VeSCA: Vehicular Stable Cluster-based Data Aggregation

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Abstract—**In-network data aggregation is a promising technique to reduce data transmission that contributes the effective usage of bandwidth and co-existence of different applications in vehicular ad-hoc networks (VANET). Early aggregation schemes in VANET are grouped into two categories; structure free and structure based data aggregation. In structure-free data aggregation, vehicles apply pre-defined delay value before forwarding a data packet to the next hop. On the contrary, structure-based data aggregation uses a hierarchical structure, based on either road information or vehicles, to perform data aggregation. To provide efficient and scalable VANET communication, data aggregation is essential for reducing per vehicle bandwidth requirements. In this paper, we propose a multi-hop structure based data aggregation method namely VeSCA where mobile nodes are grouped based on relative mobility with minimum-overhead cluster construction and cluster members apply data aggregation before forwarding data packet to the parent node. Using various key metrics including data aggregation ratio, delay and aggregated data delivery ratio, we demonstrate superior performance VeSCA compared both previous cluster based data aggregation and alternative aggregation mechanism via extensive simulations in ns-3 with the vehicle mobility input from the Simulation of Urban Mobility (SUMO). VeSCA achieves over 70% aggregated data packet delivery ratio with aggregation ratio 40%.**

I. INTRODUCTION

VANET is a promising technology expected to significantly improve the safety of our transportation systems via efficient data dissemination. Some VANET applications are intersection collision warning, lane merge assistance and emergency vehicle warning [1], [2], [3], that require delivery of event messages to the vehicles in a geographical area. Once an event is detected, a data packet is generated and transmitted in a multi-hop manner to reach the vehicles which are possibly several kilometers away. During the dissemination process, each vehicle behaves individually, senses the environment and generates periodic data packets with date repetition rate 1Hz. This distributed, individual and repetitive packet generation causes redundant data packet transmissions which degrades the available bandwidth. For efficient VANET communication, bandwidth utilization is crucial. Up to now, communication methods are based on IEEE 802.11p, which forms the standard for Wireless Access for Vehicular Environments (WAVE) [4]. IEEE 802.11p provides data rate ranging from 6 Mbps to 27 Mbps at short radio range, up to 1000m. However, IEEE 802.11p suffers from heavy traffic scenarios where dissemination of data packets in multi-hop manner causes scalability problems and eventually broadcast storm [5], high packet collision and low data packet delivery ratio. For example, consider a road scenario with rush hour of traffic where more than hundred vehicles are located in 1000m and they all broadcast data packets with sensed road condition and share quite limited bandwidth.

In-network data aggregation is a potential approach to provide scalability for multi-hop communication, reduce the per-vehicle bandwidth requirements, enable the co-existence of different applications in the same network and increase data packet reception rate. In-network data aggregation consists of merging data packets from various data sources and generating refined data packet for transmission. By using this approach, redundant data transmission can be effectively reduced.

Existing aggregation approaches for ad-hoc networks can be grouped into two categories; structure free data aggregation where nodes apply pre-determined delay value before forwarding a data packet to the next node with the goal of making data packets meet on the same node for aggregation, and structure-based data aggregation where a structural organization is constructed via splitting the road or grouping mobile nodes and data packets from the same road segments or data packets at forks are aggregated.

In wireless sensor network (WSN), data aggregation aims to gather the critical data from sensors and sends it to the sink node to achieve; energy efficiency and minimum data latency [19]. Data latency is an important metric for many applications both in WSN and VANET. However, the major objective in WSN is to maximize the network life-time via energy-efficient data aggregation. Several structure-based WSN aggregation techniques have been proposed [20], [21], [22], [23] using tree hierarchy and merge applied at the forks. However, proposed WSN based data aggregation schemes are not suitable for VANET due to distinct characteristics of VANETs including highly dynamic topology, hard delay and high data packet delivery requirement of safety applications. Additionally, WSN aggregation schemes assume that one base station namely sink node initiates queries to collect aggregated data sensed by nodes which makes such aggregation schemes not appropriate for vehicle-to-vehicle communication where multiple vehicles are sink nodes and they all perform data aggregation individually.

TABLE I: Related Work on Data Aggregation in VANET

Ref.	Aggregation Tech.	Aggregation Params.	Aggregated Data	Mobility Traces	Performance Criteria
[6]	Structure-Free	Speed	Traffic Information	-	Delay, Data Delivery Ratio,Throughput
[7]	Structure-Based	Weight of Information	Traffic Information	-	# Clusters, # Data Packets
[8]	Structure-Free	-	No Information	Gauss-Markov Model	Data Accuracy, Delay
[9]	Structure-Free	Fuzzy Reasoning	Traffic Information	-	Accuracy, Speed
[10]	Structure-Free	Age and Distance	Free Parking Space	VISSIM [11]	Delay, Transmission Range
[12]	Structure Free	Age and Distance	Traffic Information	VISSIM [11]	Accuracy
[13]	Structure-Based	Age and Sector	Traffic Information	-	-
[14]	Structure-Free	Age and Sector	Traffic Information	-	# Data Packets
[15]	Structure-Free	Fuzzy Reasoning	Traffic Information	GrooveNet[16]	# Data Packets, Delay
[17]	Structure-Based	-	Location Information	-	# Data Packets
[18]	Structure-Free	Distance	Location and Speed	Not Mentioned	# Data Packets

II. RELATED WORK

Table I summarizes related works on VANET aggregation techniques. In these works, data packets with sensed information are transmitted and aggregation is performed on received data packets. Used performance criteria are number of data packets; where aggregation is expected to decrease the transmitted data packets, delay; overall average delay of data packets, data delivery ratio; ratio of successfully delivered data packets.

[6], [8], [9], [10], [12], [14], [15], [18] focus on structure-free data aggregation techniques; [6] splits the road into segments and performs segment based data aggregation on periodic beacon messages, [8] models the data aggregation problem as a multi-objective optimization problem and exploits particle swarm optimization meta-heuristic algorithms, [9] uses fuzzy rule based technique to decide performing data aggregation, [10] splits the city area into non-overlapping hierarchical organization and performs section based data aggregation for free parking space discovery, [12] performs probabilistic data aggregation via using Flajolet-Martin sketch technique on grouped map data, [14] compares and analyzes the received data and stores it in specialized data structure which transforms the network message traffic into multi-level filtering system, [15] uses Q-Learning algorithm [24] to compute the packet delay and dynamically applies computed delay to make the data packets meet at the same node for data aggregation, [18] uses specialized data structure for aggregation process and tries to detect the attacker in the network. In particular, while performing structure-free data aggregation two main problems become prominent. First, aggregated packets need to be routed on-the-fly which eventually causes low data packet delivery ratio. Second, mobile nodes do not have their superior nodes therefore cannot decide how long to wait before forwarding data.

On the other hand [7], [13] perform structure based data aggregation; [7] performs clustering on vehicles and conveys the aggregation process to elected cluster heads, [13] uses road side unit (RSU) to collect data from vehicles and performs hierarchical data aggregation on RSU. However, performing data aggregation on highly dynamic topologies requires structured methods with minimum communication overhead. Moreover, proposed works only consider built-in mobility models for testing the approach, they do not consider different mobility scenarios.

In this paper, we propose a minimum overhead stable multi-hop cluster based data aggregation method namely VeSCA with the goal of minimizing the number of data packet broadcasting and maximizing the aggregated data packet delivery ratio. The original contributions of the paper are three folds. First, structuring part of aggregation is performed on vehicles with providing minimum overhead and maximum clustering stability. Second, we perform an extensive analysis of the performance of data aggregation over wide range of performance metrics including data aggregation ratio, aggregated data packet delivery ratio and average delay. Third, to the best our knowledge, the VeSCA is the first work to simulate data aggregation in multi-hop clustered network under realistic vehicle mobilities generated by SUMO [25].

III. SYSTEM MODEL

In the VeSCA system model, vehicles are clustered based on MO-VMaSC which is minimum overhead (MO) version of our earlier work VMaSC [26]. The vehicles form a multi-hop clustered topology in each direction of the road. Cluster members (CM) only communicate with their corresponding parent vehicle $PARENT$ (either (cluster head) CH or CM) whereas the CHs communicate with all CMs in cluster. The vehicles possess a GPS receiver (to get their position information) and 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, denoted by MAX_HOP. VIB is used in determining the members and heads of each cluster.

IV. VESCA DESCRIPTION

Next, we describe the cluster formation and the algorithm for data aggregation. The notation is presented in Table II.

A. Cluster Formation

VIB at each node includes the information of the vehicle itself and its neighboring vehicles. On a packet receipt, VIB is updated. The vehicle information includes its direction, location, velocity, current clustering state, the number of hops to the cluster head if it is a cluster member, the ID of the vehicle through which the node is connected to the cluster, the ID of the vehicles that use the node to connect to the

TABLE II: Notation

Notation	**Description**
IN_TIMER	Initial state timer
SE_TIMER	State election state timer
CH_TIMER	Cluster head state timer
CM_TIMER	Cluster member state timer
$STATE_{TIMER}$	Current state timer
LOC_{DATA}	Location information of data packet
$DIFF_{LOC}$	Location differences
AGE_{DATA}	Difference between current time and transmission time of data packet
MAX_HOP	Max. number of hops between CH and CM
CH_ADV	Cluster head advertisement message
$HELLO\_PKT$	Periodic hello packet
$DATA\_PKT$	Data packet
AGG_PKT	Aggregated data packet
$MAXMEMBER\_CH$	Max. members CH can serve
$MAXMEMBER\_CM$	Max. members CM can serve
ID_{DATA}	Data packet generator id
SEQ_{DATA}	Data packet sequence number
$PARENT_i$	Vehicle through which vehicle i is connected to the cluster
$CHILDREN_i$	Vehicles that use vehicle i to connect to the CH
$TransRange$	Transmission range

cluster head, clustering metric, and the source ID and sequence number of the data packets that are generated recently.

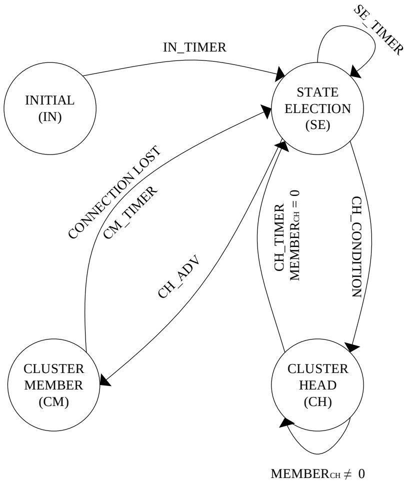

Fig. 1: State Transition of MO-VMaSC

During its lifetime, a vehicle can operate under one of the following four 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 cluster head.
- CLUSTER MEMBER (CM) is the state of the vehicle in which the vehicle is attached to an existing cluster.

Fig. 1 illustrates the possible state transitions of a vehicle. The vehicle starts in state IN, stays in this state for a duration denoted by IN_TIMER. The periodic exchange of $HELLO\_PKT$ in this state helps the node build its own VIB. The vehicle then transfers to state SE in which it makes the decision about whether to become a CH or CM. In SE, vehicles can go either CH or CM based on evaluated conditions. A vehicle transfers to CH state if the condition $CH\_CONDITION$ satisfied where it denotes the condition of having the minimum average relative speed among all vehicles in VIB. In addition, to prevent system from large size clusters, the number of vehicles that a CH can serve is limited to $MAXMEMBER\_CH$. If a vehicle in SE state receives a CH_ADV from CH then the vehicle transfers to CM state. If no CH_ADV is received then vehicle controls 1-hop CM via investigating VIB. If CM that is not MAX_HOP away from CH found, then vehicle tries to connect to this vehicle as multi-hop CM. Likewise, multi-hop cluster member number is controlled so that CM vehicles can serve up to $MAXMEMBER\_CM$ vehicles to avoid large size clusters. If none of the transitions can be made, then the node stays in state SE for a certain time denoted by SE_TIMER, then reruns clustering algorithm. The transition from state CH to SE is controlled via CH_TIMER where the number of the members of the CH denoted by $MEMBER\_CH$ is checked when the CH_TIMER is expired. If $MEMBER\_CH$ is zero then vehicle changes states to SE. Finally, the transition from CM to SE occurs if the vehicle has lost connection to the neighboring node through which it is connected to the cluster. When the CM_TIMER expires, CM vehicle checks the VIB to control if it receives packet from parent vehicle. If CM vehicle does not receive any packet from parent vehicle, CM vehicle assumes that it has lost the connection and changes state to SE. MO-VMaSC differs from our previous works VMaSC [26] in maintaining cluster structure. MO-VMaSC does not require explicit message exchange between vehicle pairs. Instead, it only uses CH_ADV of CHs and periodic $HELLO\_PKT$ to control cluster structure.

B. Data Aggregation

The goal of VeSCA is to aggregate the data packets and disseminate the aggregated packets at a certain vehicle to all the vehicles within a geographic area with small delay and high delivery ratio. The data aggregation and forwarding at a vehicle depends on its clustering state. If its clustering state is SE, the vehicle broadcasts the $DATA\_PKT$ so that it reaches a member of any cluster in the network. If the clustering state of the vehicle generating or receiving a $DATA\_PKT$ is CM or CH, the vehicle runs Algorithm 1.

As provided in the algorithm, data aggregation process starts when a data packet is received or generated at a vehicle. Then, vehicle checks whether the packet has been already received via checking the VIB (Lines $2-3$). If vehicle receives the data packet for the first time, it checks the source of the packet. If it is coming from its parent vehicle in cluster tree, denoted by $PARENT_{curr}$, then it multicasts the packet to all its children (Lines $4-5$). If packet is coming from its children or other vehicles, then vehicle investigates the VIB to find similar data packets for aggregation (Lines $7-14$). For all data packet in VIB, location and transmit time information are extracted (Lines 8). If data packet is received in current state time duration then location differences of data packets

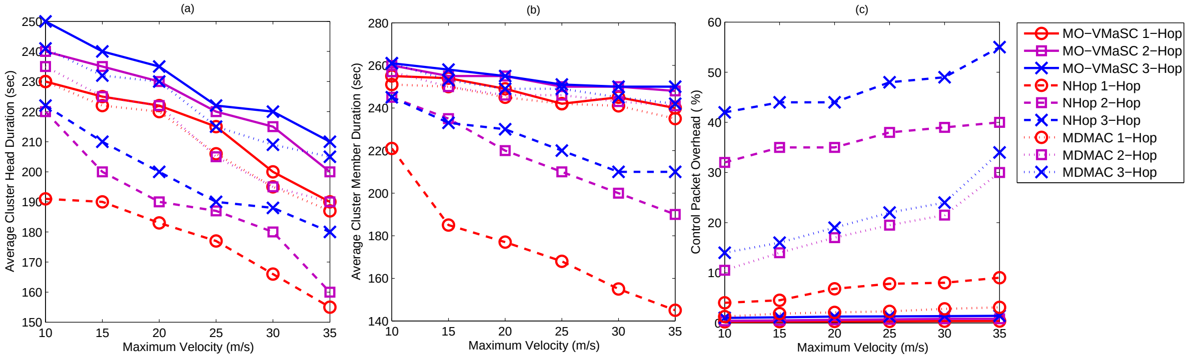

Fig. 2: Clustering Results of different algorithms at different maximum velocities for (a) Average Cluster Head Duration, (b) Average Cluster Member Duration (c) Control Packet Overhead

Algorithm 1: Data Aggregation Algorithm

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1  on $DATA\_PKT$ generating or receipt;
2  Extract $ID_{DATA}$ and $SEQ_{DATA}$;
3  if $(ID_{DATA}, SEQ_{DATA}) \notin VIB$ then
4      if $DATA\_PKT$ is from $PARENT_{curr}$ then
5          Multicast $DATA\_PKT$ to $CHILDREN_{curr}$;
6      else
7          forall the $DATA\_PKT \in VIB$ do
8              Extract $LOC_{DATA}$ and $AGE_{DATA}$;
9              if $AGE_{DATA} < STATE_{TIMER}$ then
10                 $DIFF_{LOC}$=$LocDiff(DATA\_PKT$s);
11                 if $DIFF_{LOC} < TransRange$ then
12                     Combine $DATA\_PKT$s;
13                     Construct $AGG\_PKT$;
14         forall the $AGG\_PKT \in VIB$ do
15             if $CM$ then
16                 Unicast $AGG\_PKT$ to $PARENT_{curr}$;
17             else if $CH$ then
18                 Broadcast $AGG\_PKT$ ;
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are compared. If location differences of data packets are smaller than transmission range of vehicle and if they are not aggregated before, packets are combined and aggregated data packet is constructed (Lines $9-14$). After aggregation process, instead of sending data packet individually, aggregated data packets are forwarded by controlling the vehicle current state (Lines $14-18$).

V. PERFORMANCE EVALUATION

We implemented our proposed VeSCA technique on Network Simulator-ns3 (Release 3.17) [27] and used the topology of the network generated by SUMO (Simulation of Urban Mobility) [25]. SUMO, generated by the German Aerospace Center, is an open-source, space-continuous, discrete-time traffic simulator capable of modeling the behavior of individual drivers. The acceleration and overtaking decision of the vehicles are determined by using the distance to the leading vehicle, traveling speed, dimension of vehicles and profile of acceleration deceleration.

Our scenarios consist of a two-lane and two-way road of length 5 km. The total simulation time is 600 s. The clustering process starts at 300 s when all the vehicles have entered the road. All the performance metrics are evaluated for the remaining 300 s. Table III lists the general simulation parameters of the VANET, and the default values.

TABLE III: Simulation Parameters

Parameters	Value
Simulation Time	300 s
Area range	1000 m x 1000 m
Maximum Velocity	10 - 35 m/s
MAX_HOP	1,2 and 3
Number Of Vehicles	100
Transmission Range	200 m
$HELLO\_PKT$ period	200 ms
$HELLO\_PKT$ size	64 bytes
$DATA\_PKT$ period	1 s
$DATA\_PKT$ size	1024 bytes
$MAXMEMBER\_CH$	5
$MAXMEMBER\_CM$	1
VIB_TIMER	1 s
IN_TIMER	2 s
SE_TIMER	2 s
CH_TIMER	2 s
CM_TIMER	2 s

We first evaluate and compare the efficiency of the clustering algorithm in terms of overhead and cluster stability. Then, we conduct comparative performance analysis of VeSCA data aggregation. The performance metrics used are average cluster head duration, average cluster member duration, control packet overhead, data aggregation ratio, delay and aggregated data packet delivery ratio. Cluster related metrics are used to demonstrate the stability and reduced overhead of clustering algorithm. On the other hand, data packet related metrics are used to measure aggregation performance of VeSCA in VANET scenarios.

A. VANET Minimum Overhead Clustering

The proposed multi-hop clustering, denoted by MO-VMaSC, is compared to two previously proposed VANET multi-hop clustering algorithms. The first one denoted by

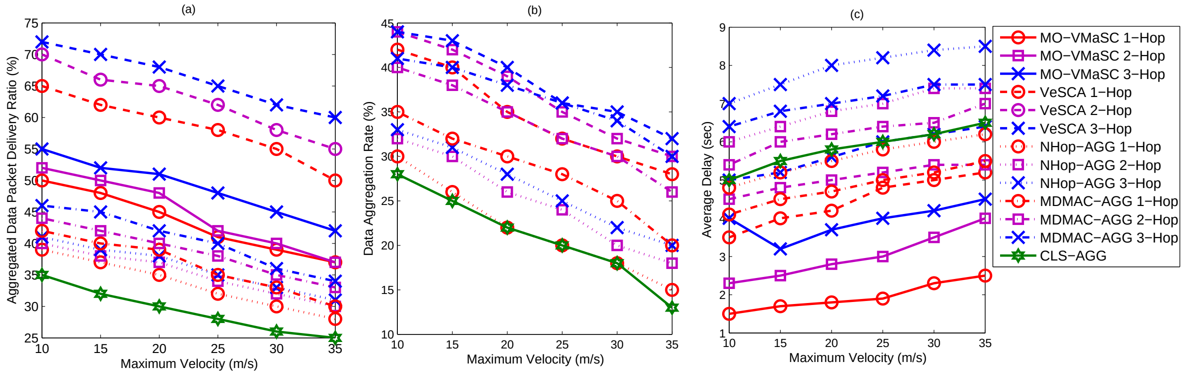

Fig. 3: Aggregation Results of different algorithms at different maximum velocities for (a) Aggregated Data Packet Delivery Ratio, (b) Data Aggregation Rate (c)Average Delay

NHop refers to [28] where the relative mobility is computed based on the variation of the packet transmission delay of two consecutive messages. The second one on the other hand is denoted by MDMAC referring to [29] where the location and velocity of the vehicles are used to estimate the duration of the vehicles staying neighbors with each other in determining cluster heads.

1) Cluster Stability: Cluster stability is measured as average time that vehicle is connected to constructed cluster either being a cluster member or a cluster head. To measure the cluster stability, cluster head and cluster member duration are computed. Cluster head duration is defined as the time period from when a vehicle changes state to CH to when a vehicle transfers from state CH to state SE or CM . Cluster head duration is computed by dividing the total cluster head duration by the total number of state changes from CH to another state. Similarly, cluster member duration is computed by dividing the total cluster member duration by the total state changes from CM to another state. Fig. 2-a and Fig. 2-b show the average cluster head duration and average cluster member duration of different clustering algorithms for different maximum vehicle velocities. For all scenarios, MO-VMaSC has higher cluster head duration and cluster member duration than NHop and MDMAC. Due to higher chance to find a member to serve in multi-hop scenarios, as the hop number increases, head duration and member duration also increase. However, increase in velocity makes network topology change rapidly and causes decrease in cluster head duration and member duration.

2) Control Packet Overhead: Clustering control packet overhead is defined as the ratio of the total number of clustering related packets to the total number of packets generated within the VANET. Fig. 2-c shows the control packet overhead of different clustering algorithm for different maximum number of hops at different vehicle velocities. For all scenarios, MO-VMaSC has lower control packet overhead (Fig. 2-c bottom 3 line) compared to other multi-hop clustering approach. This is because, MO-VMaSC has no explicit message exchange for cluster construction or maintenance like join request or join response.

B. VANET Data Aggregation

VeSCA is compared with previously proposed cluster based data aggregation approach in [7] namely CLS-AGG where network is grouped into clusters and elected CH performs data aggregation. To compare the effect of clustering on data aggregation, previously proposed multi-hop clustering techniques; NHop [28] and MDMAC [29] are integrated with Algorithm 1 namely NHop-AGG and MDMAC-AGG respectively.

1) Aggregated Data Packet Delivery Ratio (ADPDR): ADPDR is defined as the average ratio of the total number of vehicles successfully receiving AGG_PKT s to the total number of the vehicles within the target geographical area. Fig. 3-a shows ADPDR of different algorithms in different velocities with different maximum number of hops. For all scenarios, VeSCA has higher ADPDR than other cluster based aggregation techniques. The main reason behind this is the underling cluster structure where MO-VMaSC clustering maximizes the cluster life time in a way that collected data packets in parent nodes are aggregated efficiently. In addition, as the vehicle velocity increases, ADPDR value decreases. This can be explained via Fig 3-b where the velocity degrades the data aggregation rate. Highly mobile vehicles change location randomly and affect the aggregation process which eventually decreases the aggregated data delivery. In addition, as the hop number increases, ADPDR also increases. This is because of multi-level aggregation where data is aggregated in different hops up to CH for dissemination.

2) Data Aggregation Ratio: The data aggregation ratio is computed as the ratio of aggregated data packet counter to the number of generated data packets. Data aggregation ratio demonstrates the efficiency of underlying aggregation protocol in terms of how many packets are generated and how many of them are aggregated. Fig 3-b shows aggregation ratio of different aggregation techniques at different vehicle velocities. Compared to other cluster based aggregations,VeSCA has high data aggregation ratio. Moreover, we observe that increasing the maximum number of hops allowed increases the data aggregation ratio where more packets can be aggregated at forks up to parent vehicle. Furthermore, data aggregation ratio in all scenarios has tendency to decrease as the velocity increases. This is due to network dynamicity where highly mobile nodes change location randomly and generate data packets in different location.

3) Average Delay: This metric is defined as the average latency of the AGG_PKTs that travel from their source to the vehicles within the target geographical area. Fig. 3-c shows the average delay of different aggregation algorithms in different velocity scenarios. VeSCA has lower average delay value compared to other aggregation embedded approaches in all scenarios. Moreover, despite the delay value of pure MO-VMaSC is lower than aggregated version, MO-VMaSC has lower data delivery ratio. This is due to dissemination of parent nodes where they broadcast the coming data packet without performing data aggregation. Data aggregation enables parent nodes to disseminate low number of packets but it increases the average delay of dissemination process.

VI. CONCLUSION

We proposed a novel multi-hop structure based data aggregation technique VeSCA where vehicles are grouped based on relative mobility and cluster members perform data aggregation before forwarding a data packet to the next hop. Extensive simulations in ns-3 with the vehicle mobility input from SUMO demonstrate the superior performance of the VeSCA over both previously proposed cluster based data aggregation and alternative aggregation mechanisms. We observe that aggregation is directly related with the underlying cluster structure and cluster stability plays an important role in the aggregation ratio. As future work, we plan to extend the VeSCA to VANET-3GPP hybrid architectures and investigate the use of the proposed aggregation scheme in urban traffic scenarios.

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