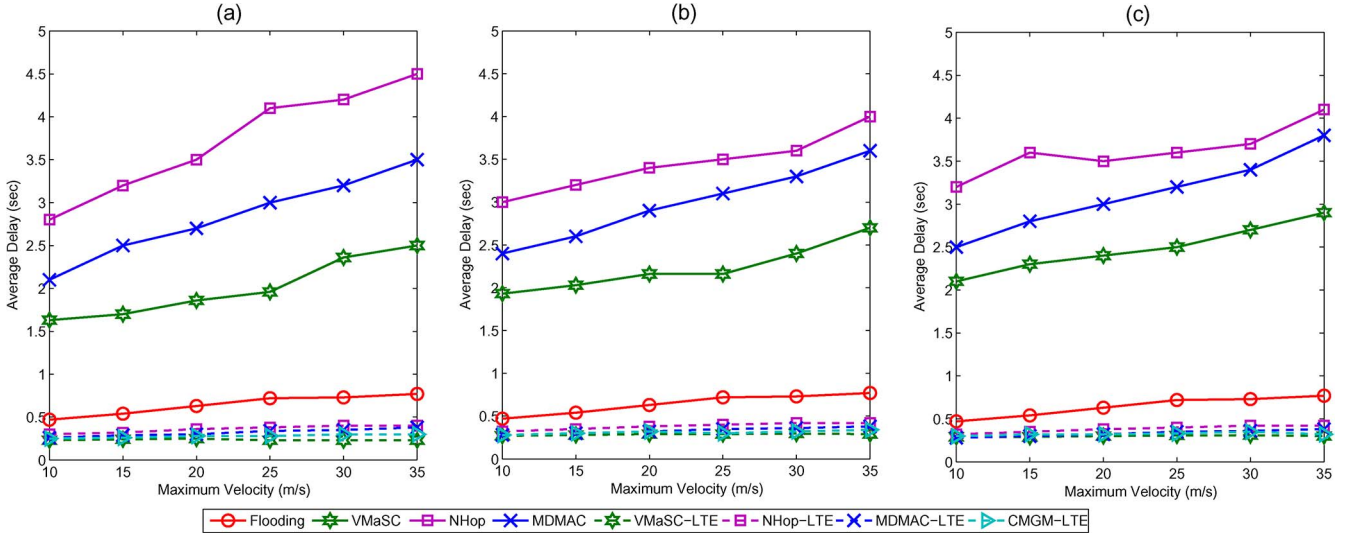


Fig. 11. Average delay of data dissemination algorithms at different maximum velocities for (a) one-hop-, (b) two-hop-, and (c) three-hop-based clustering.

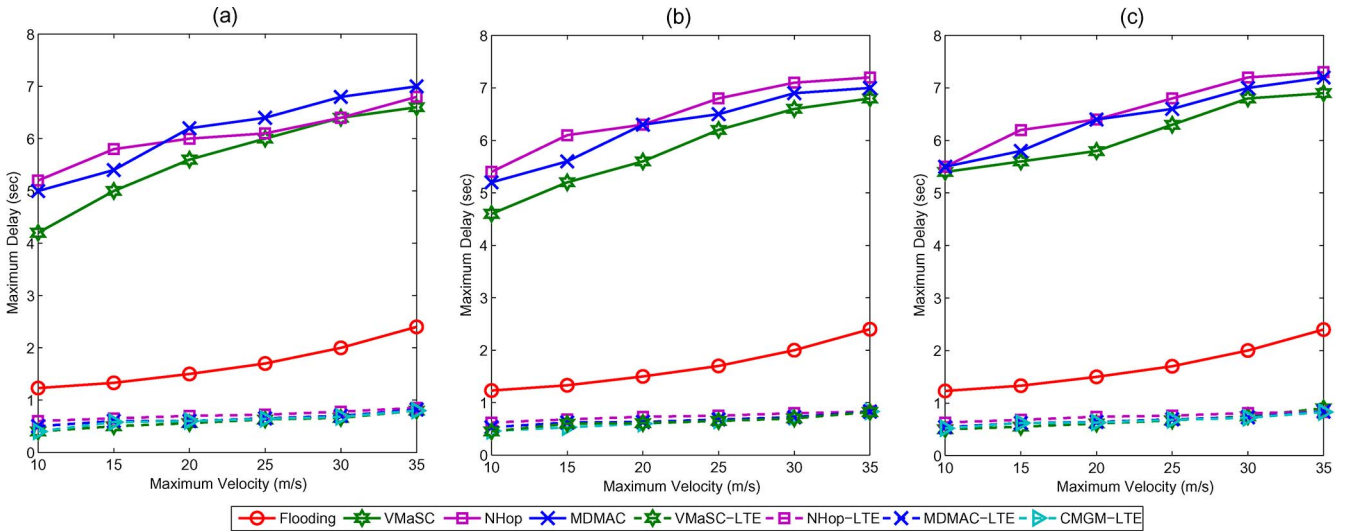


Fig. 12. Maximum delay of data dissemination algorithms at different maximum velocities for (a) one-hop-, (b) two-hop-, and (c) three-hop-based clustering.

TABLE VII
NUMBER OF CLUSTERS (LTE COST) OF VMaSC-LTE FOR DIFFERENT $MEMBER_{CH}$ AND NUMBER OF HOPS VALUES

$MEMBER_{CH}$	Number of Clusters		
	1-Hop	2-Hop	3-Hop
1	72	65	48
3	52	50	49
5	42	38	35
10	32	42	38

there exists a lot of contention around the CH. This results in the loss of packets around the CH and, thus, loss of connections to the parent node in the routing path to the CH. When the connection of a vehicle to its parent node breaks, the vehicle and all of its children transition back to the *SE* state, thus increasing the clustering overhead further and possibly creating an unnecessarily higher number of clusters.

Fig. 13 shows the dependence of the DPDR on $MEMBER_{CH}$ for different numbers of maximum allowed

hops. We observe that the DPDR increases up to 100 as $MEMBER_{CH}$ decreases. The main reason for this behavior is the decrease in the clustering overhead and contention in the IEEE 802.11p-based network with the decrease in $MEMBER_{CH}$. This demonstrates the adaptive usage of the VMaSC-LTE architecture depending on the reliability requirement of the application. As the reliability requirement of the application increases, the value of the $MEMBER_{CH}$ parameter needs to decrease at the cost of creating a larger number of clusters, thus increasing the cost of LTE usage.

VI. CONCLUSION

In this paper, we have introduced a novel architecture VMaSC-LTE that integrates 3GPP/LTE networks with IEEE 802.11p-based VANET networks. In VMaSC-LTE, vehicles are clustered in a multihop-based novel approach named VMaSC with the features of CH selection using the relative mobility metric calculated as the average relative speed with

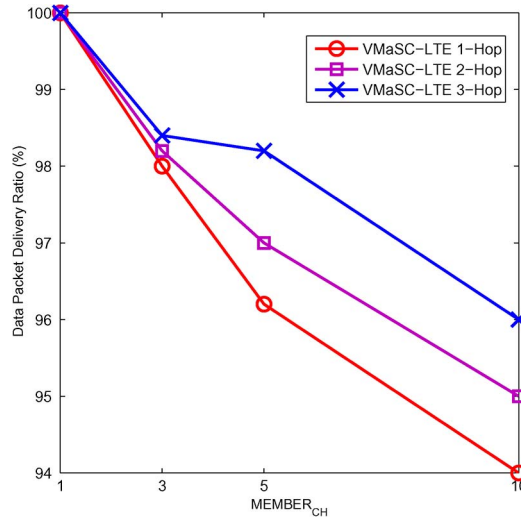


Fig. 13. DPDR of VMaSC-LTE for different $MEMBER_{CH}$ and number of hops values.

respect to the neighboring vehicles, cluster connection with minimum overhead by introducing a direct connection to the neighbor that is already a head or a member of a cluster instead of connecting to the CH in multiple hops, disseminating CM information within periodic hello packets, reactive clustering to maintain the cluster structure without excessive consumption of network resources, and efficient size- and hop-limited cluster-merging mechanism based on the exchange of cluster information among CHs. In the constructed clusters, CHs activate the LTE interface to connect the VANET to LTE.

Extensive simulations in ns-3 with the vehicle mobility input from SUMO demonstrate the superior performance of VMaSC-LTE over both previously proposed hybrid architectures and alternative routing mechanisms, including flooding and cluster-based routing. We observe that the DPDR performance of pure cluster-based data-forwarding mechanism is poor at low and high vehicle densities due to the disconnected network and broadcast storm problems, respectively. The LTE-based hybrid architecture, however, improves the performance greatly, providing a high DPDR that is stable at all vehicle traffic densities. Moreover, despite the tradeoff between DPDR and delay observed for flooding and pure cluster-based algorithms, the proposed architecture has been demonstrated to achieve both low delay and high DPDR at the cost of using the LTE infrastructure. Among the hybrid architectures, VMaSC-LTE achieves the lowest delay and highest DPDR due to better clustering stability, minimal clustering overhead, and minimal overlap among clusters. The DPDR and delay analysis at different numbers of maximum hops allowed within clusters shows that increasing the maximum number of hops up to three increases the DPDR at the cost of slight increase in the delay.

We have also defined the LTE cost metric as the cost of using LTE infrastructure to improve the data delivery performance of the hybrid architecture. The LTE cost is measured by the number of CHs in the network. We observe that the DPDR increases up to 100 as the number of members allowed in the clusters decreases. The main reason for this behavior is the decrease in the clustering overhead and contention in the IEEE

802.11p-based network with the decrease in the number of CMs. This demonstrates the adaptive usage of the VMaSC-LTE architecture depending on the reliability requirement of the application. As the required reliability of the application increases, the number of CMs needs to decrease at the cost of creating a larger number of clusters, thus increasing the cost of LTE usage.

As future work, we aim to investigate the use of VMaSC-LTE in urban traffic scenarios and extend the VMaSC-LTE architecture with data aggregation and calculation of the clustering metric with additional information such as the most probable path information of the vehicles.

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